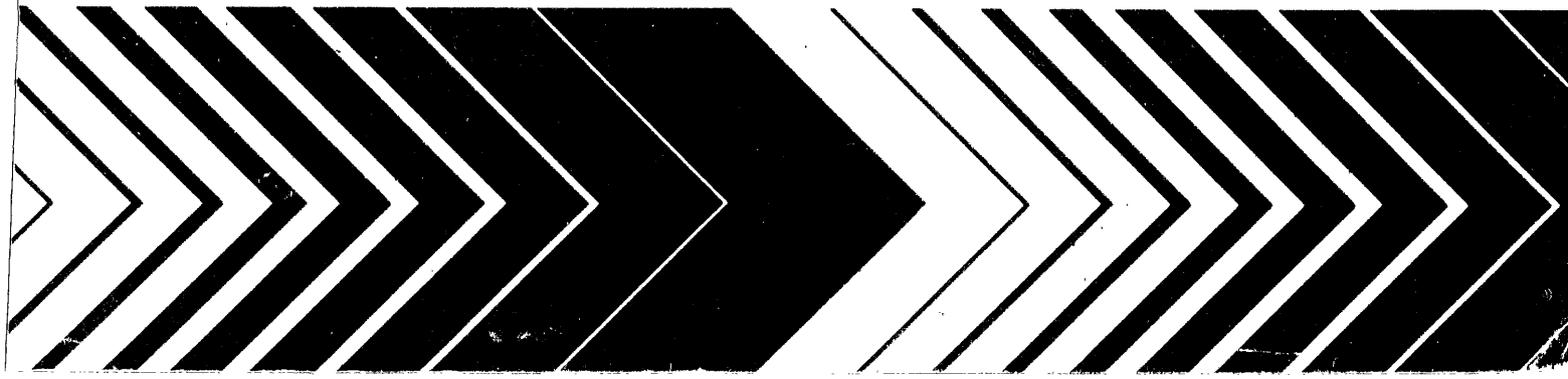


Research and Development



Lining of Waste Containment and Other Impoundment Facilities



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LINING OF WASTE CONTAINMENT
AND OTHER IMPOUNDMENT FACILITIES

by

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FOREWORD

Today's rapidly developing and changing technologies and industrial products and practices frequently carry with them the increased generation of solid and hazardous wastes. These materials, if improperly dealt with, can threaten both public health and the environment. Abandoned waste sites and accidental releases of toxic and hazardous substances to the environment also have important environmental and public health implications. The Risk Reduction Engineering Laboratory assists in providing an authoritative and defensible engineering basis for assessing and solving these problems. Its products support the policies, programs and regulations of the Environmental Protection Agency, the permitting and other responsibilities of State and local governments and the needs of both large and small businesses in handling their wastes responsibly and economically.

This report describes and details the major aspects of flexible membrane liners and other materials used in the construction of containment units for the storage or disposal of hazardous and/or nonhazardous wastes or substances. Various procedures are presented as to the selection, manufacture, construction, and use of the major types of flexible membrane liners and ancillary materials to minimize the possibility of adverse environmental impact.

E. Timothy Oppelt, Acting Director
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ABSTRACT

This technical resource document provides current technological information on liner and cover systems for waste storage and disposal units. Liner systems serve to control the release of liquid and gaseous waste components into the environment whereas cover systems, which are constructed during the closure of a landfill, serve to prevent liquids from entering the landfill, thereby reducing the potential for leachate generation. The various materials used in the construction of these systems are discussed, with particular emphasis on polymeric flexible membrane liners (FMLs). The types and properties of wastes that may be impounded in land storage and disposal units and the constituents of these wastes that can affect lining materials are discussed. The conditions inside a containment unit are described, including the mechanisms of constituent transport within and out of a unit and the service conditions for a lining system in different types of containment units. The properties of FMLs and other materials of construction for waste containment units are discussed, and the effects of exposing these materials to simulated and actual service conditions are presented. Elements of the design, specifications, construction, quality assurance, and maintenance of a lined waste containment unit are discussed. Costs for the components of a lining system, including their installation and construction, are presented. Several test methods that were useful in determining waste/FML compatibility are included. A representative list of organizations in the liner industry is presented as an appendix.

PREFACE

Subtitle C of the Resource Conservation and Recovery Act (RCRA) requires the U. S. Environmental Protection Agency (EPA) to establish a Federal hazardous waste management program. This program must ensure that hazardous wastes are handled safely from generation until final disposition. EPA issued a series of hazardous waste regulations under Subtitle C of RCRA that are published in Title 40 Code of Federal Regulations (CFR) Parts 260 through 265 and Parts 122 through 124.

Parts 264 and 265 of 40 CFR contain standards applicable to owners/operators of all facilities that treat, store, or dispose of hazardous wastes. Wastes are identified or listed as hazardous under 40 CFR Part 261. Part 264 standards are implemented through permits issued by authorized States or EPA according to 40 CFR Part 122 and Part 124 regulations. Land treatment, storage, and disposal (LTSD) regulations in 40 CFR Part 264 issued on July 26, 1982, and July 15, 1985, establish performance standards for hazardous waste landfills, surface impoundments, land treatment units, and wastepiles. Part 265 standards impose minimum technology requirements on the owners/operators of certain landfills and surface impoundments.

EPA is developing three types of documents to assist preparers and reviewers of permit applications for hazardous waste land disposal facilities. These are RCRA Technical Guidance Documents (TGDs), Permit Guidance Manuals, and Technical Resource Documents (TRDs). Although emphasis is given to hazardous waste facilities, the information presented in these documents may be used for designing, constructing, and operating nonhazardous waste LTSD facilities as well.

The RCRA TGDs present design, construction, and operating specifications or evaluation techniques that generally comply with or demonstrate compliance with the Design and Operating Requirements and the Closure and Post-Closure Requirements of Part 264. The Permit Guidance Manuals are being developed to describe the permit application information the Agency seeks and to provide guidance to applicants and permit writers in addressing information requirements. These manuals will include a discussion of each step in the permitting process and a description of each set of specifications that must be considered for inclusion in the permit.

The TGDs and Permit Guidance Manuals present guidance, not regulations. They do not supersede the regulations promulgated under RCRA and published in

the CFR. Instead, they provide recommendations, interpretations, suggestions, and references to additional information that may be used to help interpret the requirements of the regulations. The recommendation of methods, procedures, techniques, or specifications in these manuals and documents is not intended to suggest that other alternatives might not satisfy regulatory requirements.

The TRDs present summaries of state-of-the-art technologies and evaluation techniques determined by the Agency to constitute good engineering designs, practices, and procedures. They support the RCRA TGDs and Permit Guidance Manuals in certain areas by describing current technologies and methods for designing hazardous waste facilities or for evaluating the performance of a facility design. Whereas the RCRA TGDs and Permit Guidance Manuals are directly related to the regulations, the information in the TRDs covers a broader perspective and should not be used to interpret the requirements of the regulations.

This document is a Technical Resource Document. It is a thoroughly revised edition of the 1983 edition which was published by the Municipal Environmental Research Laboratory of the EPA. This edition reflects the changes in regulations and the advances in waste containment technology that have taken place since 1983. It also reflects the considerable research that has been performed in the area of waste containment and the experience that has been gained in this technology. This new edition incorporates the many responses to comments received in the peer review of the draft. This document supercedes the March 1983 edition.

Comments on this revised publication will be accepted at any time. The agency intends to update these TRDs periodically based on comments received and/or the development of new information. Comments on any of the current TRDs should be addressed to Docket Clerk, Room S-269(c), Office of Solid Waste and Emergency Response (WH-562), U.S. Environmental Protection Agency, 401 M Street, S.W., Washington, D.C., 20460. Communications should identify the document by title and number (e.g., "Lining of Waste Containment and Other Impoundment Facilities", SW-870).

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ABBREVIATIONS AND SYMBOLS

Å	Angstrom
A	Available; Area of flow; Inside cross-sectional area of a sample container; Acetone
AA	Atomic absorption
ABS	Acrylonitrile-butadiene-styrene
AEM	Acoustical emission monitoring
AET	Actual evapotranspiration
Ag	Silver
Al	Aluminum
ALR	Action leakage rate
AM	Amorphous
API	American Petroleum Institute
As	Arsenic
ASAE	American Society of Agricultural Engineers
ASTM	American Society for Testing and Materials
atm	Atmosphere, unit of pressure
β	Slope angle
b	Experimentally obtained constant
B	Boron
Ba	Barium
Be	Beryllium
Bi	Bismuth
Bit	Bitumin
BOD	Biochemical oxygen demand
BOD ₅	Biochemical oxygen demand (5 days)
BTU/lb	British Thermal Units per pound
c	Soil cohesion
C	Celsius
C _a	Adhesion
ca	Approximately
Ca	Calcium; shear strength parameters of adhesion
CaCl ₂	Calcium chloride
CaCO ₃	Calcium carbonate
CaF ₂	Calcium fluoride
cal	Calorie
cal/g	Calories per gram
CCl ₄	Carbon tetrachloride
Cd	Cadmium
CED	Cohesive energy density
CERCLA	Comprehensive Environmental Response, Compensation and Liability Act (Superfund)

CFR	Code of Federal Regulations
CH ₃ OH	Methyl alcohol
CH ₄	Methane
CHRONS	Carbon, hydrogen, oxygen, nitrogen, sulfur
Cl	Chloride
cm	Centimeter
cm s ⁻¹	Centimeters per second
CO	Epichlorohydrin polymer
CO ₂	Carbon dioxide
Co	Cobalt
COD	Chemical oxygen demand
cP	Centipoise
CPE	Chlorinated polyethylene
CQA	Construction quality assurance
CQC	Construction quality control
CR	Chloroprene rubber - neoprene
Cr	Chromium
CSPE	Chlorosulfonated polyethylene
CSPE-LW	Chlorosulfonated polyethylene - low water absorption, i.e. industrial grade
Cu	Copper
cu	Cubic
cu yd	Cubic yard
CX	Crystalline or semicrystalline thermoplastic
D	Dissolved or disintegrated; Diffusion coefficient
d	Day, denier
d _{soil}	Some particle size of the soil (often d ₈₅)
d ₈₅	Particle size, at which 85% of the soil is finer
δ	Friction angle, potential energy of organics
δ _d	Dispersive parameter
δ _h	Hydrogen bonding parameter
δ _o	Hildebrand solubility parameter
δ _p	Polarity parameter
δ _t	Total Hansen solubility parameter
ΔE	Energy required to vaporize one mole of material
ΔH _f	Heat of fusion
Δh	Hydraulic head difference
Δp	Vapor pressure difference
db	Dry basis
DDD	Dichlorodiphenyldichloroethane
DDT	Dichlorodiphenyltrichloroethane
DEHP	di(ethyl-hexyl) phthalate
DI	Deionized
DMK	Dimethylketone
DOP	Dioctyl phthalate
DRE	Destruction and removal efficiency
DSC	Differential scanning calorimetry
ε	Deformation
ea	Each
EC	Electrical conductivity
E _c	Cohesion efficiency

ECB	Ethylene copolymer with bitumen
ECO	Epichlorohydrin rubber (copolymer of ethylene oxide and chloromethyl oxirane)
e.g.	For example
Eh	Redox potential
EIA	Ethylene interpolymer alloy
ELPO	Elasticized polyolefin
EMMAQUA	Equatorial Mount with Mirrors for Acceleration Plus Water Spray (Accelerated outdoor weathering using concentrated natural sunlight)
$E\phi$	Friction angle efficiency
EP	Expanded polystyrene, extraction procedure
EPA	Environmental Protection Agency
epi	Ends per inch
EPDM	Ethylene propylene rubber
EPRI	Electric Power Research Institute
EPTC	Extraction Procedure for Toxic Characteristic
ER	Electrical resistivity
ESC	Environmental stress cracking
et al	And others
etc	And the like
EVA	Ethylene vinyl acetate
F	Fluorine; Fahrenheit
FDC	First derivative computer
Fe	Iron
FGD	Flue gas desulfurization
FLEX	Flexible liner evaluation expert
FML	Flexible membrane liner
FR	Fabric-reinforced
FS	Flow rate factor of safety; factor of safety
ft	Foot
FTB	Film tear bond
FTMS	Federal Test Method Standard
γ_d	Dry density
$\gamma_{d_{max}}$	Maximum dry density
$\gamma_{d_{tar}}$	Target density
γ_t	Total (or wet) density
GC	Gas chromatography
GC/MS	Gas chromatography/mass spectroscopy
g	Gram
g/cm	Grams per centimeter
g/kg	Grams per kilogram
g/L	Grams per liter
g/mL	Grams per milliliter
gal	Gallon
gal/sq yd	Gallons per square yard
Ge	Germanium
gpad	gallons per acre per day
gpm	Gallons per minute
GTR	Gas transmission rate
h	Hour; Height

H	Height
H ₂ O	Water
H ₂ S	Hydrogen sulfide
HAC	Hydraulic asphalt concrete
HCl	Hydrochloric acid
HDPE	High-density polyethylene
HDPE-A	High-density polyethylene - alloy
HELP	Hydrologic Evaluation of Landfill Performance
HFL	Hydrofluoric acid waste
Hg	Mercury
HIPS	High impact polystyrene
HNO ₃ -HF-HOAc	Nitric acid-hydrofluoric acid-acetic acid waste
HSGC	Headspace gas chromatography
HSWA	Hazardous and Solid Waste Amendment of 1984
i	Hydraulic gradient
i.e.	That is
IIR	Isobutylene-isoprene rubber (butyl rubber)
in.	Inch
ipm	Inches per minute
IR	Infrared
k	Darcy's coefficient of permeability
K	Potassium; permeability
kg	Kilogram
kN	Kilonewton
k _n	Permeability normal to the plane of the fabric
KOH	Potash
kPa	Kilopascal
k _p	Planar coefficient of permeability
λ	A value depending on soil density, gradation, fabric-type, etc.
L	Liter, length
lb	Pound
lbf	Pounds (force)
lb/ft	Pounds per foot
LCRS	Leachate collection and removal system
LDCRS	Leak detection, collection and removal system
LDPE	Low-density polyethylene
LF	Lineal foot
LLDPE	Linear low-density polyethylene
Li	Lithium
LiCl	Lithium chloride
LPG	Low-pressure gas
LVT	Low temperature curing cement
m	Meter
μg	Micrograms
μg/kg	Micrograms per kilogram
μg/L	Micrograms per liter
μL	Microliter
μm	Micrometer
μmho	Micromho
μmho/cm	Micromhos per centimeter

MBAS	Methylene blue active substances
mcal	Millicalorie
mcal/sec	Millicalories per second
MDPE	Medium density polyethylene
MEK	Methyl ethyl ketone
Mg	Magnesium
mg	Milligram
mg Cl/L	Milligrams of chloride per liter
mg/kg	Milligram per kilogram
mg/L	Milligram per liter
MIBC	Methyl isobutyl carbinol
mil	Inch x 0.001
min.	minute
MJ	Millijoule
mL	Milliliter
mL/L	Milliliters per liter
mL/min.	Milliliters per minute
mm	Millimeter
Mn	Manganese
Mo	Molybdenum
mo	Month
MP	Melting point; Mega poise
MPa	Mega pascals
MSW	Municipal solid waste
MTG	Minimum Technology Guidance
MTM	Matrecon Test Method
MW	Molecular weight
n	Number of reinforcement layers
N	Nitrogen; Newton
N ₂	Nitrogen
Na	Sodium
NA	Not available
na	Not applicable
NaCl	Sodium chloride
NaOH	Sodium hydroxide
NBR	Nitrile rubber
NBS	National Bureau of Standards
n.d.	No date
ND	None detected
ng	Nanogram
ng/L	Nanograms per liter
NH ₃	Ammonia
NH ₄	Ammonia salts
Ni	Nickel
N/m	Newtons per meter
NO ₂	Nitrite
NO ₃ -N	Nitrate nitrogen
NSF	National Sanitation Foundation
O ₂	Oxygen
O _{fabric}	some opening size of the fabric
O ₉₅	95% opening size of the fabric
OIT	Oxidative induction time

oz	Ounce
ϕ	Soil friction angle
ψ	Permittivity
ψ_{act}	Actual, or test, value
$\psi_{req'd}$	Required, or design, value
P	Phosphate; Primary function; Precipitation
\bar{P}	Permeability coefficient, gas
PA	Polyamide-nylon
PB	Polybutylene
Pb	Lead
PCA	Portland Cement Association
PCB	Polychlorinated biphenyls
pCi/L	Pico curie per liter
PCCP	Post-closure care period
PE	Polyethylene
PEL	Polyester elastomer
PERC	Percolation
perm	Permeance
PET	Polyester terphthalate
PIB	Polyisobutylene
Po	Polonium
POA	Percent open area
PP	Polypropylene
ppi	Pounds per inch
ppm	Parts per million
psf	Pounds per square foot
psi	Pounds per square inch
PU	Polyurethane
PVC	Polyvinyl chloride
PVC-E	Polyvinyl chloride, elasticized
PVC-OR	Polyvinyl chloride, oil-resistant
Q,q	Rate of flow
QA/QC	Quality assurance/quality control
qt	Quart
ρ	soil bulk density
R	Fabric-reinforced; radius of failure arc
Ra	Radium
RAP	Response Action Plan
RCRA	The Resource Conservation and Recovery Act
RH	Relative humidity
RLL	Rapid and extremely large leakage
RO	Surface run off
RQD	Rock quality designation
σ_n	Normal stress
σ_v	Vertical stress
S	Secondary function; Solubility coefficient
S/S	Solidification/stabilization
s	Second
S-100	Stress at 100% elongation
S-200	Stress at 200% elongation
SAE	Society of Automotive Engineers

Sb	Antimony
SBR	Styrene-butadiene rubber
SDRI	Sealed double-ring infiltrometer
Se	Selenium
sec	Second
Si	Silicon
SO ₂	Sulfite
SO ₄	Sulfate
SP	The SP grade of coarse sand under USCS
sq	Square
sq ft	Square foot
sq yd	Square yard
Sr	Strontium
ST	Soil moisture storage
STP	Standard temperature and pressure
SVT	Solvent vapor transmission
τ	Shear stress of the soil; Shear strength of the soil
θ	Transmissivity
T _i	Allowable strength of geogrids
t	Thickness of the fabric; Time
Ta	Tantalum
TBP	Tributyl phosphate
TCA	1, 1, 1-trichloroethane
TCLP	Toxicity Characteristic Leaching Procedure
TCE	Trichloroethylene
TDR	Time-domain reflectometry
TDS	Total dissolved solids
TGA	Thermogravimetric analysis
Th	Thorium
THF	Tetrahydrofuran
Ti	Titanium
T _i	Allowable strength of geogrid or geotextile
T _m	Melting temperature of crystalline phase
TMTDS	Tetramethyl thiuram disulfide
TN-PVC	Thermoplastic nitrile
TOC	Total organic carbon
TOX	Total organic halides
TP	Thermoplastic
TRD	Technical Resource Document
TS	Total solids
TSDF	Treatment, storage, and disposal facility
TSS	Total suspended solids
TVA	Total volatile acids
TVS	Total volatile solids
U	Uranium; unreinforced
USCS	Unified Soil Classification System
USLE	Universal Soil Loss Equation
UV	Ultraviolet
V	Vanadium
V _E	Percent volatiles of a sample after exposure
V _m	Molar volume

vs	versus
w _{opt}	Optimum water content
W	Width; waste; moisture (or water) content; Weight of failure zone
wt	Weight
WVT	Water Vapor Transmission
x	Xylene
X	Moment arm to centroid of failure zone
XL	Crosslinked
yd	Yard
Y _i	Moment arms to each level of geogrid
Yr	Year
Zn	Zinc
Zr	Zirconium

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CHAPTER 1

INTRODUCTION

1.1 BACKGROUND

In 1965 Congress passed the Solid Waste Disposal Act, the first federal statute to require safeguards and encourage environmentally sound methods for disposing of wastes. Congress amended this law in 1970 and again in 1976 by passing the Resource Conservation and Recovery Act (RCRA), PL-94-580. Subtitle C of this act required the U.S. Environmental Protection Agency (EPA) to establish a Federal hazardous waste management program and mandated that the EPA promulgate regulations establishing performance standards and requirements for the location, design, and construction of hazardous waste treatment, storage, and disposal facilities (TSDFs). Subtitle D established a cooperative framework for Federal, State, and local governments to control the management of solid wastes not covered by Subtitle C. The goal of RCRA is to ensure that waste TSDFs are designed, constructed, and operated in a manner that protects human health and the environment.

The EPA has issued a series of waste regulations under Subtitles C and D of RCRA in the Code of Federal Regulations (CFR). On September 13, 1979, the EPA first promulgated criteria for classification of solid waste disposal facilities and practices (40 CFR 257). These criteria established minimum performance standards for all solid waste storage and disposal facilities. On May 19, 1980, EPA issued general standards that identified which wastes were hazardous and created a system for the management of hazardous wastes which included a tracking system to monitor the movement of hazardous wastes from the point of generation to final disposal (40 CFR 260-65). These general standards also delineated basic performance objectives necessary for safe handling and control of hazardous wastes during generation, transport, treatment, storage, and disposal.

As knowledge about the environmental impacts of waste disposal increased and technology for the handling of hazardous wastes developed, Congress revised RCRA again in 1984. These amendments are also known as the Hazardous and Solid Waste Amendments of 1984 (HSWA), PL-98-616. HSWA established minimum technological requirements for new hazardous waste landfills and surface impoundments and required the EPA to promulgate regulations or issue guidance documents regarding the implementation of these requirements. Since then, the EPA has promulgated regulations detailing operation and design requirements for hazardous waste TSDFs. These regulations have been incorporated in 40 CFR 264. The EPA has also issued for comment and use draft minimum technology

guidance (MTG) documents on double liner systems for hazardous waste landfills and surface impoundments (EPA, 1985) and on final cover systems for hazardous waste landfills and surface impoundments (EPA, 1987a). Both the minimum technology requirement regulations and the MTG documents are presently under review. EPA eventually will formalize additional technology guidelines by incorporating them into the Agency's regulations. HSWA also mandated continued review of the performance standards for Subtitle D (nonhazardous) solid waste TSDFs to determine whether the current criteria are adequate for protecting human health and the environment.

One method of protecting the environment and human health is to prevent hazardous and toxic waste constituents from migrating out of a waste TSDF unit into other areas, particularly the groundwater. To a great extent, this can be accomplished by controlling the liquid components of the impounded waste. Two strategies are being used to control liquids: one is to prevent any liquids present in the unit from escaping into the surrounding environment; and the other, in the case of landfills, is to minimize leachate generation by keeping liquids out of the unit. Methods of keeping liquids out include building a cover on top of the landfill at the end of its active life, banning the disposal of liquids, preventing surface run-off from entering the unit, etc.

Placing hazardous wastes in lined TSDF units is a key element in the Federal waste management program. Except in cases where the conditions for statutory variance are met, HSWA required new hazardous waste landfills and surface impoundments to have two or more liners, a leachate collection and removal system (LCRS) between these liners, and (in the case of a landfill) an LCRS above these liners. The different components of the lining system include flexible membrane liners (FMLs), soil liners, and the components of the LCRSs. Present EPA guidance requires the bottom liner to be a composite liner consisting of both an FML and a soil liner, and the top liner to be, at a minimum, an FML. A liner is a barrier that greatly restricts the migration of liquids. No single liner, however, can prevent the migration of some liquids due to vapor transmission or leakage caused by either imperfect installation or breaches that develop during service. In addition, a liner does not have structural strength. Only as a component of an engineered system with a rigorous operational program can a liner minimize the migration into the environment of hazardous constituents placed in land storage or disposal units. FMLs are also used as barriers in final covers for landfills to control the infiltration of water (e.g. from rain, surface run-off, etc.) into the closed unit.

Other important components of a lining system include the LCRSs. These systems can be comprised of both synthetic and granular materials. In a landfill, the purpose of the LCRS above the top liner is to minimize the head of leachate on the top liner during the active life of the landfill and to remove liquids during the post-closure care period. The purpose of the LCRS between the two liners is to rapidly detect, collect, and remove all liquids that enter the LCRS throughout the active life and post-closure care period of the unit.

As a whole, the liquids management system attempts to:

- Minimize leachate generation in a landfill or a waste pile unit during its active life.
- Collect and remove all pumpable quantities of leachate generated in a unit (in the case of landfills and waste piles).
- Collect and remove all pumpable quantities of liquids that pass through the top liner of a double liner system.
- Operate the unit up through closure without the escape of liquids (in the case of waste piles and surface impoundments) or leachate (in the case of landfills).
- Control the generation of leachate within a closed landfill unit.

At present, except in cases that meet criteria for statutory variance, EPA regulations require two types of hazardous waste TSDF units to meet the double liner requirement:

- Surface impoundments.
- Landfills.

Proposed rules extending the double liner requirement to waste piles have been published in the Federal Register (EPA, 1987b). Waste piles are non-containerized accumulations of solid waste. They can be used for treatment as well as storage of dry materials and are temporary in nature. Surface impoundments are for the temporary storage and treatment of liquids. Landfills are for the permanent disposal of solid wastes on land.

At present, there are no technological design requirements for units for containing Subtitle D (nonhazardous) wastes, though proposed regulations are due to be published in the near future. Nevertheless, lining Subtitle D waste containment units may be desirable or necessary given particular site conditions or the specific waste stream in order to meet the performance standard criteria stated in 40 CFR Part 257. Subtitle D wastes include municipal solid waste (MSW), nonhazardous industrial waste, municipal sludge, municipal waste combustion ash, construction and demolition waste, agricultural waste, oil and gas waste, and mining waste.

Depending on the type of service required, waste containment units may need to function from a relatively few years, as in the case of some storage facilities, up to 100 years or more, as in the case of some landfills, and to function in such a manner that hazardous or toxic materials are under control and do not migrate from the unit in an uncontrolled manner.

1.2 PURPOSE OF THIS TECHNICAL RESOURCE DOCUMENT

Lining a containment unit is a feasible means of protecting the groundwater from hazardous or toxic waste constituents. This Technical Resource

Document (TRD) provides information on the selection, design, construction, and performance of various lining and cover systems based on current technology, with particular emphasis on FMLs and the containment of hazardous wastes. However, information appropriate to the containment of nonhazardous wastes and the use of lining materials in mining applications is also presented. The discussion of soil liners is limited to their use in composite liners in double-liner systems; for further information the reader is directed to a companion TRD (Goldman et al, 1985). The information presented in this document is intended to assist the user in determining what FMLs would be effective in containing specific wastes or waste leachates. Effective control for containment units means minimizing the migration of hazardous or toxic waste constituents into and through the lining system.

1.3 SCOPE

Chapter 2 discusses the types of waste liquids and leachates that may contact a lining system. The discussion of leachates includes the liquids that may constitute the leachates and the dissolved constituents that are carried by these liquids. This chapter describes the basic types of waste liquids and hazardous substances that may require secondary containment. Trends in the types of wastes and substances that are being contained in land-based storage and disposal units are also discussed.

Basic concepts and factors in the transport of mobile constituents of a solid or liquid waste placed in a containment unit and the escape of these constituents into the environment are discussed in Chapter 3. The paths and mechanisms by which these constituents are transported within a unit are discussed with particular emphasis on transport within a multi-layered liner system, including the FML and soil liners and the leachate collection and removal systems because the migration and partitioning of mobile constituents to specific subcomponents of a lining or cover system may adversely affect the performance of the system. This chapter concentrates on closed FML-lined landfills and FML-lined surface impoundments that meet the requirements of RCRA and its amendments.

Chapter 4 describes various types of materials and products that are used in the design and construction of lined waste containment units and presents data concerning their properties. These materials, which are needed to fulfill a variety of functions in the structure of these containment units include FMLs, geotextiles, geogrids, geonets, geocomposites, sand and gravel, concrete, pipe, and soil, which are used for preventing migration, separation, support, soil reinforcement, filtration, and drainage.

The long-term effects of waste liquids and environmental stresses on FMLs and ancillary construction materials, as demonstrated in laboratory and pilot-scale field studies, are discussed in Chapter 5. As background to this discussion, the environments that FMLs and other materials may encounter in various types of actual waste containment units are described. These environmental conditions either have been observed or are considered highly probable. The types of units discussed include MSW landfills, surface impoundments, hazardous waste landfills, waste piles, leach pads, secondary containment facilities, and tailings ponds.

Chapter 6 reviews selected field studies on FMLs and other related materials of construction in service environments with particular emphasis on the durability of these materials. Various factors that could contribute to the failure of an FML-lined unit are described. The properties of the studied materials are described to provide a basis for correlating field performance with the results of laboratory and pilot-scale tests in order to develop performance-related tests and to establish performance criteria for the use of FMLs in service environments.

Chapter 7 discusses the minimum performance and technological requirements for the design of lined waste containment units and reviews engineering options available to the designer, with particular emphasis on designing a double-lined containment unit for the disposal or storage of hazardous wastes. The same design principles would readily be adopted for single-lined units for the containment of nonhazardous wastes or materials.

Chapter 8 discusses specification documents for the construction of waste containment units with particular emphasis on the technical specifications which include the plans, specifications, and drawings that are necessary for bid packages and which are necessary to communicate to construction and installation contractors the quality of the materials of construction required by the design and the quality of work to be performed during construction.

Chapter 9 discusses various steps in constructing and installing the major components of double-lined waste containment units including:

- Earthworks, including the soil component of a composite liner.
- FMLs.
- Leachate collection and recovery systems.
- Final cover systems.

Chapter 9 also discusses special considerations in FML installation, such as installation around appurtenances, and the construction of admixed liners.

Chapter 10 reviews EPA guidelines for construction quality assurance (CQA) plans pertaining to the construction of hazardous waste containment units with particular emphasis on the tests and types of observations involved in CQA during construction of a containment unit.

The measures that must be taken in managing a waste containment unit from the time of commencement of operations through the operational and post-closure care periods are described in Chapter 11. These measures include the standard operating procedures that must be developed at the time the permit application is prepared. The need for controlling the incoming waste, and methods of monitoring the performance of the in-service lining systems, the earthworks, and final cover systems are described.

Chapter 12 discusses factors influencing the cost of constructing a waste containment unit and discusses the cost of various liner materials as well as other construction materials such as pipes, geogrids, geonets, drainage materials, etc. Some costs for earthworks construction and factors that can affect liner installation costs are presented. The cost of different storage or disposal alternatives are compared, and lastly, costs for quality assurance inspection of the materials and the construction are discussed.

More detailed information on subjects discussed in the main body of the document is presented in the appendixes. Appendix A presents examples of significant waste sources and the types of wastes generated by these sources. Appendix B lists companies that provide liner materials and services. Polymers which were formerly used in the manufacture of FMLs are described in Appendix C. Appendix D describes the pouch test for permeability of polymeric FMLs. A procedure for determining the extractables contents of exposed and unexposed FMLs is presented in Appendix E. The results of testing a wide range of unexposed polymeric FMLs and other commercial sheetings for physical and analytical properties are presented in Appendix F. A procedure for determining the volatiles contents of exposed and unexposed FMLs is presented in Appendix G. Appendix H describes the tub test of polymeric FMLs. Special considerations in designing a leachate collection system network are described in Appendix I. Appendix J summarizes the results of analyzing hazardous and toxic wastes used in the exposure tests which are discussed in Chapter 5. Appendix K presents suggested property standards for selected FMLs. Appendix L reprints the EPA Method 9090 compatibility test for wastes and FMLs (EPA, 1986). Appendix M lists observations that should be made and tests that should be performed for the CQA and construction quality control (CQC) of hazardous waste containment units. Appendix N presents locus-of-break codes that can be used in reporting the results of testing FML seams.

This document attempts to bring together current knowledge and technology related to lining and cover systems; the information presented is selected for use by site owners and operators, permit writers, and those responsible for preparing permit applications to aid them in gaining a comprehensive understanding of the numerous elements involved in the design and construction of waste containment units. This document can also be used by researchers, materials and component suppliers, and the general public as a source of information on the design of hazardous waste as well as other types of storage and disposal units.

This document refers to, but does not discuss, the following subjects:

- Site selection.
- Detailed discussion of methods of analysis of wastes, except for information on waste components that are aggressive to linings of all types.
- Monitoring of groundwater.

- Attenuation of pollutants in the native soil below the lining system (subsurface).
- Soil characteristics and behavior in waste containment applications.
- Legal aspects, except insofar as they affect the design or operation of a containment unit.

1.4 REFERENCES

- EPA. 1985. Minimum Technology Guidance on Double Liner Systems for Landfills and Surface Impoundments. EPA 530-SW-85-014, May 24, 1985. U.S. Environmental Protection Agency. Washington, D.C.
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- EPA. 1987b. Liners and Leak Detection for Hazardous Waste Land Disposal Units; Notice of Proposed Rulemaking. Federal Register 52(103):20218-20311.
- Goldman, L. J., A. S. Damle, G. L. Kingsbury, C. M. Northeim, and R. S. Truesdale. 1985. Design, Construction, and Evaluation of Clay Liners for Hazardous Waste Facilities. EPA 530/SW-86-007F. U.S. Environmental Protection Agency, Washington, D.C. 575 pp.

CHAPTER 2

CHARACTERISTICS OF WASTE LIQUIDS AND LEACHATES

2.1 INTRODUCTION

In waste management, groundwater protection, and pollution control, the liquid components of wastes contained in treatment, storage, and disposal facilities (TSDFs) are of primary concern. Even though placing bulk or noncontainerized liquid hazardous wastes or hazardous wastes containing free liquids in landfills was prohibited as of May 8, 1985 (40 CFR 264.314), the disposal of solid wastes can result in leachates generated by the percolation of liquids (e.g. rainwater) through the waste. Without adequate control, waste liquids and leachates can migrate out of a containment unit carrying constituents that may pollute the groundwater. By lining a waste containment unit with an engineered lining system which includes a low-permeability liner, e.g. a flexible membrane liner (FML), the migration of liquids out of the unit can be controlled. At the same time, liquids or constituents dissolved in the liquids present in a lined containment unit may interact with components of the lining system. Thus, knowledge of the composition of the liquid to be contained, including that of the dissolved constituents, is important in selecting the specific materials to be used in constructing the lining system for a given containment unit. Because such specific information is generally not available, the EPA has developed Method 9090 to determine the compatibility of FMLs proposed for use in constructing a liner system with the waste liquid or leachate to be contained (EPA, 1986a).

Even though inorganic constituents of a given waste liquid or leachate may affect organic solubility, the organic constituents are of principal importance in determining the compatibility of the polymeric components of a lining system and a given waste liquid since they can potentially be absorbed by polymeric compounds or extract components of a compound resulting in changes in mechanical properties. In the case of FMLs, absorption of an organic species can also result in permeation of that species. An organic waste or sludge with an organic liquid phase will most probably expose the liner to the organic species contained in the waste. The examples presented in this chapter and in Appendix A show that the wastes disposed of in industrial waste containment units cover the spectrum of chemical species. It should be noted that organics are subject to regulatory control. The effects of organics on polymeric materials is discussed in Chapter 5.

Two conditions that can be encountered, particularly in surface impoundments, by an in-service FML in contact with waste liquids containing organics are presented schematically in Figure 2-1. In the first condition, the waste liquid that contacts the FML consists of water with dissolved organics and probably some inorganics. In the second condition, the FML is in direct contact with a mixture of organic liquids. This condition has been encountered in the field when the organics, having a higher specific gravity than the aqueous waste liquid, exceed their solubility in water and pool above the FML. The concentration of organics in the waste directly in contact with the FML is considerably higher in the second condition.

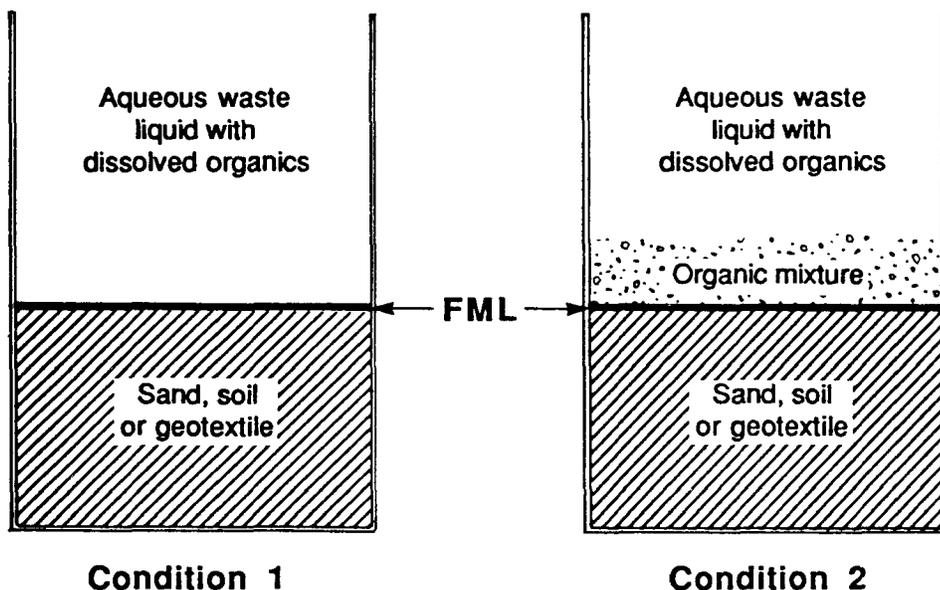


Figure 2-1. Two conditions that FMLs in contact with waste liquids or leachates can encounter in waste containment units.

Cheremisonoff et al (1979) estimated that 90% by weight of industrial hazardous wastes are produced as liquids and that these liquids contain solutes in the ratio of 40% inorganic to 60% organic. Liquids as such can no longer be placed in landfills; they must be treated to meet regulatory criteria before final disposal (40 CFR 264.314).

In addition, hazardous wastes may have to be treated to meet treatment standards being developed by the EPA (40 CFR 268, Subpart D). The RCRA Hazardous and Solid Waste Amendments of 1984 prohibit the land disposal of untreated hazardous waste subject to land disposal restrictions beyond specified dates. This statute requires the EPA to set "levels or methods of treatment, if any, which substantially diminish the toxicity of the waste or substantially reduce the likelihood of migration of hazardous constituents from the waste so that short-term and long-term threats to human health and the environment are minimized" [Sec. 3004(m)(1)].

The complex nature and variety of waste liquids greatly complicate attempts to predict the effects on the performance of FMLs of their exposure to the liquids present in waste containment units. At the present state of knowledge, the short-term integrity (<20 years) of well-engineered lining systems in properly operated containment units appears to be very good. However, the long-term integrity of liner systems in actual service in lined landfills has not been established. Interactions among the dissolved constituents and their long-term effects on the components of in-service lining systems, which are also subjected to various mechanical stresses, are uncertain and the field experience that has been accumulated is limited. Further results of actual field performance are necessary to assess the long-term integrity of in-service lining systems. Interactions between wastes and specific liner materials are discussed in Chapter 5. Long-term service life is discussed in Chapters 5 and 6.

This chapter discusses waste liquids and leachates generated by solid wastes and the dissolved constituents that are carried by these liquids which may contact the liner systems in waste containment units. Data are presented on the composition of hazardous waste leachates. Also discussed are trends in the types of wastes and substances that are being contained in land-based storage and disposal facilities. This chapter also describes the basic types of waste liquids and hazardous substances that may require secondary containment. It should be recognized that new regulations and developments in treatment technology in the future will result in a decreased volume of liquid wastes and in liquids of lower concentration which may require storage or ultimate disposal. Appendix A presents data on the composition of municipal solid waste (MSW) leachates and the composition of wastes produced by various industries.

2.2 GENERAL DESCRIPTION AND CLASSIFICATION OF LEACHATES AND WASTE LIQUIDS

The two types of liquids that may be present in a waste storage or disposal unit are leachates and waste liquids. The type of waste present will depend on whether the unit is one that contains a solid waste, e.g. a landfill, or one that contains a liquid waste, e.g. a surface impoundment. The following paragraphs describe the basic types of leachates and waste liquids. Data are presented on the composition of actual hazardous waste leachates.

2.2.1 Types of Leachates

In the context of waste management, leachate is the product of liquids percolating through solid waste and dissolving soluble constituents of the waste. The liquids that percolate through a waste come from three sources:

- Water from outside the containment unit, e.g. rainwater and surface drainage.
- Liquids originally in the waste.

- Liquids generated by the decomposition of the waste (particularly in MSW landfills).

Figure 2-2 schematically presents the generation of leachate.

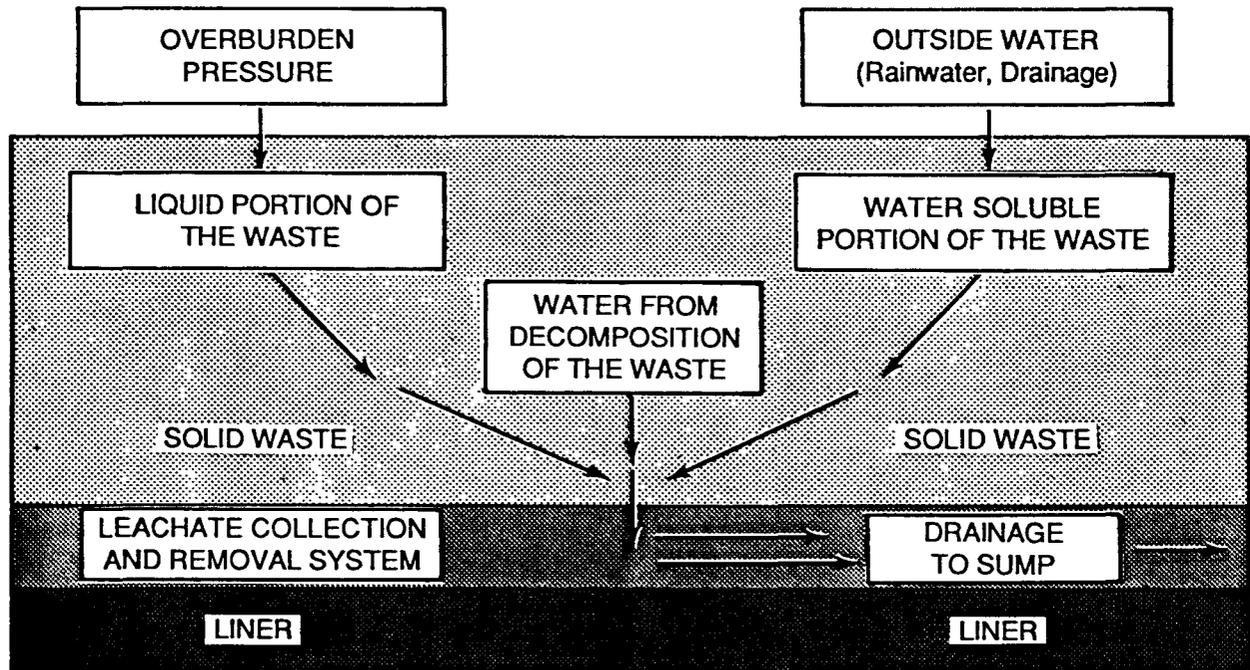


Figure 2-2. Sources of leachate generated by a solid waste.

The type of leachate produced by a landfill will depend on constituents. Chian and DeWalle (1977) have shown that leachates are generally aqueous and that dissolved organics and inorganics are present in only small quantities. Depending on the composition of the waste, however, liquid organic phases may be present.

Even though wastes containing free liquids are presently banned from disposal in hazardous waste landfills, some liquids may still be disposed of absorbed in solid wastes. The presence of free liquids in a waste is determined on a representative sample of the waste using the "Paint Filter Liquids Test," EPA Method 9095 (EPA 1986a). In this test, the waste sample is placed in a paint filter. If any liquid from the waste passes through and drops from the filter within the 5-min. test period, the waste is deemed to contain free liquids. Once solid waste has been placed in a containment unit, the weight of the overlying materials can result in the separation of liquids from the waste in which they had been absorbed.

The dissolved constituents of the leachate may be either organic or inorganic. The dissolved constituents, particularly some organic constituents, can affect the properties of the polymeric components of a lining system, just as the properties of clay soil liners can be affected by dissolved constituents at relatively low concentrations (Haxo and Dakessian, 1987).

2.2.2 Types of Waste Liquids

Waste liquids that are placed in surface impoundments fall into five general types: aqueous-inorganic, aqueous-organic, aqueous-organic-inorganic, organic, and sludges. These types are summarized in Table 2-1.

TABLE 2-1. TYPES OF WASTE LIQUIDS IN SURFACE IMPOUNDMENTS

Type	Solvent or continuous phase	Solute or emulsified liquid
Aqueous-inorganic	Water	Inorganic
Aqueous-organic	Water	Organic
Aqueous-organic-inorganic	Water	Organic and inorganic
Organic	Organic liquid	Organic
Sludges ^a	Water or organic liquid	Organic and inorganic

^aSludges contain significant amounts of suspended solids.

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

Aqueous-organic waste liquids are those in which water is the liquid phase and the dissolved constituents are predominantly organic. Examples of the dissolved components in this type of waste liquids are polar or charged organic chemicals. Examples of wastes in this class are wood-preserving wastes, water-based dye wastes, rinse water from pesticide containers, and organic production wastes.

Of all the waste liquids that are stored in surface impoundments, the most common are wastewaters that contain significant amounts of both organic and inorganic species. These aqueous-organic-inorganic waste liquids include wastewaters generated in industrial plants, e.g. chemical plants and

petroleum refineries, which are held in surface impoundments prior to treatment and disposal. Though not wastes, some in-process liquids may also be considered aqueous-organic-inorganic liquids.

Organic waste liquids are those that have an organic liquid phase and the dissolved constituents are other organic chemicals dissolved in the organic liquid. Examples of this type of waste liquids are oil-based paint wastes, pesticide manufacturing wastes, spent motor oil, spent cleaning solvents, and solvent refining and reprocessing wastes.

Sludges are the fifth type of waste liquids. They are generated when a waste stream is dewatered, filtered, or treated for solvent recovery. They are characterized by a high content of suspended solids which can consist of such solids as clay minerals, silt precipitates, fine organic solids, or high molecular weight hydrocarbons. Examples of sludges include water treatment sludges, American Petroleum Institute (API) separator sludge, storage tank bottoms, flue-gas desulfurization sludges, and filterable solids from any production or pollution control process. After the placement of a sludge in a waste storage facility such as a surface impoundment, solids and liquids or leachates separate out of the sludge due to gravitational forces, agglomeration, overburden pressures, and hydraulic gradients. These liquids are similar in form to the first four types of waste liquids shown in Table 2-1, depending on the composition of the liquid phase and the dissolved constituents.

2.2.3 Constituents of Leachates and Waste Liquids

Leachates and waste liquids generally consist of a liquid phase and suspended solids. From the standpoint of FML permeability and durability, the suspended solids are not a factor because they do not permeate an FML and, in general, will not affect its durability. The liquid phase consists of a principal liquid, dissolved organic liquids, dissolved organic solids, dissolved inorganic solids, and/or suspended organic liquids. Figure 2-3 schematically presents a generalized composition of the liquid phase of a waste. Even though the ratio of the constituents in an actual waste liquid will vary greatly, water is generally the principal component and the carrier of dissolved and suspended constituents. If water is the principal liquid, then the organic and inorganic constituents will be dissolved in the water, or, in the case of the organic liquids, be present in the water in emulsified or suspended states. The liquid phase could also be an organic solution containing dissolved organic liquids and solids and possibly some dissolved inorganics.

The relative abundance of a given dissolved constituent depends on the composition of the liquid phase. For example, if the liquid is a neutral nonpolar organic, it will tend to dissolve other neutral nonpolar organic chemicals. If the liquid phase is predominantly aqueous, it will tend to dissolve only small quantities of nonpolar organics and relatively large amounts of polar organics, some of which may be totally miscible with water. Water can dissolve relatively large amounts of some inorganic acids, bases,

and salts. Strong inorganic acids and bases, which are invariably water-based, may be particularly aggressive to some liner materials. (Note: aqueous solutions with a pH less than or equal to 2 or greater than or equal to 12.5 are prohibited from disposal in waste impoundments.)

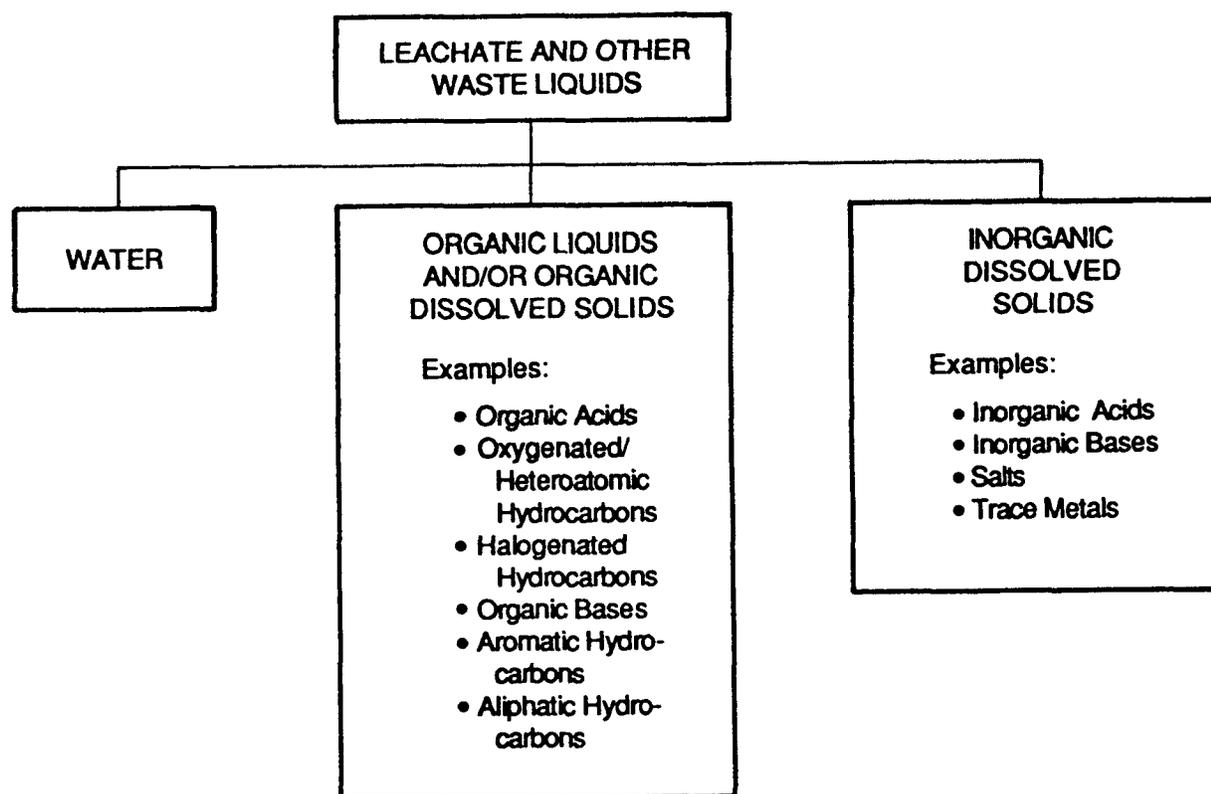


Figure 2-3. Generalized composition of leachates and other waste liquids that may contact a liner in service, showing the constituents that may be present.

Some organic constituents of a leachate or waste liquid may affect the properties of an FML or other components of a liner system because they may be absorbed by the components and, as is discussed in Chapter 3, may be highly mobile (Haxo, 1988). For the purpose of experimentally assessing the effects of organics, the organic constituents of the leachate or liquid need to be characterized in terms of the physical and chemical properties that govern their interaction with the various components of the liner system. The relative solubility parameters (Hildebrand and Scott, 1950; Haxo et al, 1988) of the organics and those of the respective liner system components are useful in estimating potential level of interaction. The proximity in the values of the solubility parameters of an organic, either neat, in solution, or dispersed in water, to those of the respective compositions of the liner

system components can affect the performance of the respective components. When the solubility parameters of the organic and the specific component are close, severe swelling and softening of that FML can occur. The use of solubility parameters in assessing and predicting the compatibility of FMLs and waste liquids is discussed in Chapter 5. The partitioning of dissolved organics between water and FMLs and other polymeric components is also discussed in Chapter 5.

Dissolved inorganic constituents of the waste liquid, such as salts, do not swell FMLs and other geosynthetics and pipe and, generally, are not factors in changes in properties of these components of a liner system on exposure to these constituents in a waste liquid. Furthermore, these constituents do not permeate the FML. On the other hand, as noted above, extreme pH of the waste liquid can adversely affect some FMLs. Results of immersion and exposure tests in leachates and waste liquids are presented and discussed in Chapter 5.

2.2.4 Composition of Actual Hazardous Waste Leachates

Complete knowledge of the full composition of a liquid that would be in contact with the lining system is desirable in assessing their compatibility. Determining the full composition of a waste liquid or leachate involves identifying the many constituents present in that liquid. Analysis of a waste liquid is usually performed to determine whether or not it is hazardous by ascertaining whether or not specific chemical species identified by the EPA as hazardous are present. In both the "Extraction Procedure (EP) Toxicity Test Procedures" (EPA, 1985), and the "Toxicity Characteristic Leaching Procedure" (TCLP) (EPA, 1986c), the extracts are analyzed for specific constituents. The number and quantity of organic constituents identified by procedures such as these may only yield a minor fraction of the total number and amount of constituents that are actually dissolved in a leachate or waste liquid. The total organic content of a waste liquid can be estimated by determining the total organic carbon (TOC) content which includes both hazardous and nonhazardous organic species. The latter species, which may be considerably greater in number than the organics specifically identified as hazardous, are often not identified. This lack of information of the complete composition of a leachate necessitates the compatibility testing of a liner system component with a representative sample of the leachate or other waste liquid to be contained.

This subsection presents data on the composition of hazardous waste leachates. Data on the composition of MSW leachates and various industrial wastes are presented in Appendix A.

To develop more complete data on the composition of hazardous waste leachates with the hope of developing a generic leachate, Bramlett et al (1987) performed standard analyses of leachates from actual hazardous waste facilities to determine the pollutants present. In this study, leachates were collected from 13 hazardous waste landfills in different parts of the continental United States. Individual samples were collected for each

analysis in accordance with EPA sample collection protocols; the samples were protected from the time of collection to the time of analysis to prevent loss of volatile constituents and changes in their character due to oxidation. A preservative, if needed, was added to each container. For example, nitric acid was added to samples for metals analyses and sodium hydroxide was added to samples for cyanide analyses. All samples were stored at 4°C until analyzed.

Analyses of the leachates were performed for:

- 35 volatile priority pollutants.
- 68 semivolatile priority pollutants.
- 13 metals.
- 102 nonpriority pollutants, which were identifiable based on the library spectra on hand (Bramlett et al, 1987).

Analyses included tests for the following constituents and parameters on each of the leachate samples:

- Volatile organics.
- Semivolatile organics, including base/neutrals and acid extractables.
- Heavy metals.
- Cyanide.
- Chemical oxygen demand (COD).
- Total organic carbon (TOC).

Analyses for volatile and semivolatile organics were performed in accordance with EPA Methods 624 and 625 (EPA, 1984a; EPA, 1984b). Trace metals, cyanide, COD, and TOC analyses were performed in accordance with the EPA guidelines presented in "Methods for Chemical Analysis of Water and Wastes" (EPA, 1983), as modified in the EPA Contract Laboratory Program protocol; specific methods are listed in Table 2-2. Gas chromatography followed by gas chromatography/mass spectroscopy (GC/MS) was used to identify volatile organics within three days after receipt of the samples by the laboratory. Semivolatile organics (base/neutral and acid extractables) were analyzed within 42 days after arrival at the laboratory.

The results of the analyses for metals, pH, redox potential (Eh), electrical conductivity (EC), total cyanide, TOC, and COD are summarized in Table 2-3 (Bramlett et al, 1987, p 58). The results presented in Table 2-4 (Bramlett et al, 1987, p 60) show the percentage of TOC in the leachate samples accounted for by the analyses for the individual organics.

TABLE 2-2. METHODS USED TO ANALYZE LEACHATE SAMPLES

Fraction analyzed	Federal Register ^a	EPA 600/4-79-020 ^b	SW-846 ^c
Volatile organics	Method 624	...	...
Semivolatile organics (base/neutral and acid extractables)	Method 625	...	...
Heavy metals:			
Antimony	...	Method 204.2	7041
Arsenic	...	Method 206.2	7060
Beryllium	...	Method 210.2	7091
Cadmium	...	Method 213.2	7131
Chromium	...	Method 218.2	7191
Copper	...	Method 220.2	...
Lead	...	Method 239.2	7421
Mercury	...	Method 245.1	7470
Nickel	...	Method 249.2	...
Selenium	...	Method 270.2	...
Silver	...	Method 272.2	7740
Thallium	...	Method 279.2	7841
Zinc	...	Method 289.2	...
Cyanides	...	Method 335.2	...
Chemical oxygen demand (COD)	...	Method 410	...
Total organic carbon (TOC)	...	Method 415.2	9060

^aFederal Register, October 26, 1984, 40 CFR Part 136 (EPA, 1984a; EPA 1984b).

^bEPA 600/4-79-020, updated March, 1983 (EPA, 1983).

^cSW-846, 3rd ed. (EPA, 1986a).

Source: Bramlett et al, 1987.

Overall, it was found that the leachates were approximately 99% water and <1% (<10,000 mg/L) organic by weight. Of the total TOC obtained by the analyses, only 4% (i.e. <400 ppm of the leachate) was characterized. Of the 4% characterized organic carbon, 39% was organic acid, 35.8% was oxygenated/hetroatomic hydrocarbons, 11% was halogenated hydrocarbons, 7.2% was organic bases, 6% was aromatic hydrocarbons, and 0.9% was aliphatic hydrocarbon. Thus, the standard EPA leaching procedure (EPA, 1986a) and analytical tests fall far short of identifying all of the organics in a leachate, some of which might partition to the FML and other liner system components and, over an extended period of time, affect the performance of these materials. Within the 96% of the unknown carbon there may be organics (such as halogenated,

TABLE 2-3. STATISTICAL DATA FOR METALS, pH, Eh, CONDUCTIVITY, TOTAL CYANIDE, TOC, AND COD

Parameter	Range of detected constituent		Mean	Standard deviation	Number of sites where constituent was detected	Mean mole fraction, x100
	Minium	Maximum				
Metal ^a						
Silver	0.3	32.8	6.55	9.56	13	0.0249
Arsenic	458	129,600	13,097.08	33,848.32	10	31.9456
Beryllium	0.2	7.4	0.81	1.96	6	0.0904
Cadmium	0.7	102	18.74	28.25	13	0.1572
Chromium	0.2	1,734	280.54	558.80	13	2.2826
Copper	2.3	17,030	1,885.07	4,525.28	13	13.0760
Mercury	45	39,300	4,973.04	10,308.36	12	0.0101
Nickel	17.3	67,110	6,416.95	17,609.15	13	22.5979
Lead	0.3	1,006	115.58	263.09	13	0.3740
Antimony	13	5,240	522.35	1,367.79	11	3.9792
Selenium	221	3,488	1,167.88	890.25	13	16.9132
Thallium	9.4	156	36.92	45.62	11	0.1223
Zinc	5.12	24,510	2,512.77	6,403.20	13	8.4268
						100
pH ^b	7.1	9.3	8.2	0.857	...	...
Eh ^b (volts)	0.343	0.093	0.226	0.126	...	...
Conductivity ^b (µmhos/cm)	4,250	12,000	14,694	6,588	...	...
Temperature ^b (°C)	19.9	32	26.7	6.2	...	...
Total Cyanide ^c (mg/L)	0.01	55	9.93	17.85	9	...
COD ^c (mg/L)	1,950	23,300	10,217	6,475	...	...
TOC ^c (mg/L)	195	11,750	3,097	3,071	...	...

^aMetal data is in µg/L (except for Hg, which is in ng/L).

^bStatistical data does not include sites where no measurements were taken.

^cAll samples were analyzed for total cyanide, TOC, and COD.

Source: Bramlett et al, 1987, p 58.

TABLE 2-4. PERCENT OF TOC^a CONTENT ACCOUNTED FOR BY ANALYSIS OF LEACHATES FOR POLLUTANTS

Hazardous waste site	TOC ^a , mg/L	"Priority" pollutants, %		"Nonpriority" pollutants, %	Total, %
		Volatile	Semivolatile		
1	2,343	1.734	2.86	2.176	6.77
2	2,004	1.565	0.876	5.86	8.30
3	2,278	0.1886	3.94	1.951	6.08
4	718	0.659	0.604	0.2917	1.55
5	195	34.4	1.137	4.89	40.43
6	1,579	0.167	2.392	0.487	3.05
7	1,048	1.90	2.20	1.939	6.04
8	11,750	0.00393	0.743	0.1820	0.93
9	309	20.98	18.12	20.41	59.51
10	4,078	2.075	1.718	0.468	4.26
11	4,909	1.995	3.06	0.500	5.56
12	6,602	1.510	1.551	0.3520	3.41
13	2,453	0.314	1.049	1.020	2.38

^aTotal organic carbon.

Source: Bramlett et al, 1987, p 60.

aliphatic, and aromatic hydrocarbons) that could have a significant impact on the performance of a liner. On the other hand, in some cases much of the unidentified carbon may arise from humic acid, lignin, and other organics which would not be absorbed and affect the liner and other components of the liner system.

In view of the small fraction of the organic carbon that was actually identifiable, a subsequent study was conducted by McNabb et al (1987). In this study, a more rigorous and complex analytical methodology was developed than was used in the study by Bramlett et al (1987). A hazardous waste sample was analyzed with the objective of maximizing the percentage of TOC accounted for by specific species or by functional groups. This method

was applied to a single hazardous waste leachate sample to yield, in the initial step, the results presented in Table 2-5. In the subsequent step, approximately 48% of the 16,000 mg/L TOC was accounted for. Of this amount, 20% was attributed to individual species and 28% to functional groups. Results of the analyses by McNabb et al (1987) are presented in Table 2-6. The same analytical protocol is being used to determine the complete composition of two additional waste liquids (McNabb et al, 1987).

TABLE 2-5. INITIAL CHARACTERIZATION OF A HAZARDOUS WASTE LEACHATE

Analyte	Units	Field blank	Sample average
Nitrogen (total)	mg/L	<10	635
Sulfate	mg/L	<3	210
Sulfide	mg/L	<10	<10
Methylene blue active substances	mg/L	<0.1	<0.1
pH	...	6.9	4.3
Conductivity	µmho/cm	10	19,500
Total organic carbon	mg/L	<3	16,000
Total organic halides	mg Cl/L	0.07	166

Source: McNabb et al (1987).

One objective of the work by McNabb et al (1987) was to develop formulations for synthetic leachates which can be used in compatibility testing. The development of a procedure to determine the composition of a waste liquid, particularly the concentration of the major organic constituents of the leachate, would be useful in developing predictive methods for assessing the compatibility of an FML with a waste, based on their respective compositions. Work described in Chapter 5 shows that some organics partition more to some FMLs than do others. This tendency of some organics will be discussed in that chapter in connection with the use of solubility parameters in assessing and predicting compatibility and in the distribution of dissolved organics between water and polymeric materials.

2.3 CHARACTERIZING HAZARDOUS WASTES AND WASTE CONSTITUENTS

To meet RCRA requirements regarding management and disposal of solid wastes, a generator or handler of a waste must determine whether the waste being generated or handled is hazardous and toxic. He has two methods of

TABLE 2-6. TOTAL ORGANIC CARBON CONTENT IDENTIFIED
BY CHEMICAL CLASSIFICATION

Chemical classification	Fraction of total TOC by weight, %	Representative compounds	TOC in leachate, mg/L
Organic acids	20.3	Benzoic acid (17.1%)	2736.0
		Phenol (3.1%)	496
		Alkanoic acids (0.13%)	20.8
		Substituted benzoic acids (0.01%)	1.6
		Substituted phenols (0.002%)	0.32
Oxygenated hydrocarbons	0.8	Ketone solvents (0.0003%)	0.048
		Alcohols (0.0002%)	0.032
		Trimethylpentanediol (0.8%)	128.0
Halogenated hydrocarbons	0.86	Total organic halides (TOX) (0.86%)	137.6
		Chlorinated solvents (0.001%)	0.16
Organic bases	0.0	None detected	...
Aromatic hydrocarbons	26.8	Aromatic compounds >500 MW ^a (26.8%)	4288
		Benzene and alkyl-substituted benzenes (0.001%)	0.16
Aliphatic hydrocarbons	0.002	n-Alkanes (0.002%)	0.32

^aMW = Molecular weight.

Source: McNabb et al (1987).

determining whether the solid waste he is managing is hazardous (EPA, 1986d); he can either:

- Use a list of wastes which the Environmental Protection Agency (EPA) has identified as hazardous (40 CFR 261, Subpart D), or
- identify a solid waste as hazardous on the basis of certain measurable characteristics, i.e. ignitability, corrosivity, reactivity, or EP toxicity, that are defined by the EPA (40 CFR 261, Subpart C).

To determine whether or not a hazardous waste exhibits the characteristic of toxicity, the waste is leached in accordance with the EP Toxicity Test Procedure (EPA, 1985) and analyzed to determine the concentration of 14 constituents, including 8 metals, and 4 insecticides, and 2 herbicides. The waste is deemed to have the characteristic of EP toxicity (and thus is "hazardous") if the concentration of any of the 14 contaminants is greater than the maximum concentration values listed in 40 CFR 261.24 (EPA, 1986d). In addition, analyses can be performed on the extract for a series of "priority pollutants" which, as noted above, generally cover only a fraction of the potential organics that are present in the waste. The EP toxicity characteristic and the EP method itself both have major shortcomings. The toxicity characteristic is the only characteristic that relates to the toxicity of a waste not identified on the list of hazardous wastes in 40 CFR 251, Subpart D. It accounts for only a small fraction of the total list of hazardous constituents identified in Appendix VIII of 40 CFR 261 (EPA, 1986d). Analyses to determine the EP toxicity characteristic of a waste give no information on the concentrations of constituents, specifically organics, that can affect the properties and performance of the polymeric components of a lining system. The shortcoming of the EP method itself is that the procedure was optimized to evaluate the leaching of inorganic rather than organic constituents. In 1984 HSWA directed the EPA to amend both the EP toxicity characteristic and the EP method [Section 3001(g) and (h)].

As an alternative to the EP method, the EPA has developed the "Toxicity Characteristic Leaching Procedure" (TCLP), which has been published as an appendix to a final rule (EPA, 1986c). This procedure is presently (May 1988) being used as one method of verifying whether or not a restricted waste or the residue resulting from treatment of a restricted waste can be legally land disposed without further treatment. One advantage of this procedure over the EP procedure is the requirements for preventing the loss of volatiles during leaching. The constituents for which the wastes are analyzed depend on the type of waste being extracted. For example, spent solvent wastes (EPA waste numbers F001 through F005) are analyzed for 25 constituents [40 CFR 268, Subpart D (EPA, 1986d)].

The EPA has proposed amending the EP toxicity characteristic by replacing the EP method with the TCLP and by expanding the characteristic to include 38 additional constituents, including a number of organics (EPA,

1986e). In spite of the increased number of organics that are analyzed in the toxicity characteristic tests, these procedures do not analyze for all organics that may be present. Though some organics on the proposed list may affect polymeric materials, many that are not on the list can also affect the performance of the polymeric components of a lining system.

2.4 IMPACT OF CURRENT AND FUTURE WASTE MANAGEMENT PRACTICE ON THE COMPOSITION OF WASTES AND WASTE LIQUIDS THAT ARE STORED OR DISPOSED OF ON LAND

In the early 1970s, discussion of hazardous wastes focused on the trace metal constituents which potentially could leach into the groundwater. Other discussion focused on containment research, development, and planning, and on the use of barrier materials to control the movement of these inorganic constituents. At that time, the use of clay lining materials was emphasized. Subsequently, considerable research and development has been performed to assess the effectiveness of polymeric materials as barriers to prevent the migration of inorganics (Haxo et al, 1985).

During the past decade, the focus has shifted toward the organic constituents which are, in some cases, more mobile and have caused pollution both of the groundwater and the air. Because of the toxic qualities of many organics, efforts have been made to improve the design and construction of waste containment units to reduce and, if possible, prevent the migration of organics out of these units.

In view of uncertainties about the effectiveness of land disposal over long exposure periods, considerable emphasis is being placed on the minimization of wastes containing hazardous constituents, on the land disposal restriction of specific wastes and wastes containing concentrations of specific waste constituents, and on the treatment of restricted wastes so that, once treatment standards are met, these wastes can be legally land disposed. However, even with waste minimization as a national policy, there will still be wastes requiring land disposal, including:

- Residuals from stabilization/solidification processes.
- Residuals from incineration, e.g. ash and wastewater.
- Residues from various waste treatment processes other than incineration and solidification/stabilization technology processes.
- Soils from spills of hazardous substances or wastes, the composition of which could vary greatly.
- Contaminated material from cleanups under the Comprehensive Environmental Response, Compensation, and Liability Act (Superfund) (CERCLA) including petroleum products and the wide range of hazardous materials that are listed in EPA rules (EPA, 1986d).

Minimization, land disposal restrictions, and treatment of hazardous wastes to achieve treatment standards can result in lower concentrations of some organics that might be in contact with components of a lining system and thus reduce the potential effects of a leachate or waste liquid on the liner system (Breton et al, 1987; McArdle et al, 1987). Some of the current waste management strategies that affect the composition of wastes and their disposal on land are briefly discussed in the following sections.

2.4.1 Waste Minimization by Recycling and Source Reduction

Through the enactment of RCRA and HSWA, Congress has established the minimization of waste generation as a national policy. Waste minimization is defined as the reduction, to the extent feasible, of hazardous waste that is generated or subsequently treated, stored, or disposed of (EPA, 1986f). It includes any waste management practice that results in either: (1) the reduction of total volume or quantity of hazardous waste, or (2) the reduction of toxicity of hazardous waste, or both, so long as the reduction is consistent with the goal of minimizing present and future threats to human health and the environment. Overall issues and options in waste minimization are discussed in a report by Versar, Inc. and Jacobs Engineering Group (1986).

In accordance with HSWA, EPA is establishing a waste minimization program to comply with the waste minimization policy.

There are three basic methods of minimizing wastes (EPA, 1986f):

- Source reduction, which refers to the reduction or elimination of waste generation at the source, usually within a process; source reduction can include process modifications, substitutions in feedstocks or improvements in purity, increased efficiency in a process, or recycling within the process. Source reduction implies any action that reduces the amount of waste exiting from a process.
- Recycling or reusing a waste as a substitute for a commercial product, or as an ingredient or feedstock in an industrial process. It also refers to the reclamation of useful constituent fractions within a waste material or removal of contaminants from a waste to allow it to be reused.
- Waste treatment, including such technologies as incineration, chemical detoxification, biological treatment, etc. Some of these technologies are discussed separately below.

It should be noted that dilution is prohibited as a means of treating a restricted waste or the residual from treatment of a restricted waste in order to achieve compliance with 40 CFR 268, Subpart D [40 CFR 268.3 (EPA, 1986b)].

Even without mandatory requirements, there are strong incentives for waste generators to proceed with waste minimization. Some of the major incentives are (EPA, 1986f):

- Increased cost of waste disposal, as a result of recent requirements of HSWA.
- Difficulties in siting new waste containment units.
- Permitting burden and corrective action requirements.
- Financial liability of hazardous waste generators.
- General favorable public attitude toward waste minimization.

Of particular importance from the standpoint of liner performance and service life is the minimization of wastes containing organic solvents and other organics that can adversely affect liner properties. In recent years there has been a significant reduction in the volume of solvent wastes produced, including both halogenated and nonhalogenated solvents. At the present time approximately 24% of these former wastes are being recycled. In the last four years there has been a 30% drop in waste generation by the chemical industry, even though at the same time there has been an increase in production (Chemical Week, 1987).

2.4.2 Incineration of Wastes

Incineration is generally considered to be a well demonstrated technology for the treatment of organic hazardous wastes including spent solvent wastes. However, incineration does produce residues, i.e. the off gas, ash, and scrubber wastewater, each of which must be managed in an environmentally sound manner. The ash can be landfilled either as such or after treatment. The wastewater must be treated before final disposal. The wastewater is usually generated in stack cleaning of the gases from the incineration. In both the ash and the wastewater there is a potential for organics that have not been completely oxidized. This potential was shown in an experiment conducted by Boegel (1987) in which residues generated in two incineration systems that burned RCRA wastes were evaluated. One system was a commercial treatment storage and disposal facility that accepted organic wastes from a variety of industrial generators, and the second operated on site at a chemical manufacturing plant. Both generated two types of residue: ash and scrubber wastewater. The ash from both facilities was landfilled. The scrubber wastewater from one facility resulted in a metal sulfide sludge; the wastewater from the other was neutralized and injected into a deep well. The ash of one exhibited extremely high concentrations of tetrachloroethylene, as is shown in Table 2-7. Tables 2-7 through 2-9 present data on the analyses of residues from the incineration of selected wastes (Boegel, 1987).

A properly functioning incinerator should burn the solvents completely, i.e. at a destruction and removal efficiency (DRE) of 99.99%; but, even when

TABLE 2-7. FACILITY A ASH ANALYTICAL DATA^a - ORGANICS

Parameter	Compositional, μg/kg	TCLP extract, μg/L	Proposed toxicity characteristic level ^b , μg/L
<u>Volatile organics</u>			
Methylene chloride	38,000	8,800	8,600
Acetone	20,000	<3,300	none
Chloroform	46	<1,700	70
2-Butanone	2,000	<3,300	7,200
1,1,1-Trichloroethane	12	<1,700	30,000
1,2-Dichloropropane	32	<1,700	none
Trichloroethylene	120	<1,700	70
Benzene	42	<1,700	70
4-Methyl-2-pentanone	2,300	<3,300	none
Tetrachloroethylene	1,200,000	48,000	100
Toluene	2,500	11,000	14,400
Chlorobenzene	27	<1,700	1,400
Ethylbenzene	380	<1,700	none
Styrene	320	<1,700	none
Xylenes	1,900	<1,700	none
Methanol	410,000	...	none
<u>Semivolatile organics</u>			
Phenol	40,000	<1,400	14,400
Nitrobenzene	29,000	<200	130
2,4-Dimethyl phenol	23,000	<1,000	none
Naphthalene	24,000	310	none
2-Nitroaniline	180,000	1,300	none
Dimethyl phthalate	55,000	370	none
Diethyl phthalate	120,000	410	none
Di-n-butyl phthalate	160,000	<200	none

^aAnalysis of a single composite sample. Aliquots of ash making up the composite were collected every two hours during the incineration run.

^bProposed level of the constituent in the extract obtained by the TCLP for determining whether or not the extracted waste is toxic, i.e. whether or not the waste is hazardous (EPA, 1986e).

Source: Boegel, 1987.

TABLE 2-8. FACILITY A ASH ANALYTICAL DATA^a - METALS

Parameter	Compositional, mg/kg	TCLP extract, mg/L	EP extract, mg/L	EP toxicity characteristic level ^b , mg/L
<u>Toxic metals</u>				
Antimony	8.0	0.094	<1.0	none
Arsenic	42.0	0.062	0.2	5.0
Barium	150	0.026	<1.0	100.0
Beryllium	<0.2	<0.005	<0.2	none
Cadmium	2.0	0.02	<0.5	1.0
Hexavalent Chromium	0.083	...	...	none
Total Chromium	71.0	0.01	<0.3	5.0
Copper	13,800	0.729	4.0	none
Lead	30.0	<0.05	<1.0	5.0
Mercury	0.2	0.00025	<0.1	0.2
Nickel	190	1.14	2.0	none
Selenium	<1.0	<0.001	<1.0	1.0
Silver	0.4	<0.005	<0.2	5.0
Thallium	2.0	<0.001	<1.0	none
Zinc	280	1.15	0.3	none
<u>Other analyses</u>				
Total solids, (mg/kg)	599,300	...	...	...
Specific gravity, (g/mL)	1.2809	...	...	...
Paint filter test	Pass	...	...	...

^aAnalysis of a single composite sample. Aliquots of ash making up the composite were collected every two hours during the incineration run.

^b40 CFR 261, Subpart C (EPA, 1986d).

Source: Boegel, 1987.

TABLE 2-9. FACILITY B ASH ANALYTICAL DATA - METALS

Parameter	Ash ^a			
	Compositional, mg/kg	TCLP extract, mg/L	EP toxicity characteristic level ^b , mg/L	Scrubber wastewater ^c , mg/kg
<u>Toxic metals</u>				
Antimony	14.5	0.03	none	<1
Arsenic	<0.1	0.004	5.0	<0.1
Barium	75	0.39	100.0	2
Beryllium	<0.2	0.002	none	<0.2
Cadmium	<0.5	0.01	1.0	<0.5
Hexavalent Chromium	0.05	<10	none	0.2
Total Chromium	361	0.085	5.0	1.5
Copper	4,600	96	none	241
Lead	340	0.56	5.0	106
Mercury	1.6	0.004	0.2	<0.1
Nickel	4,200	34	none	27
Selenium	<1	<0.05	1.0	<1
Silver	<0.2	<0.005	5.0	0.2
Thallium	<1	<0.001	none	<1
Zinc	1,160	25	none	363
<u>Other analyses</u>				
Total solids	811,000	...	...	3867
Total dissolved solids (mg/kg)	...	...	...	3500
Total suspended solids (mg/kg)	...	...	...	67
Total organic halide (wt %)	...	...	...	0.08
Total chlorine, (wt %)	...	...	...	1.59
Silica (wt %)	17.77	...	...	...
Specific gravity (g/mL)	1.9363	...	...	0.9936
pH	...	...	...	0.7

^aEach value represents the average of 6 grab samples.

^b40 CFR 261, Subpart C (EPA, 1986d).

^cEach value represents the average of 3 grab samples.

Source: Boegel, 1987.

an incinerator is functioning properly, it will probably produce ash that will need to be landfilled. Landfills will remain necessary because wastes other than pure solvents contain noncombustible constituents, e.g. metals, soils, silicates, that produce solid residue.

2.4.3 Restrictions on the Type of Wastes

The EPA is gradually restricting the amounts and types of organics that can be landfilled and has set up a schedule for action on the prohibition of land disposal of untreated hazardous wastes and the establishment of treatment standards [40 CFR 268 (EPA, 1986b; EPA, 1987)]. These restrictions can limit the concentrations of constituents that may significantly affect the properties of various components of the lining system. For instance, reducing the volatile halogenated organics, which are generally highly mobile, will reduce the potential for absorption and swelling of FMLs and thus the potential for changes in the physical properties and permeability of the FMLs. The effect of reduced concentration of such constituents in a waste liquid is discussed in Chapter 5 with particular reference to the partitioning of organics between water and FMLs.

2.4.4 Application of Solidification/Stabilization Technologies

The concentration and mobility of organics and other waste constituents in a waste can be reduced through the application of one of the solidification/stabilization technologies (S/S). These methods of treating waste liquids and hazardous residues from various treatment technologies have been used for more than 20 years to manage industrial wastes prior to land disposal. These technologies employ selected materials (e.g. portland cement, fly ash, lime, etc.) to alter the physical and chemical characteristics of a waste to reduce the mobility of pollutants when disposed of on land.

A great variety of processes have been developed, and many are in use (Conner, 1984). In general terms, S/S, as it relates to managing hazardous wastes, refers to technologies in which additives are used to transform a waste into a more manageable or less toxic form by physically immobilizing and/or chemically fixating the waste constituents. Various terms are used with respect to these technologies which are important to define. However, the definitions for S/S technologies vary depending upon their source. The following definitions are used by the EPA (Wiles, 1986; Cullinane et al, 1986) in describing these processes:

- Solidification. A process in which materials are added to a liquid or semiliquid waste to produce a solid is referred to as solidification. It may or may not involve a chemical bonding between the toxic contaminant and the additive.
- Stabilization. Stabilization refers to a process by which a waste is converted to a more chemically stable form. The term includes solidification, but also includes use of a chemical reaction to transform the toxic component to a new non-toxic compound or substance. Biological processes, however, are not considered.

- Chemical Fixation. Chemical fixation implies the transformation of toxic contaminants to a new non-toxic form. The term has been misused to describe processes which did not involve chemical bonding of the contaminant to the binder.
- Encapsulation. Encapsulation is a process involving the complete coating or enclosure of a toxic particle or waste agglomerate with a new substance, e.g. the S/S additive or binder. Microencapsulation is the encapsulation of individual particles. Macroencapsulation is the encapsulation of an agglomeration of waste particles or micro-encapsulated materials.

Even though wastes containing constituents that have been classified as hazardous have been stabilized, they may still release or leach these constituents at reduced concentrations. These wastes may need to be subjected to leaching tests to determine whether or not the stabilized waste meets treatment standards [40 CFR 268, Subpart D (EPA, 1986b)].

2.4.5 Miscellaneous Possible Hazardous Wastes

Additional wastes presently disposed of on land may eventually be listed as hazardous wastes and require disposal in hazardous waste landfills. Two such wastes include:

- Municipal solid wastes and residues from the incineration of these wastes.
- Coal-fired power plant residues, e.g. fly ash and flue-gas desulfurization sludges.

Even though constituents of these wastes probably would not significantly affect the polymeric components of the FMLs, listing these wastes as hazardous would significantly affect the total required disposal capacity of hazardous waste landfills. The effects of exposing a wide range of FMLs to these wastes is discussed in Chapter 5.

2.5 DESCRIPTION OF WASTES FROM SPECIFIC SOURCES

The discussion on wastes in the above sections has been both general and specific as it relates to the composition of the leachates or other waste liquids that may contact liner materials in service. A general discussion on hazardous wastes and their distribution in their United States can be found in EPA's Report to Congress (EPA, 1974), the report of the Chemical Manufacturers Association (1985), and the National Research Council/National Materials Advisory Board (1983). Data on wastes from various sources, including municipal solid wastes, industrial wastes, electric power plant wastes, mining wastes, and uranium tailings are presented in Appendix A. Examples of the composition of specific wastes from the following industries are presented in that appendix:

- Electroplating and metals finishing industry.

- Inorganic chemicals industry.
- Metal smelting and refining industry.
- Organic chemicals industry.
- Paint and coatings formulating industry.
- Pesticide industry.
- Petroleum refining industry.
- Pharmaceutical industry.
- Pulp and paper industry.
- Rubber and plastics industry.
- Soap and detergent industry.
- Coal-fired electric power industry.

Many of the wastes generated by these industries contain free liquids which, under current statutes and rules, must be treated before ultimate disposal to reduce leachate formation and immobilize or destroy potential polluting species. Examples of various treatments are described in Sections 2.4.2 and 2.4.4.

2.6 HAZARDOUS SUBSTANCES IN STORAGE FACILITIES REQUIRING SECONDARY CONTAINMENT

In addition to being used in storage and disposal facilities, FML lining systems are also being used for secondary containment of both aboveground and underground tanks that contain various hazardous substances. The function of a liner system for secondary containment is to prevent the migration of a liquid that may be released from a leaking tank or pipe until a repair can be made.

Ninety-eight to 99% of the liquids that are stored in underground storage tanks are petroleum products (Lysyj, 1987), such as gasoline, diesel fuel, crude oil, and lubricating oils. The remaining 1 to 2% are organic solvents of various types, as is shown in Table 2-10. Underground storage tanks are also being used for the storing of CERCLA wastes prior to disposal. In all cases, the liquids that are being stored are principally organics, many of which are solvents and pure liquids. In secondary containment applications, however, a liner is not in contact with the liquid for great lengths of time, although it may have to be in service in the ground for relatively long periods of time.

TABLE 2-10. PREDOMINANT TYPES OF ORGANIC CHEMICALS STORED IN UNDERGROUND STORAGE TANKS

Organic chemical	California		New York		Chemical Manufacturers Association	
	Number of tanks, %	Volume of tanks, %	Number of tanks, %	Volume of tanks, %	Number of tanks, %	Volume of tanks, %
Solvents:						
Ketones/aldehydes	35.6	32.9	25.2	31.5	23.5	21.7
Aromatic hydrocarbons	22.2	21.1	37.8	32.9	21.8	22.3
Alcohols	10.2	8.8	16.5	17.2	18.8	16.8
Chlorinated hydrocarbons	12.5	14.0	5.7	4.0	12.6	10.3
Esters	6.0	4.4	6.2	4.4	1.2	0.8
Alicyclic hydrocarbons	0.6	0.7	...	...	0.4	0.4
Total	87.1	81.9	91.4	90.0	78.3	72.3
Monomers	3.6	6.2	2.8	1.6	13.3	22.2
Miscellaneous chemicals	7.4	7.0	6.0	8.0	8.8	5.0
Pesticides	1.4	4.2

Note: Totals may not add up to 100% because of rounding.

Source: Lysyj, 1987.

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CHAPTER 3

WASTE CONTAINMENT ON LAND AND CONSTITUENT TRANSPORT WITHIN AND OUT OF A CONTAINMENT UNIT

3.1 INTRODUCTION

This chapter describes basic concepts and factors in the transport of mobile constituents of a solid or liquid waste contained in a storage or disposal facility and their escape into the environment. The paths and mechanisms by which these constituents are transported within a containment unit are discussed with particular emphasis on transport within multilayered liner systems, such as those described in the EPA draft Minimum Technology Guidance documents on double liner and final cover systems for hazardous waste landfills and surface impoundments (EPA, 1985; EPA, 1987). Such systems include FMLs, compacted soil liners, and systems for collecting and removing liquids, e.g. leachate. This chapter concentrates on closed FML-lined landfills and FML-lined surface impoundments that meet the requirements of RCRA and the Hazardous and Solid Waste Amendments of 1984.

The function of a liner system in a containment unit is to minimize and control the migration of polluting constituents in the waste or liquid being contained and prevent them from entering the environment either through the air or through the ground. However, even though FMLs are nonporous and cannot be permeated by liquids per se, gases, vapors and liquids can permeate an FML on a molecular level. Thus, even if an FML is free of holes, some constituents of wastes can still permeate through an FML into the liner system and may escape into the environment. A properly designed and constructed liner system should minimize and control the escape of pollutants over extended periods of time.

In a waste storage or disposal unit, the mobile constituents will migrate throughout the unit by advection in the liquid which carries dissolved constituents and by diffusion as gases, vapors, or dissolved constituents. The movement of the mobile constituents is determined by factors such as temperature, concentration, vapor pressure, partitioning, gravity, and density. The mobile constituents will tend to migrate so that there is equilibrium throughout the mass within the unit and with the surrounding environment (Haxo et al, 1988; Haxo, 1988). As covers are not placed on surface impoundments, moisture and the volatile constituents in wastewaters can escape from surface impoundments into the atmosphere.

Transport of chemical species can occur through FMLs without pinholes, punctures, or other breaks, but depends on the solubility and diffusibility of the permeating species in a particular FML. In contrast to soils, sands, silts, and clays which are porous, the driving force for permeation through FMLs is not gravity and the hydraulic head of the liquid but a chemical potential (for which concentration is a good approximation in most cases) or partial pressure gradient across the FML. Species migrate through an FML from a higher to a lower concentration. Because the concentration of most potentially contaminating or polluting constituents existing in the waste will be higher than their concentration in the environment, there will be a tendency for the mobile species to equilibrate within a unit and to move towards the outer boundaries and out of the unit.

The rate and ultimate magnitude of transport of gases, vapors, and liquids out of a land storage or disposal unit into the outer environment can be affected by the specific environmental conditions that exist in the ground or in the atmosphere. For instance, in the case of surface impoundments, wind, relative humidity, atmosphere, and temperature can have a significant effect on the evaporation of water and the escape of volatile constituents of the impounded liquid (Cohen, 1986). In the case of transport through the bottom liner system, in both a surface impoundment and a landfill, the rate would be affected by such factors as the type of soil below the liner system and the proximity to groundwater and an aquifer. Even though covered landfills can be highly "sealed" with FMLs that have low permeability, the effect of rising and falling barometric pressure forces the waste containment system to "breathe" and thus release constituents to the environment and bring air into a landfill.

All components of a liner system can potentially interact with waste constituents, whether they be gases, vapors, or liquids. These systems are multilayered composites constructed of different materials, some of which are polymeric. Each component of these systems is designed to fulfill a specific function while it is at the same time exposed to compressive, tensile, and multiaxial stresses. Interaction between waste constituents and the liner system becomes important in terms of the long-term functioning of the system because of the combined effects of mechanical stresses and interaction with the waste constituents. Of particular concern is the effect that waste constituents can have on components of the leachate drainage and collection and leak-detection subsystems. The absorption of organic waste and waste constituents could cause softening of a synthetic drainage medium, such as a geonet, with the result that the drainage system could collapse under the overburden and no longer function satisfactorily.

In this chapter, the mechanisms of transport of mobile chemical species within waste storage and disposal units and the multilayered composites that make up the liner and cover systems of landfills and surface impoundments are discussed. Some of the basic properties of both waste liquids and FMLs that affect the rate and direction of transport of waste constituents are also discussed.

3.2 PHYSICAL AND CHEMICAL ATTRIBUTES OF WASTE LIQUIDS, GASES, AND VAPORS

As is described in Chapter 2, the wastes that are contained in both MSW and hazardous waste landfills are highly complex, nonhomogeneous mixtures of solids, liquids, vapors, and gases. Such mixtures can contain a high volume of airspace and voids, which will be at atmospheric pressure. The solid materials can be either organic or inorganic or both. The organic waste is probably degradable; some solids may be water-soluble, and some may sublime into the air voids. The liquid phase is usually an aqueous solution containing dissolved organics, inorganics, and gases; there can also be liquid phases of organics, particularly in surface impoundments. The gaseous phase can contain "permanent" or noncondensable gases, such as nitrogen, oxygen, carbon dioxide, methane, and hydrogen sulfide, and vapors of liquids, such as water and the volatile organics that exist in the liquid state or dissolved in the liquid phase. The composition of each phase does not remain constant, but is subject to change with time due to consolidation of the solid waste, to movement of mobile species, and to chemical and biological activities within the waste.

Of particular importance, from the standpoint of containment, are the mobile constituents, such as liquids, vapors, and gases, which are present or generated in the landfill. The movement of these constituents is governed by their chemical and physical properties, the conditions that exist in the landfill, and the relevant driving forces (Versar, 1984). For example, dissolved volatile constituents at dilute concentrations in water, which in this case would be the leachate, will have a vapor pressure corresponding proportionally to the mole fraction of the constituent in the solution. Thus, depending on their volatility and Henry's law constant, volatile constituents will enter pores. This constant, K_2 , of a volatile solute is defined by:

$$K_2 = \frac{P_2}{X_2} \quad (3-1)$$

at infinite dilution, where P_2 is the vapor pressure above the solution divided by the mole fraction, X_2 , of the solute in the solution. Constituents in the leachate, both volatile and nonvolatile, can also be absorbed by the solids, such as the FMLs, by partitioning from the leachate phase into the solid phase. Partitioning and its effect on permeability are discussed in Section 5.4.1.7 and in more detail by Haxo et al, 1988 and Haxo, 1988. Liquid components will tend to gravitate to the bottom of the fill where they will be collected in the leachate collection and drainage system. When the liquid or leachate is in contact with the bottom liner, some dissolved constituents can then be absorbed in and pass through the FML into the leachate detection, collection, and removal system below by vapor transmission and by diffusion. The amount that would be absorbed by the liner system depends on the concentration of the constituents in the leachate and the relationship of the partitioning and solubility parameters among the various components of the liner and drainage system.

Gases, vapors, and dissolved chemical species tend to move through a mass in accordance with their chemical potential or activity. The movement of chemical species is from a high potential to a low potential. In the transport of a chemical species through a membrane between two ideal solutions of chemicals and vapors, chemical potential is directly related to the concentration or the vapor pressure of the permeating species. In most situations, however, there is deviation from ideality. Nevertheless, concentration is a reasonable approximation of chemical potential. Concentrations of the mobile constituents will tend towards an equilibrium throughout an impoundment unit and the surrounding environment predominantly by gas and vapor transmission as driven by chemical potential.

3.3 CHARACTERISTICS OF BARRIER MATERIALS

3.3.1 Introduction

The materials that are used in lining waste containment units consist of both porous and nonporous materials. The porous materials include clay soils which are used both in the composite bottom liner and in the cover system of a closed landfill. In addition to the clay soils, a variety of other porous materials are also used, including sand, gravel, and various geotextiles for drainage and venting. The nonporous materials are principally the FMLs and the various sprayed-on asphaltic-type materials.

Both porous and nonporous materials are permeable to various gases, vapors, and liquids; however, the mechanisms for permeation are substantially different. Basically, liquids, vapors, and gases permeate the porous materials through interconnecting pores or capillaries within the material; gases and vapors permeate nonporous materials on a molecular basis, which requires that the permeating molecules move individually among the polymer chains which are continually in molecular motion.

In this section, transport through the two basic types of materials that are used as liners, porous and nonporous, is discussed and the terminology that is used in this TRD with respect to permeation is set forth. The term "permeability" is used to describe transport through both types of materials, even though the two types have widely different structures. In general, therefore, the term "permeability" does not imply anything about the mechanism of permeation; several permeation or transport mechanisms may be operating concurrently, depending on the barrier.

3.3.2 Permeation Through Porous Materials

With the exception of some metals and plastics, most materials that are encountered are porous in nature. They include such building materials as soils, bricks, concrete, limestone, and wood. They also can include various filtration media that are used in the purification of water, etc. For a material to be termed porous, it must be one of the following two types:

- The material contains spaces, voids, or pores that are embedded in a solid or a semisolid matrix, i.e. pores that are not interconnected.

These pores can contain fluids, air, waste, or a mixture of different fluids.

- The material contains pores that are connected in such a way that a fluid introduced on one side of the material will flow from pore to pore and emerge on the other side.

Examples of porous materials that do not contain interconnected pores include closed cell foams used for flotation and blown or expanded polystyrene insulation. The vast majority of porous materials, including the soils and the other porous materials that are used in the construction of waste containment units, however, are of the second type. These materials contain interconnecting three-dimensional networks of capillary channels of non-uniform sizes and shapes and of different surface characteristics. Flow through these materials can take place within extremely complicated microscopic boundaries. This pore structure is inseparable from the convective, diffusive, and interfacial effects that take place within the pores.

Lambe and Whitman (1969) discuss flow phenomena in soils of a single component liquid, such as water. Figure 3-1 illustrates schematically the path of one-dimensional flow of a liquid on the macroscopic scale as well as the microscopic scale. The flow path on a microscopic scale is the highly tortuous path that liquid must follow in passing from pore to pore through a soil to get from point P to point Q. On a macroscopic scale, a soil can also be treated as continuum without regard to pores or pore shapes so that a liquid can be considered to flow from point P to point Q along a straight line at an effective velocity. Most of the technical information that has been developed on the permeability of soils, particularly by engineers, uses the model of macroscopic flow to describe the flow of a liquid through soil.

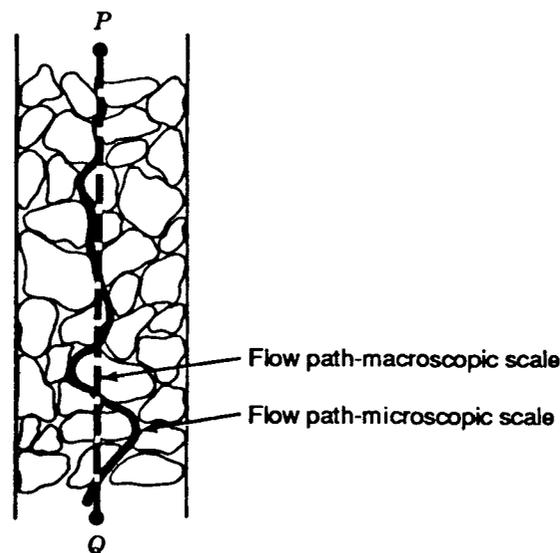


Figure 3-1. Flow pattern of liquid through a soil on macroscopic and microscopic scale.

Macroscopic flow through saturated porous media follows Darcy's law which was determined experimentally by measuring the flow of water through a saturated column of sand. Darcy's experiment is presented schematically in Figure 3-2. The flow rate was found to be proportional to the difference in hydraulic head divided by the length of the column, as is shown in the following equation (Lambe and Whitman, 1969):

$$Q = k \frac{h_1 - h_2}{L} A = kiA \quad , \quad (3-2)$$

where

Q = the rate of flow,

k = a constant (Darcy's coefficient of permeability),

h_1 = the height above a reference level to which the water rose in a standpipe inserted at the the entrance end of the filter bed,

h_2 = the height above a reference level to which the water rose in a standpipe inserted at the exit end of the filter bed,

L = the length of sample,

A = the total inside cross-sectional area of the sample container, and

$i = \frac{h_1 - h_2}{L}$, the hydraulic gradient.

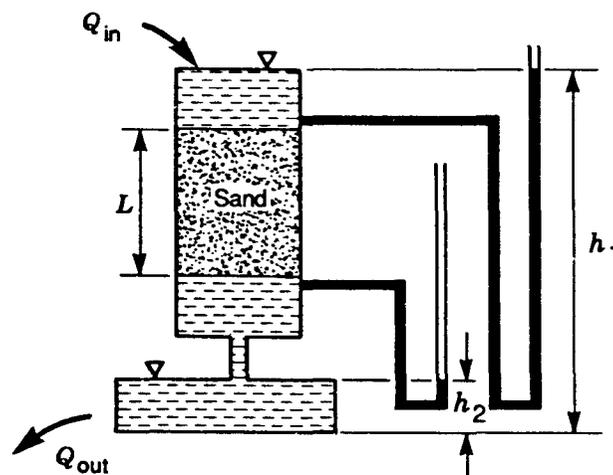


Figure 3-2. Darcy's experiment. (Based on Lambe and Whitman, 1969, p 252).

With most liquids in saturated soils, the flow follows Darcy's law; however, in the case of waste liquids and contaminated water, the flow can deviate from the law due to interactions between the waste liquid and the surface of the soil particles. These interactions become important in the effect of escape of dissolved species through the FML component of a composite liner on the underlying soil component, and also can be of concern in the dikes that form the support for the liner system in waste facilities.

Dullien (1979), in his treatise on porous media, discusses permeation through porous media in terms of interaction among three main factors, i.e. transport phenomena, interfacial effects, and pore structure. He presents highly pertinent information on the role of pore structure and uses this information to interpret experimental results that have been reported in the literature.

Dissolved chemical species, either organic or inorganic, not only can permeate a soil advectively (i.e. the liquid acts as the carrier of the chemical species), but also by diffusion in accordance with Fick's two laws of diffusion; thus, in some cases, the chemical species can precede the flow of the liquid carrier.

Daniel et al (1988) discuss the transport of inorganic components by diffusion through compacted clay soils and present data showing that the effective diffusion coefficient for anions diffusing through compacted clay soils is about $2 \times 10^{-9} \text{ m}^2/\text{s}$ and that breakthrough of dissolved species can occur much sooner than predicted by models developed from the hydraulic conductivity of the soil, the hydraulic gradient, and the effective porosity of the soil. Daniel et al (1988) also show that cations tend to diffuse more slowly due to ion-exchange and other reactions, and that the compaction and water content have little influence on the diffusion coefficient. On the other hand, they observed that subtle variations in geochemical factors can cause significant changes in the rate of diffusion transport.

3.3.3 Permeation Through Nonporous Materials

In contrast to the porous soils and various admixes that have been used as principal barriers to prevent the migration of mobile constituents from waste containment units, FMLs are nonporous membranes. It should be pointed out that FMLs are special types of synthetic membranes. All synthetic membranes are not necessarily nonporous; many are in reality porous, as they are manufactured with very small holes and are used as filters, as desalinization membranes, and as membranes for chemical and biological purification, dialysis, and reverse osmosis (Kesting, 1985). Membranes that are used as FMLs are nonporous and are generally considered to be homogeneous materials, though in some classifications they may be considered nonhomogeneous due to additives, fillers, the crystalline content of semi-crystalline FML compounds, and fabric reinforcement in manufactured sheeting. Even though polymeric FMLs are manufactured as solid nonporous materials, they contain interstitial spaces between the polymeric molecules through which small molecules or other chemical species can diffuse. Thus,

all polymeric FMLs are permeable to a degree. The permeant, in this case, migrates through the material on a molecular basis by an activated diffusion process and not as a liquid which can flow through the pores of a soil and carry dissolved chemical species, as is described in the previous subsection. This transport process of chemical species through an FML involves three steps:

- The solution or absorption of the permeant at the surface of the FML.
- Diffusion of the dissolved species through the FML.
- Evaporation or desorption of the permeant at the downstream surface of the FML.

The driving force for this type of activated permeation process is the "activity" or chemical potential of the permeant which is analogous to mechanical potential and electrical potential. The chemical potential of the permeant decreases continuously in the direction of the permeation, as is shown in Figure 3-3, which schematically presents variations of permeant chemical potential and concentration with distance through a membrane in permeation in the steady state.

In the transmission of a permeant through a membrane, Step 1 depends upon the solubility of the permeating species in the membrane and the relative chemical potential of the permeant on both sides of the interface.

In Step 2, the diffusion through the membrane involves a variety of factors including size and shape of the molecules of the permeating species, and the molecular characteristics and structure of the polymeric membrane (Crank and Park, 1968). For example, the presence of fillers, crystalline domains, and crosslinks tend to reduce diffusion rates by interfering with molecular movement of the polymer chains. The presence of plasticizers or the swelling of the membrane by solvents tends to increase the rates of diffusion by opening up the molecular structure of the polymer. Higher temperatures result in higher rates of diffusion due to increased molecular motion of both the permeating species and the polymer in the FML.

A steady state of the flow of the constituents will be established when, at every point within the FML, flow can be defined by Fick's first law of diffusion:

$$Q_i = - D_i \frac{dc_i}{dx} \quad , \quad (3-3)$$

where

Q_i = the mass flow of constituent "i" in $g \text{ cm}^{-2} \text{ sec}^{-1}$,

D_i = local diffusivity in $\text{cm}^2 \text{ sec}^{-1}$,

c_i = the local concentration of constituent "i" in g cm^{-3} , and

x = the thickness of the FML in cm.

It should be noted that the concentration of constituent "i" referred to in Fick's law is within the mass of the FML. For gases, the mass units can be expressed as volume units, e.g. cm^3 at standard temperature and pressure.

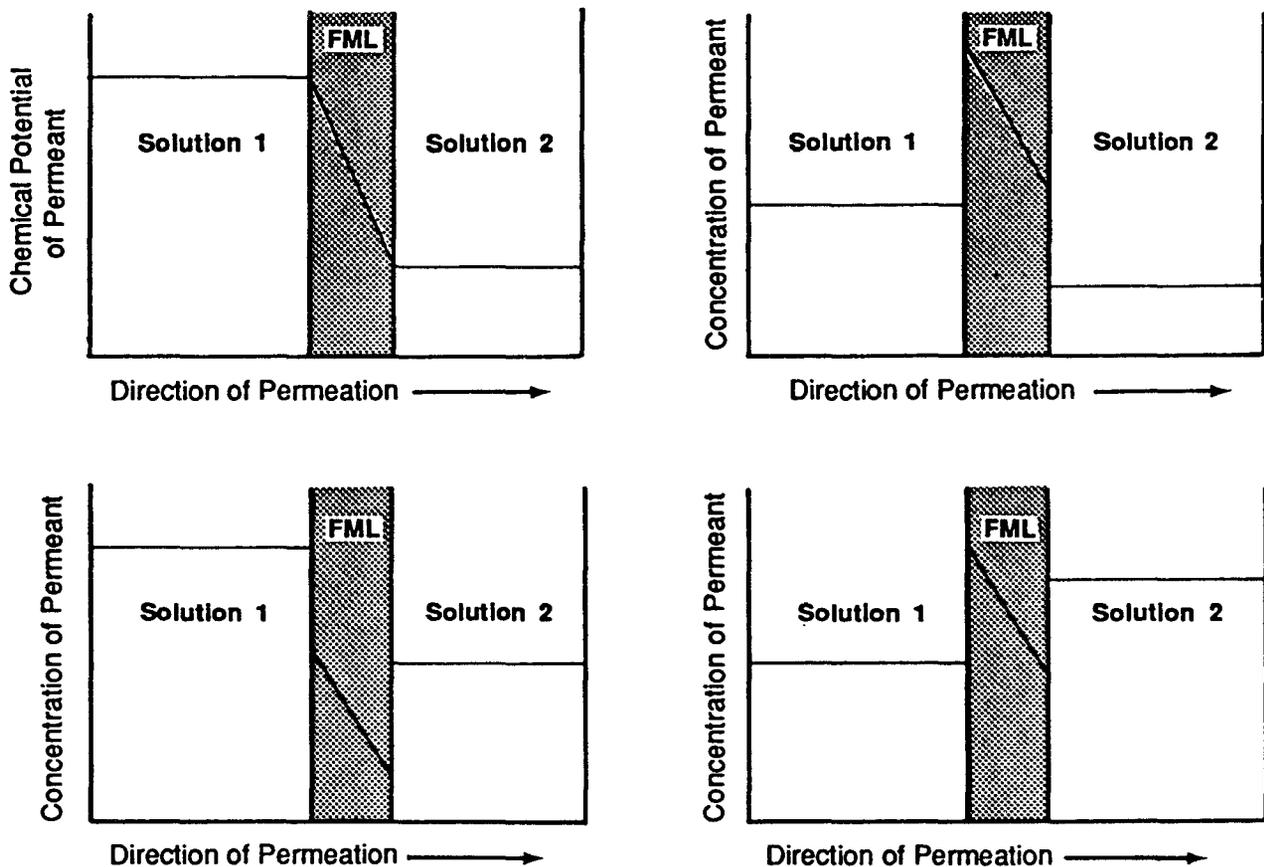


Figure 3-3. Schematic representation of the variation of permeant chemical potential and concentration with distance through the thickness of a membrane in permeation in the steady state. (a) Relationship between chemical potential and distance; (b) and (c) concentration-distance profiles commonly encountered when the partition coefficient between membrane and solution differs from unity; (d) chemical potential of the permeant is much less in Solution 2 than in Solution 1. The concentration gradients within the FMLs assume pure Fickian diffusion with constant diffusivity. (Based on Yasuda et al, 1968, p 796).

Step 3 is similar to the first step and depends on the relative chemical potential of the permeant on both sides of the interface at the downstream membrane surface.

Chemical potential is an idealized concept which indicates the direction in which the migration or permeation will go. It will always go from high to low potential. To use concentration directly to replace chemical potential requires the individual molecules of the permeating species to neither interact with each other nor interact with the membrane they are permeating. This condition approximately exists when a permanent or noncondensable gas, such as oxygen, nitrogen, and helium, permeates a membrane. However, the individual molecules of organic species can interact with each other and with the polymer to increase solubility of the species in the FML, and as a result partition to the FML. This subject is discussed further in Chapter 5 with respect to permeation of organics in dilute aqueous solutions through FMLs (Section 5.4.1.7). If concentration and chemical potential are equal, then the concentration of the constituent can be used directly to determine the rate of permeation. The relationship between the concentration in phases that contact each other and the chemical potential is determined by the solubility parameters of the species and partitioning of the permeating constituent between the fluid containing the permeant and the membrane, as well as partitioning of the permeant between the membrane and the fluid on the opposite side.

Concurrent with the absorption of volatile organic species by an FML and their transmission through the FML, the FML can retain a portion of the organics and swell and, in turn, become somewhat more permeable. Though other compositional factors contribute, the extent to which an FML will absorb a vapor or liquid depends largely on the near matching of the respective solubility parameters of the organic and the FML, as is discussed in Chapter 4 (Section 4.2.2.4.3). Mass flow, Q_i , of constituent "i" can also be defined by the following equation:

$$Q_i = -D_i S_i \frac{dp}{dx} , \quad (3-4)$$

where

Q_i = the mass flow of constituent "i" in $g \text{ cm}^{-2} \text{ sec}^{-1}$,

D_i = local diffusivity in $\text{cm}^2 \text{ sec}^{-1}$,

S_i = Henry's law constant of component "i" in $\text{sec}^2 \text{ cm}^{-2}$,

p = the vapor pressure of constituent "i" in $g \text{ cm}^{-1} \text{ sec}^{-2}$, and

x = the thickness of the FML in cm.

When the solubility parameters of the membrane and the permeating constituent are similar, it is likely that Henry's law constant also termed solubility coefficient, S , and the diffusion coefficient, D , will be dependent on the concentration of the permeating constituent throughout the FML as will the permeability coefficient, \bar{P} . An "integrated" permeability coefficient, \bar{P} , is often used as a convenient method of describing permeation between two vapor pressures, as is shown in the equation:

$$\bar{P}_i = \frac{Q_i x}{p_2 - p_1} \quad , \quad (3-5)$$

where

p_1 = the vapor pressure of constituent "i" on Side 1 of the membrane,
and

p_2 = the vapor pressure of constituent "i" on Side 2 of the membrane.

Film thickness may also change with the concentration due to swelling, but the usual practice is to use the unswollen film thickness and incorporate all corrections into the integrated permeability coefficient.

In steady-state permeation, permeants that cause swelling result in a nonlinear concentration profile through the FML. Most of the resistance to transport is localized on the outflow side of the FML. This situation is analogous to permeation of composite membranes. In addition, if the swelling results in the relaxation of stresses produced during membrane manufacture, the permeability will change with the degree of swelling.

3.4 TRANSPORT PROCESSES AND DRIVING FORCES INVOLVED IN THE MIGRATION OF CHEMICAL SPECIES

In a landfill, the mobile constituents (i.e. the liquids, gases, and vapors) will move through the airspaces in the waste mass. The liquids which contain dissolved constituents can move downwards by gravity and upwards through channels by capillary wetting of solid particles. The gases and vapors will move by diffusion through the available airspaces. Due to the solubility of gases and vapors in liquids and the volatility of the liquids, there are exchanges between the constituents, depending on such driving forces as concentration, vapor pressure, and temperature. These latter driving forces are all related to the chemical potential of individual species. Though the temperature within a landfill tends to be reasonably consistent, there are variations from the top to the bottom during the course of a year, perhaps even a day. The flow of vapors and waste constituents will be towards the lower temperature; thus, there will be a driving force towards the bottom of a landfill for all liquids. Vapors (e.g. water vapor) tend to condense on colder surfaces. Since relative humidity within a waste will probably be 100%, moisture condensation may occur in the leachate drainage and detection systems.

Depending on the solid waste and the surface tension of the waste liquids, there can be considerable movement in all directions via the wetting of the solid particles. This wicking action is a possible means of raising components from lower parts of a landfill to the top, where they can escape to the atmosphere or, in the case of dissolved salts, form high concentrations of salts on the top of the landfill cover (Lutton, 1982; Bell and Parry, 1984).

In the case of surface impoundments in which an aqueous phase predominates, constituents of the waste that exceed their solubility in the aqueous phase may either rise to the top, as in the case of oils and low-specific gravity materials, or collect on the bottom, as in the case of many halogenated solvents. Those that rise to the surface may interact with the liner and cause swelling and damage; those that collect on the bottom may contact the FML and similarly swell and damage the FML.

3.5 TRANSPORT OF WASTE CONSTITUENTS WITHIN A CLOSED LANDFILL

From the standpoint of the effects that a leachate may have on the liner system of a closed landfill, it is necessary to know the path that the different mobile waste constituents travel as they move through the landfill. They can be absorbed by the various components of the liner system, the leachate collection system, or the cover system, causing changes in the properties of these components that may affect their ability to function as designed.

Of particular importance is the possible increase that absorbed organics would have on the permeability of the FML barrier. An increase would allow organic chemical species to enter the leachate detection, collection, and removal system more readily. Those organics that permeate through the FML may then be absorbed from the vapor phase by drainage nets and other polymeric components of the system, causing these components to soften. As they would be under load, they may lose their transmissivity and their designed drainage quality. (The design of double liner systems is discussed in Chapter 7).

In addition to the potential downward movement of these species toward the liner system, volatile organics can move upwards toward the cover by diffusion as can liquids, to some extent, by capillary action. Volatile constituents may permeate through the FML in the cover system into the soil where they could possibly adversely affect plant growth. They would then migrate into the atmosphere. The use of an FML in covers should aid in the control of escaping gases and vapors by improving collection efficiency and reducing permeation losses as well as decreasing intrusion of waste into the landfill.

3.6 ESCAPE OF CONSTITUENTS FROM WASTE STORAGE AND DISPOSAL FACILITIES

Because polymeric materials are not totally impermeable (Haxo et al, 1988; Haxo, 1988), the performance goal of a liner system for a waste

containment unit is to allow, for extended periods of time, no more than a minimum escape of potentially polluting chemical species into the environment. This level of escape should be below the level that would have any adverse effects on human health and the environment.

In spite of the measures taken to prevent the escape of constituents from a waste into the environment, small amounts can escape by diffusion even from a closed, double-lined landfill. The magnitude of what does escape can be affected to a certain extent by various hydrogeological and environmental factors; for example, escape through the bottom liner can be affected by the type of soil below the containment boundary and the proximity to groundwater. The escape of volatile organics to the atmosphere from a closed landfill can be affected by weather conditions; for example, the wind, temperature, relative humidity, and rain. The rate of escape can be controlled by venting systems in landfill covers which are designed to prevent the accumulation of gases, particularly of methane in MSW landfills, and to control their escape. Changes in barometric pressure can result not only in the movement of air into a landfill, but also in the movement of gas and vapor components out of a landfill. Variations in barometric pressure have been found to affect the leachate levels in sump systems; decreased barometric pressure has resulted in higher levels of leachate in a collection sump (i.e. in a higher hydraulic head on the lining system), as is shown in Figure 3-4 (Kirkham et al, 1986).

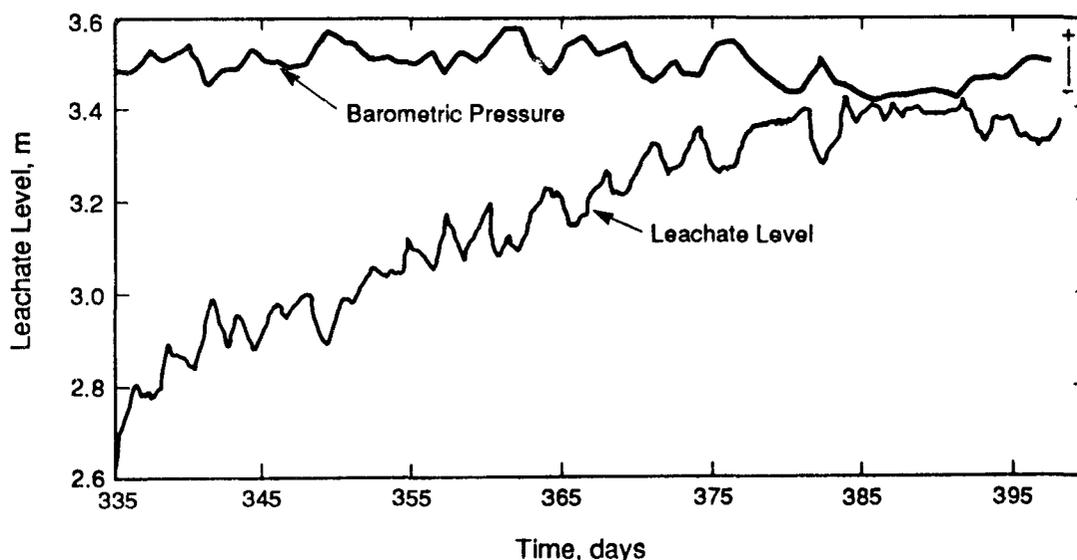


Figure 3-4. Comparison of leachate levels in a leachate collection sump to atmospheric pressure. (Source: Kirkham et al, 1986).

In the case of surface impoundments, where the surface is exposed to the atmosphere, volatile constituents can leave the impoundment and move into the atmosphere, as is discussed by Thibodeaux et al (1984). This aspect has been of concern due to potential air pollution. Various efforts have been made to use FMLs as covers, such as those described by Kays (1986). Covers have been used on reservoirs in the past to reduce evaporation of water. However, many surface impoundments are used as evaporation ponds to reduce water content prior to disposal or further treatment. Wastes containing liquids and solids of high density and low solubility in water have been covered with water to prevent escape of waste constituents into the atmosphere (Farmer et al, 1980). The transport of organic pollutants into the environment and multi-media modeling techniques predicting their fate in the environment are discussed by Cohen (1986).

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CHAPTER 4

FMLS AND OTHER CONSTRUCTION MATERIALS

4.1 INTRODUCTION

This chapter discusses various types of materials used in the construction of lined containment facilities, particularly those for the storage or disposal of wastes. These materials, which are used to fulfill a variety of functions in the structure of such facilities, are listed in Table 4-1 by their function. Depending on the service that may be required, these materials may need to perform from a relatively few years, as in the case of some storage units, up to 100 years or more, as in the case of some landfills, and to function in such a manner that hazardous materials are under control and do not migrate from the unit in an uncontrolled manner.

TABLE 4-1. MATERIALS USED IN THE CONSTRUCTION OF LINER AND LEACHATE CONTROL SYSTEMS FOR WASTE STORAGE AND DISPOSAL FACILITIES AND THEIR FUNCTIONS^a

Material	Barrier	Sepa- ration	Support	Soil rein- forcement	Filtr- ation	Leachate drainage and collection ^b
FMLs	P	S	...	n/a	n/a	n/a
Geotextiles	n/a	P	...	P	P	P
Geogrids	n/a	S	...	P	n/a	n/a
Geonets	n/a	S	...	n/a	n/a	P
Composites	P or S	P or S	...	P or S	P or S	P or S
Sand/gravel	...	S	...	...	S	P
Concrete	...	...	P	...	...	S
Pipe	...	...	...	...	...	P
Soil	P or S	...	P	...	...	...

^aP = primary function; S = secondary function; n/a = not applicable.

^bAlso part of the leak-detection system.

Emphasis is placed on polymeric materials consisting of the FMLs, geotextiles, geogrids, geonets, geocomposites, and pipe. Discussion of soils for liners or soils for membrane/soil liner composites is referenced largely to the TRD on soil prepared by Research Triangle Institute (Goldman et al, 1985). Sands and gravels and concrete are discussed in Chapter 7 on design and construction. Also discussed in this chapter are the admix liners and sprayed-on FMLs.

Preliminary to the discussion of polymeric components that are used in the construction of liner and leachate control systems, the basic characteristics of polymers that are common to polymeric products are discussed with particular reference to those properties that are of importance in the performance of the component in service. These include such characteristics as composition, the effect of temperature on properties, the creep and relationship of polymers under mechanical stress, the effect of multiaxial straining, permeability to gases, water, and organic liquids, the sensitivity to organic liquids, stress cracking and fatigue under stress, long-term durability of polymers in waste containment environments, and the importance of considering the combination of properties in the evaluation of polymeric materials. The components of liner systems are discussed individually.

The following subjects are discussed with respect to FMLs:

- The polymers used in currently available FMLs.
- The manufacturing processes.
- The fabrication and seaming of FMLs into liners.
- The properties of importance to liner performance in service, such as permeability, mechanical properties, chemical resistance, and durability.
- Testing and evaluation of FMLs in the laboratory with respect to analytical properties, physical and mechanical properties, permeability, environmental effects, performance testing, and fingerprinting.

The geotextiles, geogrids, geonets, geocomposites, and pipe are also discussed individually with regard to their respective compositions, manufacture, testing, and long-term durability.

Admix liner materials and sprayed on FMLs are described with respect to types, compositions, properties, and installation.

Information and data are included in this chapter, as well as the succeeding chapters, on a wide range of materials which have been used for the lining of containment and conveyance facilities, but are not currently used in the lining of containment facilities for hazardous wastes. The information on these materials should be useful for general consideration in many containment applications. A broad range of information on properties is included which may be useful in the selection and design of new materials and components.

4.2 POLYMERIC MATERIALS

Several of the products used in the construction of liner systems for waste storage containment units are based on polymeric materials. The use of polymeric products in civil-engineering applications has increased impressively over the past decade, particularly in the design and construction of waste management facilities. These products include various rubber and plastic membranes that have very low permeability to gases, vapors, and liquids, woven and nonwoven textiles that have various degrees of permeability, various special open constructions designed for high permeability and liquid flow, and plastic pipes.

Of particular importance is the wide range of functions that polymeric products perform in liner systems for hazardous waste containment units. These products are based on a wide range of polymers including rubbers (elastomers), plastics, fibers, and resins. With this great diversity in materials and products, an array of tests must be performed on the materials and the products to assess their quality and ability to perform in a specific application. For hazardous waste containment applications thorough testing and evaluation of candidate materials are necessary, even when a material of a given generic polymer type may be the material of choice. This reflects the differences that exist in the grades of polymers and additives used in FMLs, in other geosynthetics, and in plastic pipe.

Each construction material in a liner system requires testing and evaluation in terms of the specific facility and environmental condition in which it is designed to perform. Thus, if a material will probably be exposed to a waste liquid or its vapors, it must be compatible with that particular waste stream and be able to maintain its properties over extended periods of time. Similarly, if the material is to be subjected to loads and to elevated temperatures, it must be able to function as required without failure.

The following polymeric materials of construction are being used or being suggested for use in liner systems (EPA, 1985):

FMLs--To provide a barrier between hazardous substances and mobile polluting substances and the groundwater; in the closing of landfills, to provide a low-permeability cover barrier to prevent intrusion of rain water.

Geotextiles--To provide separation between solid wastes and the drainage and leachate collection system or between the membrane and cover or embankment soils; to reinforce the membrane against puncture from the subgrade or the waste that is placed above it; to provide drainage, such as in leachate collection and leak-detection systems; to provide filtration around drainage pipes.

Geogrids--To provide reinforcement of soils on side slopes and embankments.

Geonets--To provide drainage above and between liners.

Plastic Pipes--To provide drainage in leachate collection and removal systems and in leak-detection systems. Pipe is also used in the construction of monitoring ports, manholes, and system cleanouts.

This section reviews some of the basic characteristics of the polymeric materials and products that are used in the construction of systems and indicates the effects of these characteristics on field performance.

4.2.1 Basic Characteristics of Polymeric Materials

All of the materials discussed in this section are based on polymers, which are products of the chemical, plastics, rubber, and fiber industries. From the viewpoint of composition, an almost infinite range of polymeric materials can be produced, though only a small fraction is used in the manufacture of geosynthetics and pipe. The polymeric materials used in the manufacture of the FMLs and the ancillary construction materials are listed in Table 4-2. Polymers within a given type can vary in grade and by the process by which they were produced. In addition, differences between materials based on the same polymers are introduced by the product manufacturers through compounding with various ingredients designed to enhance or develop specific characteristics. Knowledge about the composition of a material used in the construction of a waste management facility can be important when dealing with hazardous substances and waste liquids containing organics.

Four general types of polymeric materials are used in the manufacture of these materials:

- Thermoplastics and resins, such as PVC and EVA.
- Crosslinked elastomers, such as neoprene and EPDM.
- Semicrystalline plastics, such as polyethylenes.
- Highly crystalline, oriented polymers, such as polypropylene and polyester fibers.

In designing containment facilities and designing the tests needed to assess important design properties, recognition must be given to basic characteristics of polymeric compositions. As polymeric materials differ in some properties from many of the traditional materials used in construction, some of the important features and characteristics of the polymers used in products for the construction of liner systems are briefly discussed. General discussions of some of the basic characteristics of polymers can be found in Moore and Kline (1984), Rosen (1982), and the Modern Plastics Encyclopedia (1980-81).

TABLE 4-2. POLYMERS USED IN THE MANUFACTURE OF MAJOR PRODUCTS FOR THE CONSTRUCTION OF WASTE MANAGEMENT FACILITIES

Polymer	Type	Product			
		FMLs	Geo-textiles	Geogrids and geonets	Plastic pipe
Butyl rubber (IIR)	Rubber	X	...	...	...
Chlorinated polyethylene (CPE)	Rubber	X	...	...	...
Chlorosulfonated polyethylene (CSPE)	Rubber	X	...	...	...
Ethylene propylene rubber (EPDM)	Rubber	X	...	...	...
Ethylene vinyl acetate (EVA)	Resin	X	...	...	...
Neoprene [chloroprene rubber (CR)]	Rubber	X	...	...	...
Polyamide [nylon (PA)]	Fiber/resin	X ^a	X	...	...
Polybutylene (PB)	Resin	X	...	...	X
Polyester terphthalate (PET)	Fiber/resin	X ^a	X	X	...
Polyester elastomer (PEL)	Resin/rubber	X	...	...	...
Polyethylene (PE): Linear low-density (LLDPE)	Resin	X	...	...	...
High-density (HDPE)	Resin	X	X	X	X
Polypropylene (PP)	Resin	X	X	X	...
Polyurethane (PU)	Resin/rubber	X	...	...	...
Polyvinyl chloride (PVC): Plasticized	Resin	X	...	...	...
Unplasticized	Resin	...	...	...	X

^aUsed as reinforcing fabric in FMLs.

4.2.1.1 Composition and Structure of Polymers--

The polymers that are used in the polymeric construction materials discussed in this chapter are synthetic, i.e. they are manufactured by the process of polymerization. In this process a polymer molecule is prepared by a reaction of 100 or more small basic molecular units or monomers, e.g. ethylene, to form long chains which vary in length from a few hundred to thousands of repeating units. The chains are held together by primary bonds between the atoms in a chain. Some polymerization processes lead to highly linear molecules, i.e. each monomer enters the molecule in an ordered form, head to tail; in other processes the randomness of the process results in branched chains, such as in low-density polyethylene and many synthetic rubbers. During polymerization the length and size of the individual chains varies to yield a distribution in molecular weight from a few hundred to thousands, as is shown in Figure 4-1. Depending on polymerization conditions and the process, polymerization can yield different distributions from relatively broad distributions to comparatively narrow distributions. Variations in molecular weight distribution can affect both processing and ultimate physical properties of the polymer. The distribution of the monomer units along the chain, however, can be highly ordered, such as in HDPE, or random, such as in LDPE and some of the fibers. Where the monomer arrangement is random, the polymer will be amorphous, as is shown schematically in Figure 4-2. Where the arrangement of the basic repeating units is highly ordered, portions of the long molecules can fit together to form crystalline domains and thus the polymers are semicrystalline, as is also shown schematically in Figure 4-2. By stretching the mass of a semicrystalline polymer, the crystallites become oriented, such as are found in fibers. Oriented crystallites are shown schematically in Figure 4-2.

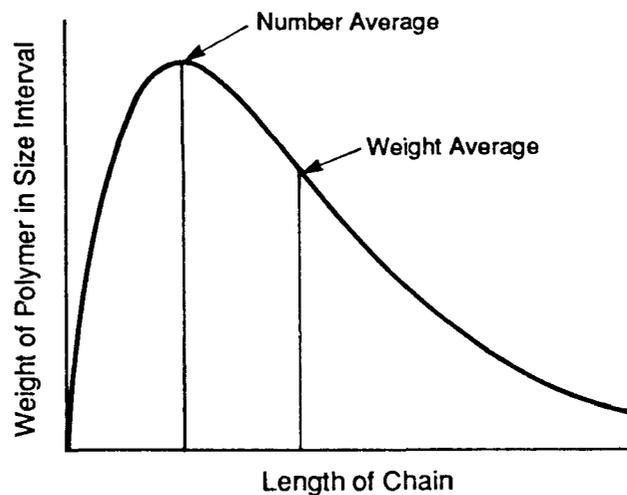


Figure 4-1. Distribution of molecular weights in a high polymer.

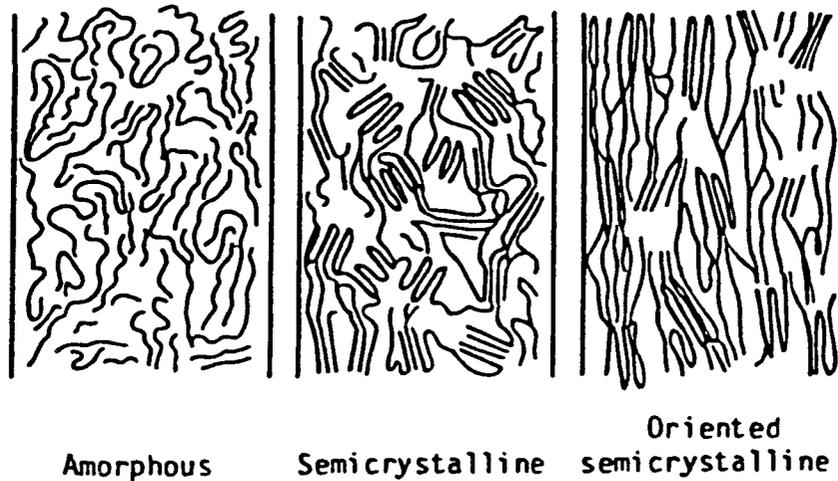


Figure 4-2. Schematics of polymer structures.

These molecular structures are thermoplastic, i.e. at elevated temperatures the crystals can melt and become amorphous. Also, increasing temperature will cause softening of the three structures. The secondary forces, that is the forces between the large molecules, determine the temperature range at which the molecules form resins or rubbers. When the forces are smaller, the molecules act independently to yield an elastic rubber material; when the forces are greater, the material becomes hard and resinous at room temperature, although at higher temperatures it will soften and become elastic (Rosen, 1982).

Amorphous polymers, such as rubbers, can be changed chemically and physically by tying the individual polymer molecules together with primary bonds to form, in essence, one large molecule. This process of bonding polymer molecules together is crosslinking or vulcanization; in vulcanization, sulfur crosslinks are formed between the individual larger polymer molecules of rubber. A crosslinked mass becomes insoluble in solvents and less susceptible to changes in properties with changes in temperature.

4.2.1.2 Polymers Vary in Modulus and in Elongation at Break--

Polymeric materials range from soft foam-like materials to high modulus structural materials. Polymeric materials that are used in waste management facilities are intermediate in modulus or stiffness. However, their uniaxial elongation at break ranges from 15% to as much as 1000%. Both properties are important considerations in designing storage and disposal facilities for wastes and hazardous substances, particularly for the liner system.

4.2.1.3 Polymers are Viscoelastic and Sensitive to Temperature and Rate of Deformation--

All polymeric compositions are viscoelastic; that is, when undergoing a deformation they show, in varying degrees, both viscous and elastic behavior. The elastic component behaves like a metal spring and is independent of rate of deformation and essentially independent of temperature. The viscous component behaves like a dashpot used in damping a shock and is highly dependent upon the rate of deformation and upon temperature. Three different sample models showing different combinations of springs and dashpots for viscoelastic materials are shown in Figure 4-3. Rubbers, such as natural rubber and some polyurethanes, tend to have highly elastic components, whereas many of the plastics have highly viscous components. In performing tests in extension or compression and in service, the temperature and rate of deformation that the polymeric material encounters becomes important.

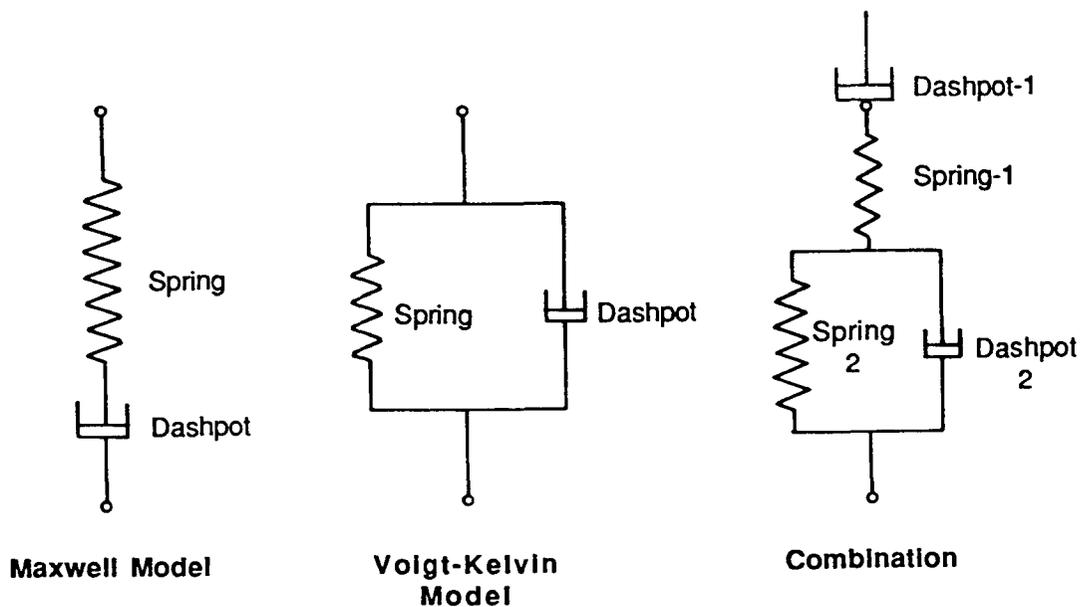


Figure 4-3. Models of viscoelastic materials showing different arrangements of springs (elastic component) and dashpots (viscous component).

Most of the polymers used in the manufacture of the products discussed in this section can vary greatly in properties with temperature, even within the temperature range $[-40^{\circ}$ to 80°C (176°F)] in which waste containment facilities may operate. At low temperatures some polymers become glassy and brittle and at elevated temperatures the thermoplastic polymers become soft and plastic. These characteristics greatly affect the applications in which a given polymer can be used. The effect of temperature on polymer properties is discussed more fully later in this chapter.

Due to the viscous component of polymeric compositions, the speed at which they are deformed greatly affects the magnitude of the values that are obtained, e.g. tensile or tear values. Modulus or stiffness values generally increase considerably with speed of deformation. The effect on tensile strength and elongation at break values varies with the polymer. In the case of semicrystalline materials, such as the PEs, high-speed testing will not allow time for crystals to align themselves during the test, thus resulting in lower tensile at break values than those obtained at lower speeds. In service environments deformation rates can range from rapid impacts to long-term creep.

4.2.1.4 Amorphous and Crystalline Phases in Semicrystalline Polymers--

Semicrystalline polymers, such as polyethylene and polyester elastomers, contain two basic phases:

- An amorphous phase in which the molecular structure is random, such as in a rubber.
- A crystalline phase in which the molecular structure is highly ordered.

The crystalline phase imparts stiffness to the polymer and resists the absorption of organic species; the amorphous phase is softer and can absorb and transmit organics. Deformation of a semicrystalline polymer results over time in molecular rearrangement in the crystalline phase. Excessive deformation results in yielding or drawing of the polymer and orientation of the crystalline phase in the direction of deformation with increases in tensile strength in that direction such as occurs in drawing fibers to produce high tensile strength. At the same time the tensile strength in the direction perpendicular to the deformation can drop substantially.

4.2.1.5 Polymers Tend to Creep and to Relax in Stress--

Compared with more traditional materials of construction, such as steel, concrete, and wood, polymeric materials have a relatively high tendency to creep, that is, to increase in length or change dimensions under constant load or to relax in stress when placed in constant strain. Creep is illustrated schematically in Figure 4-4 for a four-parameter model in extension. During creep the molecules slip to new positions from which they do not recover, which results in a permanent set. This characteristic of creep is important to long-term exposure such as would be encountered by all components in a liner system. For example, an FML placed on an uneven surface will tend to deform and be strained in accommodating the irregularities of the surface. In-place drainage nets and pipes are under constant load and an FML placed over a protrusion is under constant stress.

Relaxation of stress under constant strain can also occur in liner systems to relieve stress that may have been introduced in a component during construction. The relaxation of stress can cause loss of seal in a gasket.

The absorption of organics can soften the polymer and aggravate these tendencies.

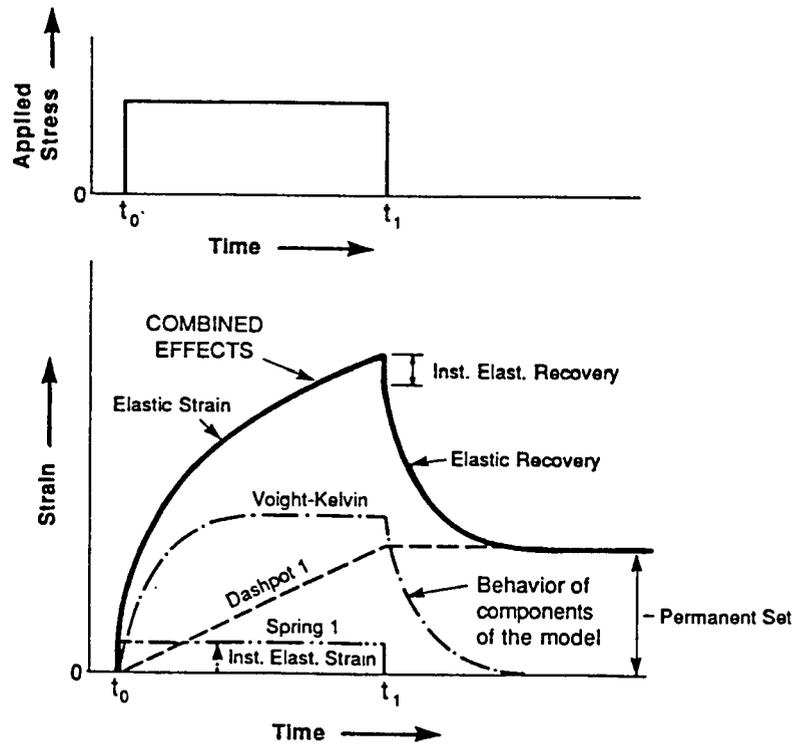


Figure 4-4. Strain response or creep of the combination four-parameter model (Figure 4-3) of a viscoelastic polymeric compound to an applied stress and its removal is shown as a function of time by the solid curve. The contributions of the individual four components of the model to the overall strain are shown individually by the dotted curves.

4.2.1.6 High Coefficient of Linear Thermal Expansion--

Polymeric materials have thermal coefficients approximately 5-10 times greater than those of metals and concrete, as is shown in Table 4-3. Having thermal coefficients in this range can be important in the performance of materials that are exposed to temperature changes. For the more rubber-like FMLs, changes in dimension with temperature are not a major problem; however, for stiffer FMLs, such as the polyethylenes, changes in temperature can cause considerable deformation, buckling, and flexing of a liner when exposed to normal weather and high stress in a liner placed without sufficient slack in hot weather when exposed to cold weather.

4.2.1.7 Importance of Thermal and Strain History--

Polymeric materials tend to have "memory," that is, the deformation during processing and forming into sheets leaves "frozen" residual strain in

many polymers. This results in a "grain" effect which can lead to different property values in different directions of test; consequently, tensile and tear testing should be performed in both machine and transverse directions. Residual strain in extruded sheeting can cause shrinkage in the machine direction and expansion in the transverse direction when the sheeting is warmed. In the manufacture of synthetic fibers, the polymer filament is drawn from spinnerets as it is being formed from a melt. This process orients the crystalline domains as they are forming to yield high strength in the fiber direction. On heating the fiber above the melting point of the crystals, the fiber will shrink and partially return to its original length.

TABLE 4-3. COMPARISON OF THE COEFFICIENT OF LINEAR THERMAL EXPANSION OF POLYMERIC COMPOSITIONS WITH OTHER CONSTRUCTION MATERIALS

Material	Temperature, °C	Coefficient of linear expansion (cm/cm/°C x 10 ⁻⁶)
Polymeric compositions:		
Polybutylene	...	125-140
Polystyrene	20-25	70-80
Polypropylene	20-25	81-100
Polyester terphthalate	...	65
Low-density polyethylene	20-25	100-220
Medium-density polyethylene	...	140-160
High-density polyethylene	...	110-130
Polyethylene/vinyl acetate	...	160-200
Natural rubber	17-25	77.0
Nylon 6	...	80-83
Polyvinyl chloride:		
Rigid	...	50-100
Flexible	...	70-250
Nonpolymeric materials:		
Aluminum	40	23.13
Steel	40	13.22
Concrete	...	10-14
Glass	...	10

Sources: Lange, 1972; Moore and Kline, 1984; Modern Plastics Encyclopedia, 1980-81.

4.2.1.8 Multiaxial Straining of Polymer Materials--

In actual service the components of a liner system are strained multiaxially because stress is simultaneously applied to the component in two or more directions. This multiaxial straining reflects the irregularities in

the surface on which the component is placed, the uneven loads that are applied, and the irregular shapes of the components. This is in contrast to the, uniaxial straining encountered in laboratory tests, e.g. tensile tests, which are normally used for specification and quality control purposes in assessing lots or batches of the polymeric component. A uniaxial test, such as normally used in measuring tensile properties, generally gives unrealistically high elongations at break compared with those encountered in service for many of the polymeric materials, particularly those that yield or draw on extension, such as the PE FMLs. In biaxial and multiaxial tests, the materials that are extended in one direction have considerably lower elongations and tensile values in the transverse direction as they break or split at the much lower elongation in that direction. Multiaxial straining is discussed more fully in Section 4.2.2.4.2.

4.2.1.9 Broad Range of Permeability--

The permeability of the polymeric sheetings to various gases and vapors can vary over several orders of magnitude. Generally, the presence of plasticizers in the compound increases permeability and the presence of crystalline structure reduces permeability. Also of importance is the relationship between the solubility characteristics of the permeant and the polymer; the more soluble the permeant is in the FML, the higher the probability of permeation. The permeability of polymeric FMLs is discussed more fully later in this chapter.

4.2.1.10 Polymers are Sensitive to Organic Liquids and Vapors--

As the polymeric compositions used in liner systems are organic in nature, they are sensitive to organics, which they can absorb from waste liquids and vapors. They can swell or, if they contain soluble fractions, can be leached and shrink. In either case, depending on the material several properties (e.g. tensile strength, modulus, permeability) of the composition can simultaneously change and the performance characteristics can be altered. The sensitivity of polymers to organics indicates the need for compatibility testing, which is discussed in Chapter 5.

4.2.1.11 Resistance to Stress-Cracking and Static Fatigue--

Polymeric materials, as with many other materials, are subject to loss of strength and to fracture when under mechanical stress for extended periods of time. Some semicrystalline polymeric compositions, e.g. PE and PEL, when placed under stress in chemical environments in which the surface of some grades of a material is affected by a chemical species present, can crack or craze in moderately short times. Thus, the resistance of FMLs of semicrystalline polymers that might be used in contact with waste liquids over long periods of time should be assessed along with that of the seams of the FMLs. Environmental stress-cracking (ESC) resistance is discussed in greater detail in Section 4.2.2.5.4 which is concerned with tests to measure the effects of environmental exposure. The subject of stress-cracking resistance and methods of assessing this property testing are presented by Howard (1964).

4.2.1.12 Effects of Long-Term Exposure--

In the development of polymeric compositions for construction materials, long service life under adverse environments was a major objective in their selection, design, and formulation. With proper protection through the use of stabilizers, antioxidants, and other antidegradants, polymers used in the manufacture of FMLs, geosynthetics, and pipe can be highly resistant to degradation and sustain essentially no adverse change in molecular structure when exposed underground and in normal weather. Nevertheless, polymeric compositions are still subject to loss in properties due to swelling by water and organic solvents which separate the polymer molecules and reduce strength and increase permeability. Generally, however, molecular structure of a polymer remains essentially undamaged by swelling alone, as is shown by the return to its original properties when the swellant is removed, though some polymers may interact with the waste.

Polymer molecules in polymeric compositions have been found to be highly resistant to biodegradation, though some compounding ingredients used in their formulation, such as some plasticizers, may be biodegradable. Current technology in the manufacture of polymeric FMLs include the use of biocides which have proven to be effective in inhibiting or eliminating biodegradation of plasticizers. If not protected by a biocide, biodegradation may result in adverse changes in the properties of the composition. The use of many of the polymeric construction materials in environments that have a high potential for microbial activity, e.g. MSW landfills, is of major concern to engineers in designing structures that call for extended service lives, e.g. 40 to 100 years. The presence of microbial action has been found to have no effect on many synthetic polymer molecules over long periods of time. The nonbiodegradability of polymers, such as polyethylene, has been further demonstrated by the fact that these same synthetic polymers used in packaging have created problems in disposal as they do not degrade and become part of the biomass by natural processes. Considerable research effort has been devoted to developing methods of degrading these materials by microbial activity.

Research and testing have indicated that, under conditions in which the antioxidants have been removed, thin polymeric films subjected to soil-burial have shown indication of degradation through loss in tensile strength. In a series of tests performed by Colin et al (1981) on soil-burial of extracted 1-mil film, the sensitivity to biodegradation increased from polyester and polypropylene to low- and high-density polyethylenes to Nylon 66. The authors point out that the results did not eliminate the possible presence of residual antioxidants in the polypropylene or efficient oxidation inhibitors in the polyethylenes. Albertsson (1978) has shown that pulverized antioxidant-free polyethylene compositions placed in nutrient media have shown indications of oxidative degradation.

A review of the literature with respect to biodegradation of synthetic polymers and the development of biodegradable polymers (Potts, 1978; Schnabel, 1981; Kumar et al, 1983) indicates the following generalizations which

account for the high resistance to biodegradation and biodeterioration of the polymers and polymeric materials that are discussed in this chapter:

- Carbon-chain polymers, such as PE, PP, and PVC, are particularly resistant to biodegradation. Nylon, with nitrogen in the chain, has been found to be biodegradable under certain circumstances.
- The susceptibility of a polymer to biodegradation decreases with increasing molecular weight. The polymers used in the manufacture of geosynthetics and pipe have molecular weights in the thousands; consequently, they are beyond the range of the polymers that can be assimilated and metabolized by enzymes and microorganisms. Ethylene oligomers (low molecular weight polymers) up to 32 carbons in length can be absorbed and metabolized by microbes, but higher molecular weight PEs cannot be either absorbed or metabolized.
- Microorganisms appear to attack polymer chain ends, which are inaccessible in the mass of a polymeric composition, particularly in those polymers that are semicrystalline. Orientation of semicrystalline polymers into fibers makes the ends more inaccessible and increases resistance to biodegradation.
- Polymers are insoluble in water which makes them inaccessible to water-borne enzyme systems.
- The state of subdivision is an important factor in the biodegradation of polymers. Reduced surface area reduces the accessibility of the polymers to microorganisms, such as in the case of FMLs or pipe.
- The susceptibility of polymers to biodegradation is reduced or inhibited by molecular chain branching.
- Biodegradation processes are retarded or inhibited by a variety of additives, such as antioxidants.
- Exposed groups on the surface, e.g. chlorine, can be attacked but not similar groups below the surface of the polymer product.
- The rates of biodegradation depend greatly on environmental conditions, many of which probably do not exist in the environment of FMLs and other components in service. For instance, it has also been found that, in the absence of oxygen, even among natural biodegradable polymers, there has been little or no degradation.

The service life in landfill environments of FMLs and other synthetic polymeric materials of construction used in liner systems was the subject of discussion of a panel of polymer experts held by the EPA (Haxo and Haxo, 1988).

The panel reviewed potential degradation of polymeric materials by such means as thermal degradation (i.e. heat), photodegradation (i.e. light, particularly UV light), high energy radiation, biodegradation, chemical degradation, and mechanical stress with particular reference to environmental conditions under which polymeric components of lining systems would function.

All types of polymers used in the manufacture of components for liner systems were considered. Polyethylene compositions, which are used to manufacture FMLs, geonets, geotextiles, and pipe, were often emphasized in the discussion because of their wide use in these products.

Some of the principal conclusions drawn from the information available to the panel were:

- The basic conditions to which polymeric FMLs and other components of a liner system are exposed in both MSW and hazardous waste landfills include comparatively low ambient temperatures, lack of light, moisture, aerobic and anaerobic atmospheres depending on the component of the liner system and the location within the fill, and low concentrations of dissolved constituents. In limited situations, higher temperatures (e.g. 90°C) in some radioactive wastes, are encountered. Thus, polymeric materials placed in service in liner systems do not generally encounter the types of conditions that are normally considered to cause degradation of the base polymeric resins.
- The particular polymers used in the manufacture of products for the construction of landfill liner systems will not degrade in the environments they will encounter in landfills because of the lack of highly aggressive conditions that would cause degradation. These polymers include the polyethylenes, modified olefinic polymers, and some polyesters.
- The polymers under discussion and first-grade compounds of these polymers should maintain their integrity in landfill environments for considerable lengths of time, probably in terms of 100's of years. Nevertheless, when these polymers or compounds are used in products such as FMLs, drainage nets, geotextiles, and pipe, they are subject to mechanical and combined mechanical and chemical stresses which may cause deterioration of some of the important properties of these polymeric products in shorter times.

4.2.1.13 Combinations of Properties in Polymeric Compositions--

A given polymer will tend to have a distinct pattern of mechanical, chemical, and aging properties which can, within limits, be modified by compounding. Assessing materials based upon a single property, such as tensile strength, can lead to an inadequate selection of a material for a given application because of changes in the values for other unmeasured important properties, such as chemical resistance. Also, the effects on

different properties of the polymeric composition to aging and exposure can differ greatly. For this reason, a group of properties of a polymeric material are usually measured and the resulting property values are reviewed as a group before a selection is made.

4.2.2 Polymeric Flexible Membrane Liners (FMLs)

The first polymeric FMLs were based on butyl rubber (Lauritzen and Peterson, 1953); since then, a wide variety of FMLs based on different polymers have become available. Sheetings are produced by calendaring, extrusion, or spread-coating processes. Sheetings made by calendaring are sometimes fabric reinforced to improve tear strength and dimensional stability during installation. Sheetings made by spread-coating are fabric reinforced. Many polymeric FMLs are produced in relatively narrow sheetings that are seamed in the factory to make large panels which are transported to a construction site, where they are seamed to form the liner. Some of the FMLs made by extrusion processes are prepared in width up to 33 ft, which can be brought in rolls to the field for installation.

The following steps are involved in the manufacture of polymeric FMLs through installation in the field:

- Production of the basic polymer or polymers.
- Compounding of the polymer.
- Manufacture of the sheeting.
- Fabrication of narrow sheeting into panels.
- Installation in the field of panels or rolls of sheeting to form the liner.

An individual organization may perform one or more of these steps, depending on the material and the company. Figure 4-5 illustrates the structure of the FML industry. Appendix C presents a representative list of organizations and personnel in the individual segments of the industry.

This section discusses various aspects of the technology of polymeric FMLs, particularly with respect to their use as lining materials for waste storage and disposal facilities. The different types of polymers used to manufacture all currently available FMLs are described and discussed. Polymers that have been used and are currently in service are described in Appendix C which includes information on various polymers used to manufacture the FMLs and membranes that were studied in the work reported in this document. Some of these were developmental materials. The processes used in the manufacture of polymeric FMLs are briefly described and illustrated. Critical steps involved in liner installation, such as field seaming of the membranes, are also described. The principal properties of FMLs essential to their function as a lining material are discussed. The methods of assessing polymeric membranes for lining waste storage and disposal facilities are then discussed.

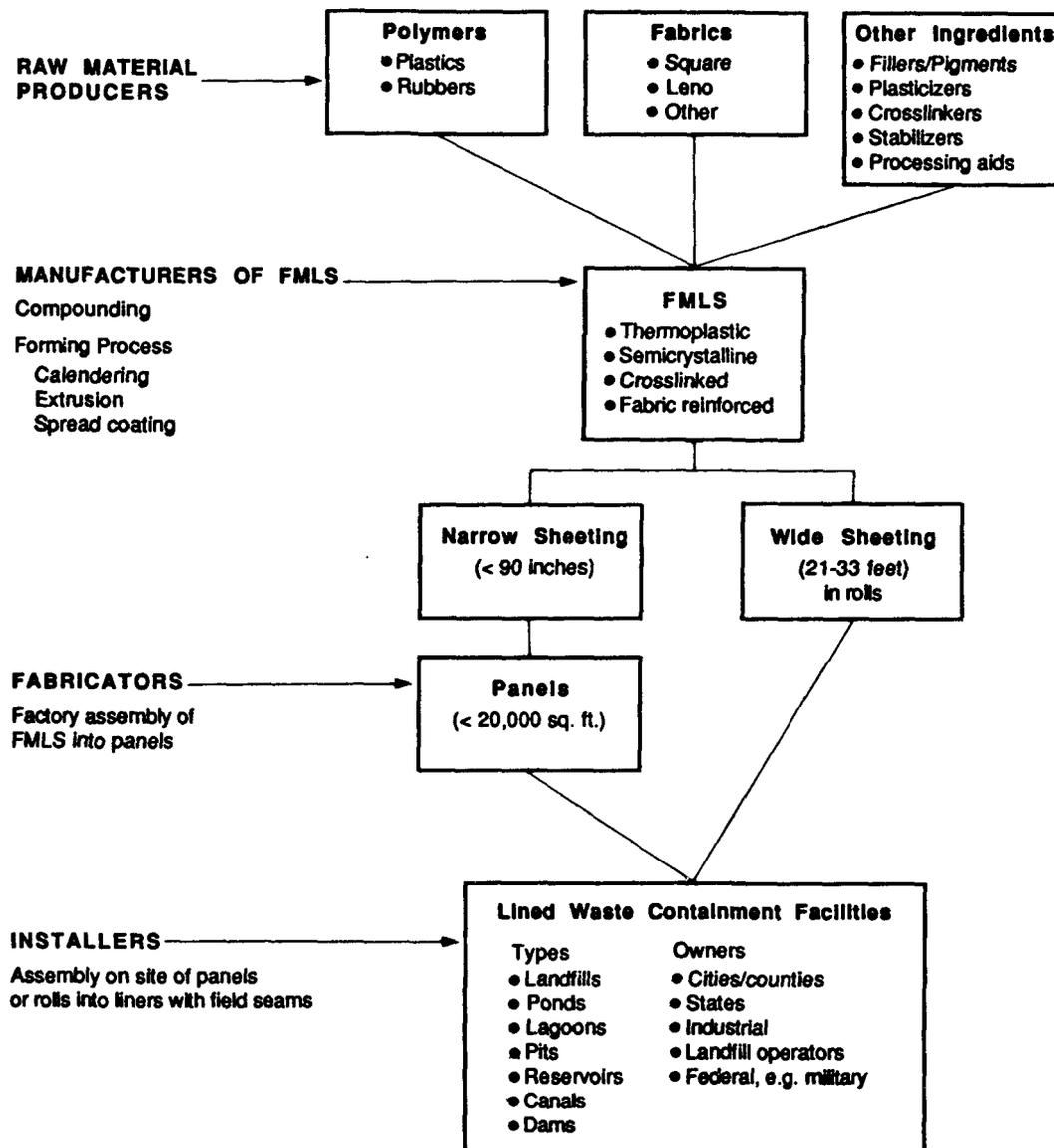


Figure 4-5. Basic structure of the polymeric FML industry from raw material producers to liner installers. A representative list of organizations and personnel in the individual segments of the industry is presented in Appendix B.

4.2.2.1 Polymers Used in Currently Available Polymeric FMLs--

A wide range of polymeric FMLs have been used to line waste storage and disposal facilities. For a variety of reasons, both economic and technical, a number of the FMLs have been discontinued and are no longer available. The polymers described in this section are those that are used in currently available FMLs; the remainder are described and discussed in Appendix C. Each of these materials has a history of use for lining containment and conveyance facilities. Table 4-4 lists the different types of polymers that have been used in the manufacture of FMLs, and indicates whether a given polymer was used in vulcanized or unvulcanized form, and whether or not FMLs based on the given polymer were manufactured with fabric reinforcement. Those polymers that are discussed in Appendix C are indicated.

TABLE 4-4. POLYMERS USED IN MANUFACTURE OF FMLS

Polymer	Type of compound used in FMLs		Fabric reinforcement	
	Thermo-plastic	Cross-linked	With	Without
Butyl rubber (polyisobutylene-isoprene rubber-IIR) ^a	No	Yes	Yes	Yes
Chlorinated polyethylene (CPE)	Yes	Yes	Yes	Yes
Chlorosulfonated polyethylene (CSPE)	Yes ^b	Yes	Yes	Yes
Elasticized polyolefin (ELPO) ^a	Yes	No	No	Yes
Elasticized polyvinyl chloride (PVC-E)	Yes	No	Yes	No
Epichlorohydrin rubber (CO, ECO) ^a	Yes	Yes	Yes	Yes
Ethylene propylene rubber (EPDM) ^a	Yes	Yes	Yes	Yes
Neoprene (chloroprene rubber-CR) ^a	No	Yes	Yes	Yes
Nitrile rubber (NBR) ^a	Yes	---	Yes	---
Polyester elastomer (PEL)	Yes	No	Yes	Yes
Polyethylene (PE)	Yes	No	No	Yes
Polyvinyl chloride (PVC)	Yes	No	Yes	Yes

^aFMLs based on these polymers are not currently available. These polymers discussed in Appendix C.

^bMade and used as a thermoplastic but contains a small amount of curative which crosslinks the compound during exposure.

The physical and chemical properties of polymeric FMLs vary considerably, as do methods of installation and seaming, costs, and interaction with different wastes. The composition and properties of FMLs of a given generic polymer type can differ considerably, depending on the compound formulation. Polymers are rarely used alone in a product; whether used singly or in blends, they are usually compounded with a variety of ingredients (e.g. fillers, plasticizers or oils, antidegradants, and curatives) to improve either selected properties or the balance of properties depending on end-use and to reduce compound cost. Properties of a polymeric FML also depends on its construction e.g. its thickness, whether or not it is fabric reinforced, the type of fabric reinforcement used, and the number of plies. Because the grade and source of polymers of a given generic type vary, differences between FMLs also arise from the polymer itself. Successful use of a polymer in some environments may require specific compounding.

Most compounds used in the manufacture of lining materials are based on one polymer; however, to improve specific properties of a compound, two or more polymers are at times blended or "alloyed." Consequently, generic classifications of lining materials based on individual polymers are sometimes difficult to make, even when one polymer predominates in a compound. Most polymeric FMLs are now based on uncrosslinked compounds and, therefore, are thermoplastic. This is true even for membranes that use crosslinkable polymers such as CPE and CSPE, which become more chemically resistant by crosslinking. Thermoplastic FMLs have become preferred because they are easier to seam and repair effectively during installation in the field. Thermoplastic FMLs can be seamed by various heat sealing or welding methods. If they are noncrystalline, they can be seamed with various adhesives and neat solvents or "bodied" solvents (a solvent containing dissolved liner compound to increase the viscosity and reduce its rate of evaporation).

In the following subsections each polymer is discussed with respect to composition, general properties and characteristics, general use, and use in membranes. Whenever appropriate, an indication is made of the use of a given polymer in blends with other polymers compounded specifically for lining purposes.

4.2.2.1.1 Chlorinated polyethylene--Chlorinated polyethylenes (CPE) form a family of polymers produced by chlorinating high-density polyethylene. They contain 25-45% chlorine and 0-25% crystallinity. CPE can be crosslinked but, in liner compositions, it is generally used as a thermoplastic and is compounded with either oil or plasticizer, and with such fillers as carbon black and various fine inorganic powders. CPE is often blended with other polymers, but to be classified as a CPE FML, at least half the polymer content must be CPE. Polyvinyl chloride (PVC) or chlorosulfonated polyethylene (CSPE) is sometimes added to a CPE compound to improve its tensile and thermal properties.

Because CPE is a completely saturated polymer (it has no double bonds, $-C=C-$, in the polymer chain which are points of chemical attack), most CPE compositions resist weathering well on outdoor exposure and are not susceptible to ozone cracking. CPE FMLs can be formulated to withstand intermittent contact with aliphatic hydrocarbons and oils, but continuous exposure to aromatics shortens the service life of this liner material. In most cases, CPE liners are not recommended for containment of aromatic liquids (Dow Chemical Company, 1977).

CPE can be "alloyed" in minor amounts with PVC, PE, and numerous synthetic rubbers. It is blended in minor amounts with ethylene polymers to soften them and to improve their resistance to environmental stress-cracking, and with flexible polyvinyl chloride to improve cold crack resistance.

CPE FMLs are available in both unreinforced and fabric-reinforced versions of different thicknesses. Because CPE FMLs are generally not cross-linked, they can be seamed by bodied-solvent adhesives, solvent-welding, or heat sealing by air-heat guns, hot wedge welders, or dielectric means.

4.2.2.1.2 Chlorosulfonated polyethylene--Chlorosulfonated polyethylenes (CSPE) form a family of saturated polymers (no double bonds in the polymer chain) prepared by treating polyethylene (in solution) with a mixture of chlorine and sulfur dioxide. Available CSPE polymers contain from 25-43% chlorine and from 1.0-1.4% sulfur. The CSPE most commonly used in membrane liner manufacture contains 25% chlorine and 1.0% sulfur. Membranes are supplied primarily in the thermoplastic (uncrosslinked) form; however, they contain a minor amount of metal oxide which causes the compound to crosslink in the presence of moisture. Two versions of CSPE sheetings are available: (1) a "potable" grade which contains magnesium oxide, and (2) an "industrial" grade which contains a lead oxide or other lead compounds. Both oxides are crosslinking agents, but the lead oxide imparts a faster and tighter cure to the CSPE than does the magnesium oxide. Of the two grades, the industrial grade swells less on contact with industrial wastes. The FML compound of both grades generally contains at least 45% of CSPE polymer by weight.

When properly formulated, CSPE compositions are characterized by ozone resistance, light stability, heat resistance, good weatherability, and resistance to deterioration by such corrosive chemicals as acid and alkalis (DuPont, 1979). CSPE compositions have good resistance to growth of mold, mildew, fungus, and bacteria, but only moderate resistance to oils and many organic chemicals.

CSPE FMLs are almost exclusively manufactured with fabric reinforcement. Though some of the early CSPE FMLs were reinforced with nylon fabric, CSPE FMLs are reinforced now with polyester fabrics. Of these fabrics 10 x 10 scrim predominates, but 8 x 8 and 6 x 6 types have also been used. Fabric reinforcement improves dimensional stability and gives needed tear strength to the sheeting for its installation and use on slopes; fabric also reduces distortion of the sheeting by shrinkage whenever it is exposed to the sun. Unreinforced CSPE FMLs have low tensile strength and tend to soften and shrink on exposure to sunlight and heat.

Unexposed thermoplastic CSPE FMLs can be seamed while thermoplastic by radiant heat sealing, dielectric heat sealing, hot-air guns, heated wedges, solvent welding, ultrasonics, or with "bodied-solvent" adhesives. FMLs based on this polymer resist cracking and failure at low temperatures as well as weathering, even when exposed without a soil cover. Since thermoplastic CSPE FML tends to crosslink when exposed to ultraviolet radiation or to heat and moisture, repairing damaged sheeting that has been aged can be difficult because the crosslinked material is not readily soluble and is no longer thermoplastic. Moderate aging can result in a skin cure that will require abrasive treatment to remove the cured skin and allow seaming with a bodied solvent. Highly aged sheeting, that is completely crosslinked, has been satisfactorily seamed for some purposes with a proprietary adhesive.

4.2.2.1.3 Polyester elastomers--Polyester elastomers (PELs) form a family of melt-processable segmented thermoplastic copolyester elastomers containing recurring polymeric long chain ester units derived from dicarboxylic acids and long chain glycols and short chain ester units derived from dicarboxylic acids and low molecular weight diols. They are both semi-crystalline and thermoplastic, covering a durometer hardness range of 92 on the "A" scale to 72 on the "D" scale (ASTM D2240). The PELs combine high modulus, elasticity, and low temperature flexibility with oil, fuel, chemical and biodegradation resistance. These polymers were introduced commercially in 1972.

Polyester elastomer derives its strength from crystallizable polyester blocks which form crystalline regions or domains that are dispersed in an amorphous matrix. The melting point of these crystalline domains is around 400°F, which indicates serviceability to relatively high temperatures. PELs have good tear and abrasion resistance, along with high resilience.

The commercial polyester elastomers that are used in the manufacture of FMLs have hardnesses in the range of 50 to 65 durometer hardness on the "D" scale. FMLs based on PEL are fabric reinforced and are manufactured by calendaring or by extrusion. Because PELs are thermoplastic, seams of PEL FMLs are usually prepared by thermal methods and rarely with adhesives.

4.2.2.1.4 Polyethylene--PEs are a family of semicrystalline polymers that are based principally on ethylene. They range from liquids to hard plastics and have a range from a few hundred molecular weight to hundreds of thousands molecular weight. The basic mechanical properties of a specific PE are determined largely by molecular weight and crystallinity, as indicated in Figure 4-6.

Polyethylenes are produced by various polymerization processes and with a variety of catalysts. These processes and catalysts may be varied to produce polymers which have been classified in a long-standing practice by ASTM D1248:

Type of polyethylene	Name	Range of density, g/cm ³
Type I	Low-density polyethylene (LDPE)	0.910 to 0.925
Type II	Medium-density polyethylene (MDPE or LLDPE)	0.926 to 0.940
Type III	High-density polyethylene (HDPE)	0.941 to 0.959
Type IV	High-density polyethylene (HDPE)	>0.960

Note: The liner industry has not been following the ASTM classification and is using the term "HDPE" loosely to cover the PE polymers that are classified as "MDPE" or "LLDPE" by ASTM. The designation "HDPE" is being used in most of the technical and trade literature relating to these products and in EPA documents. At this point, to avoid confusion in terminology, the use of the term "HDPE" is continued in this Technical Resource Document to describe the medium- and high-density types of PE FMLs and other HDPE geosynthetics that are commonly used in the liner industry. It is recommended, however, that the designations of PE presently used in the manufacture of these products should follow ASTM D1248 designations. This means that almost all of the resins currently being employed should be called MDPEs. The term "HDPE" should be used solely to designate those resins that fall under the classification of PE Type III and IV of ASTM D1248.

It is recognized, nevertheless, that due to production, sampling, and testing variables, there is variation in the density of polyethylene of a given type that is manufactured; the accepted tolerance range is $\pm 0.002 \text{ g cm}^{-3}$ of the normal value of density.

The oldest and most common of the polymerization processes is a high pressure process which produces highly branched polymers having lower density and low crystallinity. This is a Type I PE, also designated as LDPE. At the high end of the density range, the Type IV HDPEs are prepared at low pressure and are homopolymers of ethylene with no measurable side branches.

Type II and Type III PEs are made in a variety of processes in which ethylene is polymerized with controlled amounts of a comonomer, such as 1-butene, 1-hexene, or 1-octene. These produce short branches of ethyl, butyl, or hexyl-side branches, respectively. As the number of side branches incorporated into the ethylene backbone increases, the density of the PE decreases. Thus, it may be possible to have polymers having similar molecular weights and densities produced by entirely different polymerization and/or catalyst routes.

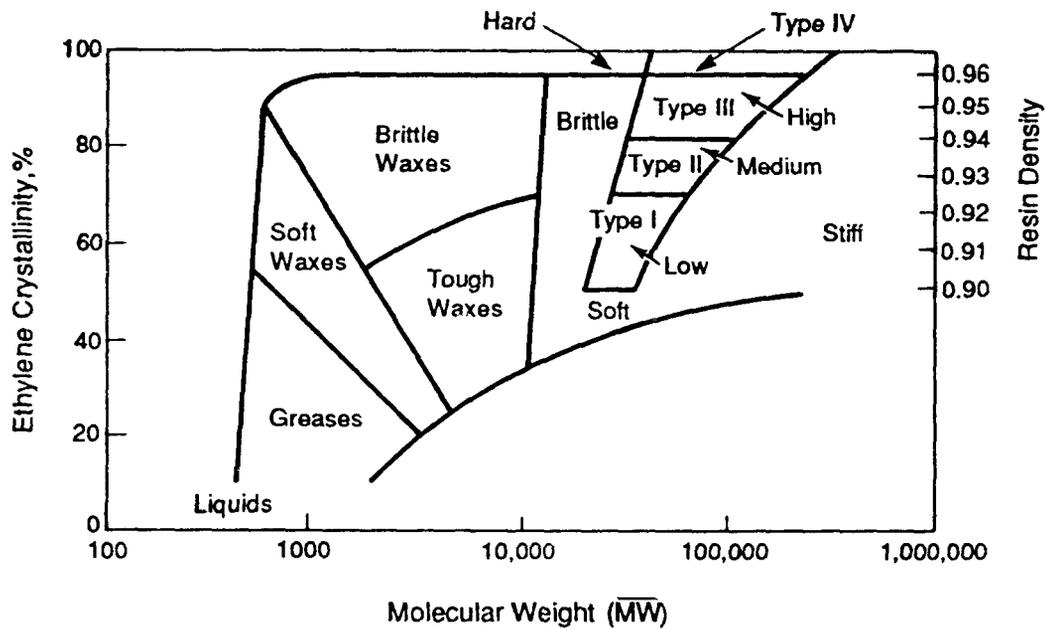


Figure 4-6. Relationship among crystallinity, molecular weight (weight average), and mechanical properties of polyethylene. (Based on Rodriguez, 1982).

Note: Although the values for percent crystallinity for a PE of a given density vary somewhat with the method of determination. The values for those polyethylenes potentially useful in the manufacture of FMLs for water containment facilities tend to range from about 0.92 at the low end of low-density to 0.97 at the high end of high-density PE.

Figure 4-7 presents a comparison of the structures of the various PEs and copolymers of different densities.

The density of the PE polymers used in most PE FMLs is in the medium-density range; they are not homopolymers of ethylene but in reality copolymers of ethylene and short-chain α -olefins, such as 1-butene, 1-hexene, and 1-octene. Inasmuch as the PE FMLs contain 2 to 3% carbon black to impart UV resistance, they may have densities above 0.940 due to the higher density of the carbon black, i.e. 1.80 g/cm³. To determine the density of the base PE resin in a PE FML, the carbon black content can be corrected for as follows:

$$D_n = D_p - 0.004C \quad (4-1)$$

where

D_n = density of base resin,

D_p = density of compound, and

C = weight percent of carbon black in the compound.

In addition to the carbon black, PE FMLs contain antioxidants to improve aging and UV resistance; they also may contain a variety of additives such as antiblock agents, slip agents, and other processing aids. The PE base resins often contain trace metal residues from the polymerization catalysts.

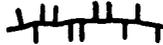
Density of PE resin	Low	Medium	High
Polymerization process	High pressure	Low pressure	Low pressure
Molecular structure	Branched with long chains	Linear with short chains	Linear with a few small side chains
			
Short-chain branches	C_1, C_2, C_3, C_4	C_2, C_4, C_6	C_2, C_4
Long-chain branches/ molecule	30	0	0

Figure 4-7. Schematic comparison of the structures of PE and ethylene copolymers of different densities; C = number of carbon atoms in the short chains.

The high crystallinity of the PEs compared with many other polymeric compositions used in manufacturing FMLs results in polymers that are particularly resistant to swelling and permeation by many liquids, gases, and vapors. However, some of the higher density PE FMLs are subject to environmental stress-cracking (ESC), which is discussed in Section 4.2.2.5.4. Basically, it has been observed that FMLs based on PE resins having densities in excess of 0.942 g cm^{-3} will generally not meet FML performance requirements for resistance to ESC (Dewsnap et al, 1986).

Several means have been used to increase the environmental stress-cracking (ESC) resistance of HDPE; they include increasing molecular weight, the blending of HDPE with various elastomers, such as EPDM, butyl, and CPE (Howard, 1964), and the copolymerization of ethylene with α -olefins (terminally unsaturated) such as 1-butene, 1-hexene, and 1-octene. The blending of EPDM with HDPE has been used commercially in the manufacture of an FML with substantially better ESC resistance than the HDPE alone. This blend was termed "HDPE-A". FMLs based on this blend were used for several years. However, at the present time (June 1988), the manufacture and use of HDPE-A have been discontinued as PEs with better ESC and solvent resistance have been developed using copolymers of ethylene and α -olefins.

The forming of PEs into sheeting for use as FMLs is done principally in an extrusion process, as described in the section of this chapter on processing. As PEs are thermoplastic and semicrystalline, they soften and melt when heated above their respective melting points in the range of 120° to 140°C; therefore, seaming of PE FMLs can be performed by various thermal methods. All of these methods require that the surfaces be cleaned and free of oxidized polymer and be melted so that the molecules in both FMLs that are being joined can molecularly mix. If a molten extrudate from a welder is used to join the FMLs, the extrudate should melt both surfaces and then molecularly mix with the surfaces of both FMLs. The extrudate should be based on the same PE compound and have the same density as the FMLs it is joining.

4.2.2.1.5 Polyvinyl chloride--Polyvinyl chloride (PVC) is produced from vinyl chloride monomer by any one of several polymerization processes. It is a versatile thermoplastic polymer that is compounded with plasticizers and other modifiers to yield compositions with a wide range of physical properties from flexible rubber-like materials to hard plastics.

PVC FMLs are generally produced by calendering in various widths and thicknesses. Most PVC FMLs are unreinforced, but they can be reinforced with fabric. PVC FML compounds contain 25% to 35% plasticizer to make the flexible and rubber-like sheetings. They also contain 1% to 5% of a chemical stabilizer, and various other additives, including colorants. A wide variety of plasticizers are used in PVC sheeting; the choice of plasticizer depends on the application and service conditions under which the sheeting is used. Plasticized PVC FMLs have good mechanical properties: tensile strength, elongation at break, and puncture and abrasion resistance. As they are thermoplastic, they can be seamed by solvent and thermal methods.

PVC FMLs have been the most widely used polymeric FMLs. They have good resistance to many inorganic chemicals (Chan et al, 1978). Although the polymer inherently resists the effects of oils, many organic chemicals (hydrocarbons, solvents, and oils) attack PVC sheetings plasticized with monomeric plasticizers, e.g. the phthalates which are biodegradable. PVC compounds that possess high resistance to oil attack can be prepared with special polymeric plasticizers. For example, polyester plasticizers and polymers, such as nitrile rubber, CPE, and ethylene vinyl acetate (EVA), can be used to replace the extractable monomeric plasticizers, and thus make PVC compositions that are more resistant to many waste liquids. Some of these compositions may have less low temperature resistance compared with those with monomeric plasticizers.

Because the PVC resins are sensitive to ultraviolet light and need to be plasticized, a PVC liner, which may contain a volatile plasticizer, should be covered with soil or other suitable cover to protect it. Carbon black is often used as an ultraviolet stabilizer, but, because it makes the sheeting black, the temperature of the sheeting is raised when exposed to the weather and plasticizer evaporation is increased. In some burial tests and in some liner applications, PVC FMLs have become stiff due to loss of plasticizers to the soil and biodegradation by microorganisms. Monomeric plasticizers can

also be extracted somewhat by water or long-term exposure. Plasticized PVC can be protected against biodegradation (biodeterioration) by a broad spectrum of macroorganisms to varying degrees through the use of biocides or biostabilizers.

4.2.2.2 FML Manufacture--

4.2.2.2.1 Compounding of FML compositions--Most polymeric membranes are based on single polymers, but blends of two or more polymers are being developed and used in liners. Also, different grades of a given type of polymer can be used. Generic classifications based on individual polymers have become increasingly difficult even though one polymer may predominate.

All polymers are compounded with auxiliary ingredients which serve different purposes. The basic compositions of the different types of compounds are shown in Table 4-5. The crosslinked compositions are usually the most complex because they contain a crosslinking system. Thermoplastics, except for CSPE compounds, contain no curatives. Although supplied as thermoplastic, CSPE liners contain crosslinking agents that allow the polymer to crosslink during service. Crystalline materials have the simplest composition and generally consist of the polymer, a small amount of carbon black for ultraviolet protection, antidegradants, and possibly processing aids.

TABLE 4-5. BASIC COMPOSITIONS OF POLYMERIC FML COMPOUNDS

Component	Composition of compound type, parts by weight		
	Cross-linked ^a	Thermo-plastic ^a	Semicrys-talline
Polymer or alloy	100	100	100
Oil or plasticizer	5-40	5-55	0-10
Fillers:			
Carbon black	5-40	5-40	2-5
Inorganics	5-40	5-40	...
Stablizer/inhibitor	1-2	1-2	1
Crosslinking system:			
Inorganic system	5-9	b	...
Sulfur system	5-9	...	...

^aAvailable in unreinforced and fabric-reinforced versions.

^bAn inorganic curing system that crosslinks over time is incorporated in CSPE FML compounds.

Several of the auxiliary components of a formulation can be affected during service when they are either immersed in the liquid or exposed to the weather. Low molecular weight fractions in the base resin or blend can be lost. The oils and plasticizers are potentially extractable and, in some cases, biodegradable; some stabilizers can be extracted. Loss or change in any of these components can affect properties and durability of the compound.

Most of the FMLs currently manufactured are thermoplastic. Though FMLs based CPE or CSPE are more chemically resistant in the crosslinked form than in the thermoplastic form, they are generally supplied as thermoplastics, which are easier to seam reliably and to make repairs in the field. Thermoplastic FMLs can be heat-sealed or seamed with a solvent, bodied solvent, or special adhesives. Semicrystalline FMLs are generally seamed by thermal welding or fusion methods.

FMLs of all but the semicrystalline type compositions are available with fabric reinforcement which increases strength and thermal stability. The fabric constructions vary from thread counts of 6 x 6 to more than 20 x 20. As the thread count increases, the area between the threads that allows contact between the plies is reduced. The adhesion between plies is dependent upon this area and good "strike-through" and "knitting" of the polymeric layers during manufacture. Good initial ply adhesion and its retention during service are important to prevent delamination.

4.2.2.2 Forming processes--A variety of FMLs manufactured by different processes for different materials as illustrated in Figure 4-8.

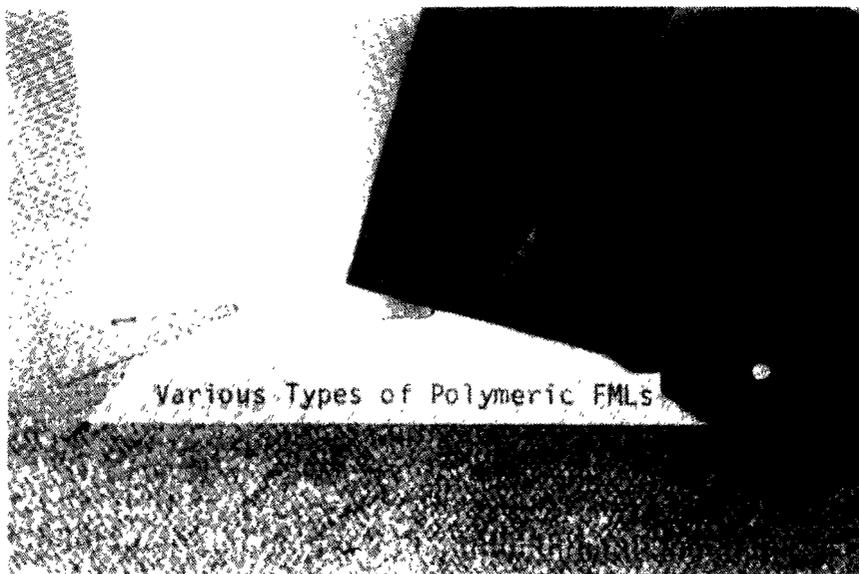


Figure 4-8. Various types of polymeric FMLs available for lining applications.

The three basic methods used in the manufacture of polymeric sheeting for liner use are calendaring, extrusion, and spread or knife coating. Calendaring is used in forming both unreinforced and fabric-reinforced sheeting, whereas extrusion is only used in making unreinforced sheeting. Spread coating is used for making fabric-reinforced sheeting in which the fabric is comparatively tight, i.e. the number of thread ends per inch is greater than 20.

Calendaring is the most common method of forming thermoplastic FMLs. It is also used in forming vulcanized rubber FMLs. In this process, heated rubber or elastic compounds are passed between the heated rolls of a calender to form a sheet of predetermined thickness. A calender usually consists of three to four rolls, as is shown in Figure 4-9. Unreinforced sheeting is usually of single-ply construction; however, some manufacturers have used multiple plying of unreinforced liners to eliminate the formation of pinholes through the sheet. By manufacturing sheeting in this manner, the probability of a pinhole in one ply coinciding with a pinhole in another is remote. However, delamination of the plies has occurred on long immersion in waste liquids and some organic solvents.

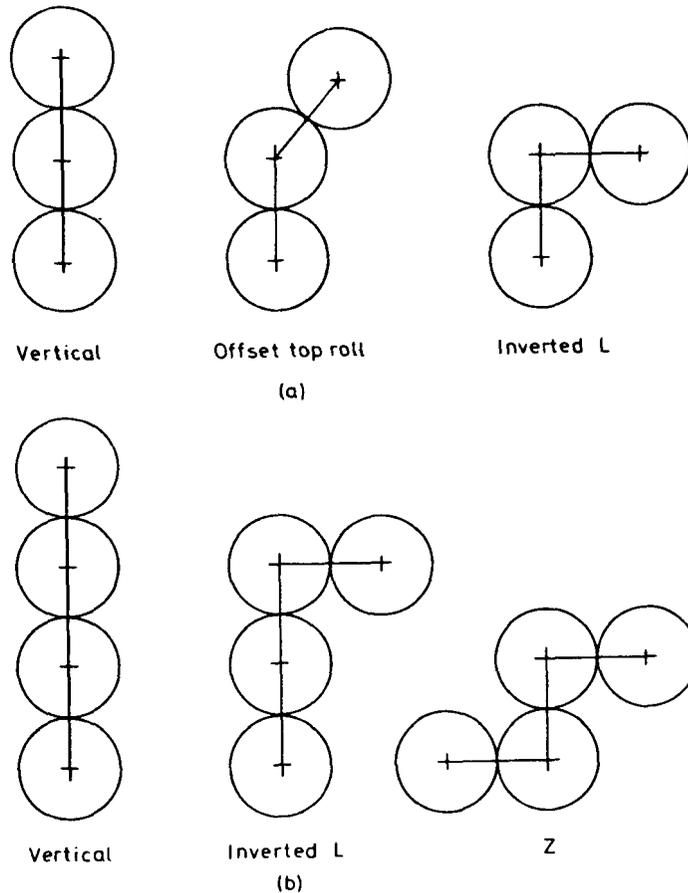


Figure 4-9. Roll configuration of calendars: (a) three-roll calendars, and (b) four-roll calendars (Blow, 1971).

Fabric can be placed between the plies of the polymeric compound to reinforce the FML. In this case, sufficient material must be placed on both sides of the fabric so that pinholes are not generated between the fabric and the outside of the sheeting. Also, there should be sufficient compound present to strike through the open weave of the fabric and achieve direct contact of the rubber on both sides of the fabric. Fabric reinforcement is usually achieved through the use of open fabrics or scrim of nylon, polyester, polypropylene, or glass fiber. The thread count or ends per inch usually range from 6 x 6 to 10 x 10 per inch, but most are 10 x 10 ends per inch. Figure 4-10 shows several types of fabric. A coating is applied to the finished fabric after weaving in order to tack the yarns in place so that the finished fabric construction pattern will not lose its shape. Different coating formulations are used, depending on the end use. Fabrics to be used with vulcanized elastomeric FMLs are usually treated with an adhesive coating which chemically reacts with the FML compound during the curing cycle to produce adhesion to the polymer compound.

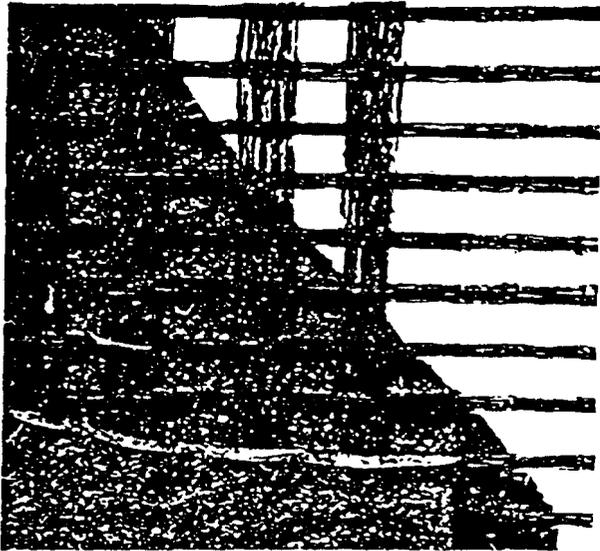
Extrusion methods are used primarily in the manufacture of PE and other semicrystalline FMLs. For the thinner FMLs and films, it is common to form a tube of the FML or film and to slit it to form a lay-flat sheet. For the thicker gage PE FMLs flat sheets are extruded directly with different equipment. For example, as shown in Figure 4-11, a large circular die extruder can produce FMLs 22 ft in width. Flat extruders can produce sheeting up to 10 to 12 ft in width and a proprietary extruder is capable of producing sheeting up to 33 ft in width.

Some manufacturers set up special straining operations to clean out grit that may be in the compound. This operation immediately precedes the calendering or extrusion. In this step, grit and other coarse particles are screened out to yield a grit-free compound for the calender or extruder.

Spread coating is performed only on fabrics having high numbers of thread ends per inch. In this process, the coating compound is applied as a viscous "dough" made of a high concentration of the compound dispersed in a solvent. The fabric is first passed over a spreader bar to remove wrinkles and creases and then passed beneath a stationary blade which spreads the compound and controls the thickness of the polymer coating. The solvent is evaporated by drawing the coated fabric through a heated chamber and the solvent is recovered. Upon removal from the heated areas, the sheeting is cooled and rolled (Blow, 1971, p 285).

4.2.2.3 Seaming of Polymeric FMLs--

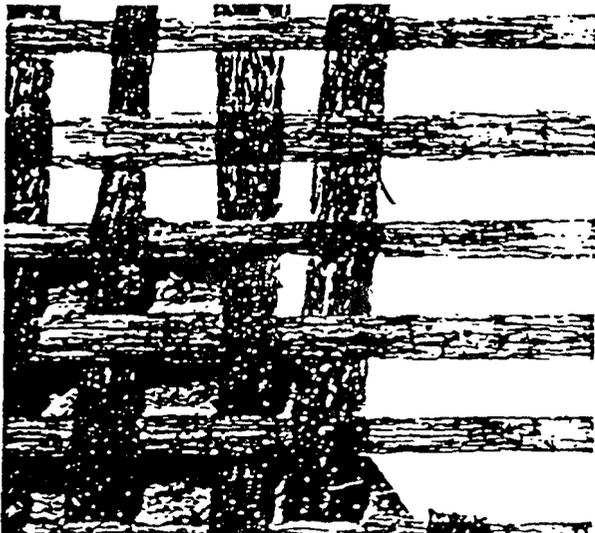
Critical to the effective performance of FML liners of impoundments and solid waste landfills is the construction of continuous watertight barriers of approximately uniform strength. According to the available information, seams appear to be the most likely source of FML problems and failures. As is indicated in the above subsection, many polymeric FMLs, particularly those made by calendering, are manufactured in relatively narrow widths, i.e. less than 90 inches. Sheets are cut from the rolls and seamed together in the factory to make large panels. These panels, in turn, are assembled at



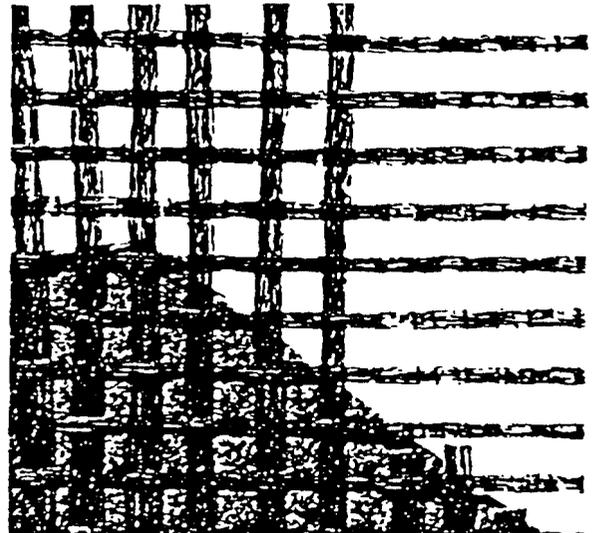
Manufacturer F. 30 mils (0.76 mm), B-5602. Photo P222-D-65685



Manufacturer A. 60 mils (1.52 mm), B-4606. Photo PX-D-68886



Manufacturer G. 30 mils (0.76 mm), B-5540. Photo PX-D-68887



Manufacturer H. 30 mils (0.76 mm), B-5560. Photo PX-D-68888

Figure 4-10. Nylon-reinforced, butyl lining samples showing different weaves and weights of nylon used by four manufacturers at 6X magnification. (Hickey, 1971a).

the construction site to make large, continuous liners which can range up to many acres in area. Therefore, a liner installed in this manner contains both factory and field seams. In the favorable factory environment, durable seams can be made by a variety of methods depending on the type of polymer. Several types of FMLs are made in extrusion processes in wider sheetings, i.e. in widths ranging from 21 to 33 feet; these FMLs are brought to the site in large rolls and seamed in the field, thus eliminating factory seaming. Seaming in the field can pose difficulties, largely due to variability in the ambient conditions.

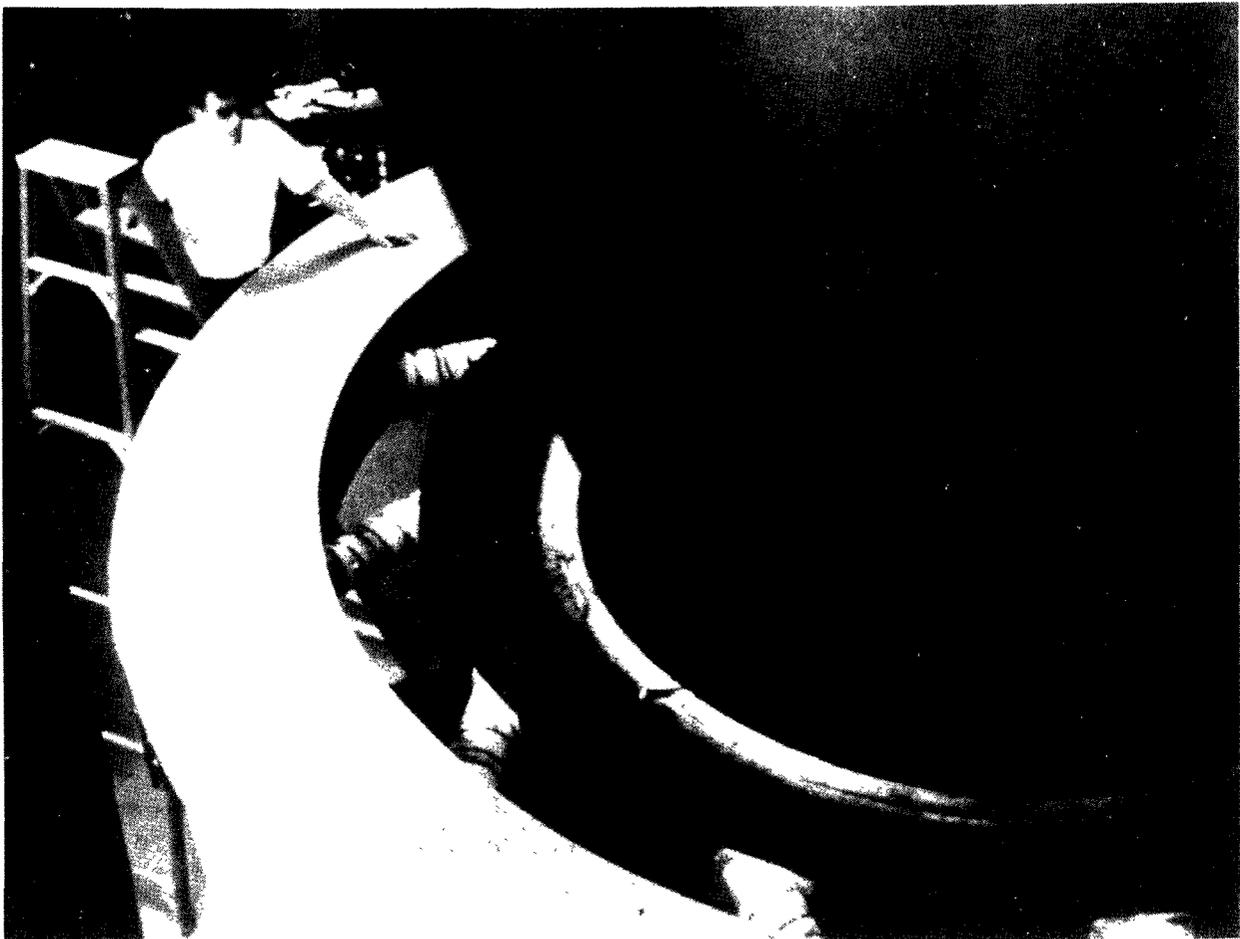


Figure 4-11. Extrusion of polyethylene FML using an extruder with a circular die. Courtesy of Poly-America, Inc.

In order to function as a liner, an FML must be capable of being bonded by one or more bonding systems which can produce bonds that are strong and chemically resistant and meet the following requirements:

- The bond should be based on primary chemical bonds.
- The bond between the sheets must approximate the strength of the sheeting and must maintain its strength throughout the service life of the sheeting.
- The seaming process should not damage or degrade the parent FML, such as weakening the FML at the edge of the weld.
- The bond between the sheets or panels must be continuous for the length of the seam.
- The bond must be capable of being formed in the field.

The principal requirement of the bond is that the polymeric molecules of the two FMLs being joined become molecularly mixed without the inclusion of dirt or oxidated particles, and the interface essentially disappears so that the mass at the original interface becomes homogeneous. This can be accomplished either by the use of solvents to dissolve the polymer on both sides of the interface and allow the molecules to mix or to melt the polymer and allow the molten polymer from both FMLs to mix before the seams harden or crystallize as they cool. A residual interface may allow waste liquid to enter and destroy the adhesive bond.

A variety of bonding systems are used in the seaming of FMLs. Selection of the optimum system for a given FML will depend largely on the polymer. Certain techniques or seaming systems are incompatible with certain FMLs. For instance, dielectric seaming requires polarity in the polymer; therefore, it cannot be used to seam polyethylene FMLs. Furthermore, because of the specialized equipment required, the use of dielectric seaming is restricted to the factory. In addition, adhesives are generally designed for use with a specific FML and should not be used with other lining materials even though the two materials may be based on the same polymer. Manufacturers may recommend a specific seaming technique, a specific type of adhesive, or a variety of techniques or adhesives.

Seaming techniques that are currently used either in the factory to fabricate panels of thermoplastic FMLs, or in the field to assemble the panels or rolls of FMLs into a final liner, or both, include the following:

- Solvent methods:
 - Solvent "welding" with neat solvents.
 - Bodied solvents.
 - Special adhesives.

- Thermal methods:
 - Heat gun.
 - Heat sealing.
 - Dielectric seaming.
 - Extrusion welding.
 - Hot wedge.
 - Ultrasonic.

Table 4-6 presents a list of the possible alternative methods for seaming polymeric materials depending upon the polymer, type of compound, and location of seaming, i.e. factory or field. Also indicated on the table are the systems included in the exposure tests. Figure 4-12 illustrates the configuration of the various seams and the methods of seaming that are used.

4.2.2.3.1 Solvent methods--Because of the solubility of noncrystalline thermoplastic polymer compositions in appropriate solvents and the lack of crosslinks, an FML based on a noncrystalline thermoplastic polymer can be seamed with solvent mixtures or with solvents in which the liner compound has been dissolved to form a "bodied solvent." Seaming by these techniques is described below.

Solvent "Welding". Solvent "welding" of noncrystalline thermoplastic sheetings with neat solvents can be achieved by coating the mating surfaces of the sheetings with a solvent or a mixture of solvents suitable for the compound. The two surfaces are then pressed together firmly, e.g. by "stitching" with rollers on a firm base. The time for such a seam to "cure" or set up ranges from 5 minutes to an hour, depending on the type of sheeting and environmental conditions. Up to 28 days may be needed for the solvent to evaporate completely from within the seam and for it to achieve full strength. Though this method can be used both in the field and in the factory, it is sensitive to weather conditions, e.g. temperature, humidity, and wind. Volatile solvents which may be desirable at lower temperatures will evaporate too quickly at higher temperatures or may fail under humid conditions to yield an adequate bond because of moisture condensation.

In forming seams by the solvent-welding method a solvent or blend of solvents must be chosen for the specific plastic to be bonded (Been, 1971, p 125; Bodnar, 1962, p 483). The solvent must quickly dissolve the surface of the FML and impart tack to the sheeting but not totally dissolve it. The choice of an appropriate solvent is facilitated by knowledge of the volatility and solubility parameters of the solvent and of the solubility parameters of the liner composition (Barton, 1975). In making repairs, it is also necessary to change or refresh the exposed surface to remove dirt, exudation from the sheeting, e.g., waxes, and moisture. The surface may need to be abraded and buffed to remove an oxidized layer which may not be soluble.

Bodied Solvents. The use of a bodied solvent to seam thermoplastic sheets is an adaptation of the solvent "welding" method described above. A bodied solvent is a solution of the liner compound to be seamed in a mixture of solvents. The "adhesive" is applied to both surfaces and the two surfaces

TABLE 4-6 BONDING SYSTEMS AVAILABLE FOR SEAMING POLYMERIC FMLS IN FACTORY AND FIELD

Type of FML	Type of compound ^a	Place used	Solvent methods		Thermal methods						
			Neat	Bodied	Heat seal ^b	Heat gun	Die-lectric ^c seaming	Extrusion welding		Hot wedge	Ultra-sonic
								Lap	Fillet		
CPE	TP	Factory	X	X	X	X	X	...	...	X	X
		Field	X	X	...	X	...	...	...	X	X
CSPE	TP	Factory	X	X	X	X	X	...	...	X	X
		Field	X	X	...	X	...	...	...	X	X
LDPE	TP/CX	Factory	...	...	X	X	...	...	...	X	X
		Field	...	...	...	X	...	X	X	X	X
MDPE	TP/CX	Factory	...	...	X	X	...	...	...	X	X
		Field	...	...	...	X	...	X	X	X	X
HDPE	TP/CX	Factory	...	...	X	X	...	...	...	X	X
		Field	...	...	...	X	...	X	X	X	X
PEL	TP/CX	Factory	...	...	X	X	...	...	...	X	X
		Field	...	...	...	X	...	...	...	X	X
PVC	TP	Factory	X	X	X	X	X	...	...	X	X
		Field	X	X	...	X	...	...	...	X	X
EVA	TP/CX	Factory	...	...	...	X	X	...	...	X	X
		Field	...	...	...	X	...	...	...	X	X

^aTP = thermoplastic; CX = semicrystalline.

^bApplication to the FMLs of 20 mil or less in thickness.

^cUsed only in the factory with polar polymers.

CONFIGURATION	METHOD OF SEAMING
<p>LAP SEAM</p>	<p>Made by heat sealing, dielectric sealing, and solvent welding</p> <p>Made with bodied solvents, adhesives, and by extrusion welding</p> <p>Made with an adhesive, heat seaming, dielectric seaming, solvent welding, and heat gun</p>
<p>DUAL-BONDED LAP SEAM</p>	<p>Made with dual hot wedge and hot air seaming methods</p>
<p>FILLET WELD SEAM</p>	<p>Made by extruding molten compound of the same composition as the FML over the lapped edge; a gum tack may be used for holding the edge of the FML down</p>
	<p>Similar to above, except a heat gun is used to tack edge of FML</p>
<p>BUTTERFLY SEAM</p>	<p>Made by a special heat sealing device</p>

NOT TO SCALE

Figure 4-12. Configurations of seams used in joining FML sheets and panels and method of seaming. The "tacks" used sometimes in preparing the fillet-weld seams are not part of the seam under test and, when possible they are opened before the seam is tested. A cap strip (not shown) over the upper edge is sometimes used, especially with fabric-reinforced FMLs.

are pressed together after becoming "tacky." There should be no surface "skinning" or drying of the adhesive when the two surfaces are joined.

The major advantage of a bodied solvent over a straight solvent is the increased viscosity of the solution which allows more control of the evaporation of the adhesive and aids in making seams on a slope. Another advantage of bodied solvents is that the dissolved polymer fills voids or imperfections in the surface of the sheeting and thus improves the consistency and strength of the seams. As with solvent "welding," bodied solvents can only be used with thermoplastic materials that can be dissolved in a suitable mixture of solvents.

The bodied-solvent technique can be used to seam sheetings in the factory and is particularly useful in the field (Haxo, 1983, p 97; Been, 1971, p 132). It has been used considerably in the seaming of CSPE, CPE, and PVC membranes and in making field repairs during the installation of these membranes. Testing of seams must wait until the solvent in the seam has evaporated through the membrane or has been driven out by heat.

4.2.2.3.2 Thermal methods--A variety of thermal seaming methods are applicable to thermoplastic FMLs which soften, melt, and flow at higher temperatures to fuse the sheets being joined. The thermoplastics are listed in Table 4-4. Thermal seaming methods include: heat sealing, heat gun, dielectric seaming, extrusion welding, hot wedge, ultrasonic, and various combinations. Factory seams of cured elastomeric FMLs are vulcanized.

Heat Gun. Seaming with a heat gun has been used for all types of thermoplastic membranes under both factory and field conditions, including repair of unexposed liners. In this method, high temperature air or an inert gas, such as nitrogen, is directed between two sheets to melt the surfaces to be joined. The two pieces are then forced together with pressure and allowed to cool to form a lap seam (Bodnar, 1962, pp 481-82).

The major advantage of the heat gun method is its broad range of application to many thermoplastic materials. The two disadvantages are the great care required to obtain uniform, reproducible seams and the tendency of the hot air to oxidize and degrade the surface of the FML during the seaming process and thus produce a poor bond. This method also requires that the surfaces to be joined be clean and free of moisture, dust, oil, and all solvents. These requirements pose problems when seaming in the field, particularly when seaming FMLs that have been exposed to waste streams and to the weather.

Heat Sealing. In this thermal seaming method, the heat required to melt and bond the two layers of thermoplastic is applied through the sheets by clamping them between a pair of jaws which are quickly and reproducibly heated, normally by passage of an electrical current through a resistance wire. The sheets remain clamped for a preset period following cessation of the current and the molten polymer solidifies to form a lap bond (Been, 1971, p 158).

The advantage of heat-sealing is that the complete bonding cycle is readily controlled by a timer and, thus, seams can be made rapidly and reproducibly. As exposure of the heated plastic to air is minimal, the problem of oxidation and embrittlement is reduced.

Another form of heat sealer not sharing the advantages of the clamp type is a heated roller which can be used manually to simultaneously press and melt together both sides of the seam (Bodnar, 1962, p 482). Both roller and clamp heat sealers share a serious disadvantage in that heat must pass through the seam and, thus, are generally limited in application to relatively thin sheetings. With thicker sheetings, the bonding process is very slow and the heated surfaces tend to become fluid, flow, and thin down before the bonding surfaces are sufficiently molten for fusion to occur.

Dielectric Seaming. In dielectric seaming, heat is generated internally within the pieces of sheeting to be joined by directing electromagnetic energy in the radio-frequency region to the seam. The energy field oscillates and causes the permanent or induced dipoles in the polymer to oscillate with the same frequency, creating internal friction and heat. Advantages of dielectric heating are that the entire cross section of the sheeting is heated quickly and uniformly, the heating process can be instantly started and stopped, the method is very efficient as it does not generate waste heat, and the process is readily controlled and highly reproducible. Pressure is applied until the area being seamed has cooled and a strong bond formed.

Dielectric seaming can only be used with FMLs based upon thermoplastic polymers synthesized from easily polarizable monomers. The presence of water in an exposed FML can result in internal blowing and sponging of the FML. This technique is suitable only for factory operations where the environmental requirements of the equipment can be met and cannot be used in the field. FMLs that can be seamed by this technique are based on such polymers as PVC, CPE, and CSPE; PEs cannot be seamed by this technique. Within these limitations, dielectric seaming provides very rapid and reliable seaming (Rothstein, 1971, p 161), but it is not suitable for field seaming of FMLs.

Extrusion Welding. Seaming of HDPE FMLs is being performed in the field with a variety of proprietary and specially designed seaming equipment based on the extrusion of molten HDPE of the same composition as the liner either between the FMLs being seamed to form a lap weld or at the edge of the top sheet to form a bead or fillet. Also, seaming equipment based on heat guns has been devised in which coiled plastic welding rods or strips can be melted and placed. The rod is fed to the seam area to form a fillet-weld seam.

In the first extrusion welding procedure, a jet of hot air is injected into the overlap area to blow away debris and heat the area to be welded. Directly following the hot air, a ribbon of molten polymeric compound of the same composition to that of the sheets being joined is injected into the overlap through an extruder nozzle. A roller moving behind the extruder

nozzle presses the overlap together so the sheets will be fused by the extruded ribbon. Welding speed, pressure roller movement, and temperature are adjustable with the extrusion equipment. The result can be a homogeneous weld that is immediately load bearing.

In the second extrusion welding procedure, a hand-held extruder, in which pellets or strips are fed and melted, places a bead or fillet of the molten PE at the edge of the overlap of the two FMLs that are being seamed. The surfaces of the FMLs are normally buffed and cleaned prior to seaming; also, the edge of thicker FMLs are beveled to give greater surface and to ensure that air pockets are not left at the edge of the top FML. In performing this seam, the top FML is positioned and tacked to the lower FML through the use of heat guns or gum tape between the two FMLs. This type of seaming is used both in assembling the FMLs and in the repair and patching of FMLs.

With extrusion and fusion seaming methods, continuous seams of extended length can be made in the field at a broad range of ambient temperatures. The critical temperature is that of the FML and the extrudate. Welding can be carried out at sheet temperatures $\geq 5^{\circ}\text{C}$. With extra measures such as 1) slowing down welding rate, 2) preheating the sheet, and 3) setting up wind shields for the welder, welding is possible down to sheet temperatures of -15°C . Success at these low temperatures should be verified by test welds.

Extrusion seaming methods, as with all other seaming methods, require careful preparation of the surfaces to be bonded (e.g. drying and buffing, removal of any oxidized layer, as well as proper adjustment of temperatures at the surfaces of the layers to be joined) to assure blending and molecular mixing of the polymeric compound at the interface.

Hot-Wedge Welding. The hot-wedge method (Neidhart, 1979) consists of a hot electrically-heated element in the shape of a blade or V-shaped wedge that is passed between the two sheets to be sealed. Contacting the two sheets to be seamed together, the heated element melts, and smears the two surfaces causing fresh material to come to the surface. Immediately following the melting, roller pressure brings the molten surfaces together to form a homogeneous fused bond.

The hot-wedge method is particularly suited for the thicker [greater than 30 mils (0.76 mm)] LLDPE and HDPE materials, but it is also used with the reinforced thermoplastics. Single-hot-wedge and dual-hot-wedge systems are both available. The dual-hot-wedge weld forms a continuous air channel between two welds. The air channel can be used as a means of testing the bond continuity when air pressure is injected into it. Welding rate (movement of the machine) as well as temperature and roller pressure are adjustable and continuously monitored. Adjustments are made according to environmental conditions such as ambient temperature and moisture.

The hot-wedge method has been used in both the factory fabrication of panels and in field installation. It is particularly suited to long,

continuous, straight seams. However, without special modification, it does not appear to be suitable for making repairs because of the irregularity of the shapes required to patch liners.

Ultrasonic Welding--A newly introduced welder for seaming FMLs involves the use of ultrasonic energy that is designed to dissipate the vibrational energy at the point of contact of the two FMLs to be seamed, causing the FMLs to become molten as a result of the heat generated by frictional activity. Immediately upon melting the membrane surfaces pass through two rollers which squeeze the two sheets together to create a bond from one to two inches in width. The welder is mounted on a three-wheel frame. The rollers, which are motor driven, serve to propel the unit at a controlled rate along the seam line. This seaming method has been applied to thermoplastic FMLs from 0.010 to 0.125 in. in thickness.

4.2.2.3.3 Other bonding methods for seaming FMLs--In addition to the seaming methods described above for thermoplastic and semicrystalline FMLs, other methods are used in the seaming of crosslinked FMLs, i.e. butyl rubber (IIR), EPDM, CR, and some thermoplastics. Discussions of these seaming methods are included for information because FMLs currently in service were seamed by these methods, and because results of research and testing are reported in this document on materials seamed by these methods.

Hot Vulcanization. High temperature vulcanization was used in the factory to prepare panels of IIR, EPDM, and CR FMLs. This seaming was performed under controlled conditions of pressure and time to achieve vulcanization and bonding across the interface of the two FMLs being joined.

Vulcanizing Adhesives. Vulcanizing adhesives achieve their strength from the crosslinking or vulcanization of the polymeric base. The vulcanization may be either a long or short-term operation and may occur under service conditions. Usually, a vulcanizing adhesive is a two-part system, one containing the polymer base, and the other the crosslinking agents. A complete system, as supplied by the manufacturer, includes a two-part cement, a rubber-base gum tape, and a lap sealant; it is designed for use in both the factory and the field.

Solvent Cements and Contact Adhesives. "Solvent cements" is an expression used by the adhesive industry to refer to any of a large variety of adhesives that are applied dissolved in a nonaqueous solution. The strength of the bond is achieved either contemporaneously with or after the volatilization of the solvent. Thus, a solvent cement can be anything from a solution of a thermoplastic resin to a contact cement. Two types of solvent cements are of interest to the lining industry:

- Contact cements.
- Cements that volatilize their solvent while forming the adhesive bond.

Surfaces to be bonded by the second type of adhesive are usually pressed together while the solvent cement is still "wet". Because polymeric membrane materials can have low permeability to a number of solvents, it is important to choose a solvent cement based on a solvent that can volatilize out of the seam assembly. This can happen when the solvent in the cement either dissolves or partially dissolves the surface of the sheeting and forms what might be called an "interpenetrating" bond with the lining material.

Contact cements are adhesives that are applied wet to surfaces of sheetings that are to be bonded and allowed to dry to a "non-tacky" and solvent-free state before the two surfaces are joined. The use of this type of adhesive requires careful alignment of the lining material before bonding because the joined surfaces should not be realigned after assembly. After joining, the seam should be rolled with a steel or plastic roller in a direction perpendicular to the edge of the seam.

Based upon meeting safety requirements, solvent cements could be used either in the field or in the factory to seam FMLs; however, they are more likely to be used only in the field.

Tapes. Tapes have been used in the past to seam FMLs in the field. They are made with pressure-sensitive adhesive applied either to both sides of a flexible substrate or to a flexible backing. The latter is removed once the tape has been placed on one of the surfaces to be joined. Tapes can be used to hold the sheetings in place while another seaming technique is used, or they can be used to provide the permanent bond.

Tapes have been used to seam PE FMLs in the field; however, the use of tapes alone for making seams in FMLs for waste disposal facilities is not recommended. More recently, they have been used in the positioning of FML sheets for fillet extrusion seaming.

Mechanical Methods. Mechanical methods for seaming, though adequate for water containment, are not considered adequate for seaming liners for waste storage and disposal facilities.

4.2.2.3.4 Repairing and seaming of exposed FMLs--An investigation by Haxo (1987) indicated that there is no current technology that can be used to repair leaks and other damage in FMLs that are in service below wastes. Applying the basic criteria used in assessing and testing liners and seams in FMLs that are being installed, it appears highly questionable that conditions required for preparation of adequate seams and permanent repairs can be met with FMLs exposed below wastes. Liners exposed to the weather only, e.g. on the slopes of surface impoundments, can be repaired if the proper conditions of cleanliness and dryness are met. Repairing with formed-in-place plugs holds some promise for short-term use; however, permeability and compatibility of the plugging material with the waste liquid should be assessed.

4.2.2.4 Properties and Characteristics of FMLs Important to their Function in Liner Systems--

The principal characteristics of an FML that are important to its function as a liner for a TSDf include low permeability to waste constituents, its mechanical properties, chemical compatibility with the waste liquid to be contained, which is determined by the FMLs' chemical properties, and its durability for the lifetime of the facility. Laboratory and pilot-scale tests of FMLs are used to assess these characteristics. In the following subsections, these characteristics of FMLs are discussed, and test data on unexposed FMLs are presented.

4.2.2.4.1 Permeability--The primary function of a liner is to prevent the flow of mobile liquids and other chemical species. Thus, the permeability of an FML to these species must be assessed. As is discussed in Chapter 3, transport through FMLs occurs on a molecular level and depends on the solubility of the permeating species and its diffusibility in the FML. A concentration or partial pressure gradient across the FML is the driving force for the direction and rate of transport. The species migrates through the FML from higher to lower concentration; thus, at a small difference in concentration, the transmission can approach zero for specific species. In contrast, soils and clays are porous and the driving force for permeation is the hydraulic head. When used below an FML in a composite liner, permeation through the soil will occur only by diffusion (Chapter 3), if there is no hole in the FML.

The permeability of FMLs to different species can vary by orders of magnitude, depending on the composition and solubility of the migrating species in the FMLs (Haxo et al, 1984a and 1984b; August and Tatzky, 1984). The permeation of a given species is also affected by such factors as crystallinity, filler content, density, crosslink density of the polymer, thickness of the FML, temperature, and the driving force across the membrane. Also, swelling of an FML during service can significantly increase its permeability to some species.

The different topics discussed in the following paragraphs include the following:

- Permeability to gases, including the effect of temperature on gas permeability.
- Permeability to water vapor.
- Permeability to solvent vapor.
- Permeability to organics and organic tracer dyes.
- Permeability to ions and water-soluble tracer dyes.
- Effect of thickness on permeability.

Data for the permeability at 23°C of a series of polymeric FMLs to carbon dioxide, methane, and nitrogen are presented in Table 4-7. Data are reported as gas transmission rates, which are indicative of FML performance, and as permeability coefficients, which are material properties and reflect the permeabilities of the FML compounds. Gas transmission rates (GTR) in mL(STP)/m²·d·atm are converted into permeability coefficients (\bar{P}) in barrers [10⁻¹⁰ mL(STP)·cm/cm²·s·cm Hg] using the following equations (ASTM D1434):

$$\bar{P} = 0.01532 \times (\text{thickness in mm}) \times \text{GTR}. \quad (4-2)$$

The results of the gas permeability measurements show:

- Major differences in gas transmission rates among the FMLs, which reflect variations in polymer type, compound composition, and thickness. For example, the transmission rates of carbon dioxide, measured at 23°C with a pressure gradient of 20 psi, ranged from 122 mL(STP)/m²·d·atm for CSPE 6R to 5260 mL(STP)/m²·d·atm for EPDM 91.
- Permeability of FMLs of a given generic polymer type can differ due to compounding differences (e.g. in filler and plasticizer contents). For example, the gas permeability coefficient of one CSPE compound (CSPE 55) to carbon dioxide was 3.6 times greater than the gas permeability coefficient of the other CSPE compound (CSPE 6R).
- Permeability of a given FML can vary greatly with the gas. For example, all FMLs had a much greater permeability to carbon dioxide than to methane or nitrogen, and a greater permeability to methane than to nitrogen.
- Gas transmission through FMLs of a given composition will decrease with increased thickness. For example, the two HDPE FMLs were essentially of the same composition. One was a 0.61-mm sheeting, and the other was a 0.86-mm sheeting. The thinner sheeting had higher gas transmission rates to the two gases with which they were both tested.
- Higher polymer crystallinity yields lower permeability coefficients, as is shown by comparing the permeability coefficients of the LDPE, LLDPE, and HDPE FMLs; all contained carbon black, except the LDPE FML which was clear.

An FML (ELPO 36) was tested for permeability to carbon dioxide, methane, and nitrogen at three different temperatures (10°, 23°, and 33°C). The results are presented in Figure 4-14. Data are reported as GTR for a 0.158-mm thick specimen under a pressure difference of one atmosphere. These results show that permeability of a given FML to gases increases with temperature in accordance with Arrhenius's equation.

Water Vapor Permeability. The permeability of FMLs to water vapor is important in a variety of applications, including covering reservoirs and other impoundments, lining canals and tunnels, and being moisture barriers in buildings and structures.

TABLE 4-7. PERMEABILITY OF POLYMERIC FMLS TO GASES AT 23°C,
DETERMINED IN ACCORDANCE WITH ASTM D1434, PROCEDURE V

Polymer	FML description			Gas transmission rate (GTR), mL(STP ^a)/m ² ·d·atm			Gas permeability coefficient (P̄), barrer ^b		
	Serial number ^c	Thickness, mm	Com- pound type ^d	CO ₂	CH ₄	N ₂	CO ₂	CH ₄	N ₂
IIR	44	1.60	XL	512	120	19.7	12.5	2.92	0.480
CPE	77	0.72	TP	106 ^e	6.31 ^e	1.45 ^e	1.16 ^e	0.069 ^e	0.016 ^e
CSPE	6R	0.82	TP	122	21.6	26.2	1.52	0.270	0.33
CSPE	55	0.86	TP	418	124	27.1	5.47	1.62	0.36
ELPO	36	0.58	CX	1450	280	125	12.8	2.47	1.10
EPDM	83R	0.89	TP	2720 ^f	...	...	36.8 ^f	...	...
EPDM	91	0.90	XL	5260	1400	314	72.0	19.2	4.30
EPDM	8	1.50	XL	...	470 ^g	...	...	10.7 ^g	...
CR	90	0.90	XL	716	80.9	31.1	9.81	1.11	0.43
PB	221	0.71	CX	818	248	62.3	8.84	2.68	0.67
HDPE	265(0.945)	0.61	CX	729	138	...	6.77	1.28	...
HDPE	269(0.945)	0.86	CX	467	104	...	6.11	1.36	...
LDPE ^h	21(0.921)	0.25	CX	6180 ^f	1340 ^f	...	23.5 ^f	5.10 ^f	...
HDPE	265(0.945)	0.61	CX	729	138	...	6.77	1.28	...
LLDPE	281(0.923)	0.46	CX	1370	322	...	9.59	2.25	...
PVC	93	0.25	TP	7730 ^f	1150 ^f	...	29.4 ^f	4.38 ^f	...
PVC	88	0.49	TP	3010	446	108	22.4	3.32	0.81
PVC	59	0.81	TP	2840 ^f	285 ^f	...	35.0 ^f	3.51 ^f	...
PEL ⁱ	...	0.022	TP/CX	357	...	...	0.119	...	...

^aSTP = Standard temperature and pressure.

^bOne barrer = 10⁻¹⁰ mL(STP)·cm/cm²·s·cm Hg.

^cMatrecon liner serial number; R = fabric-reinforced; numbers in parentheses are densities.

^dXL = crosslinked; TP = thermoplastic; CX = semicrystalline.

^eMeasured at a pressure gradient of 40 psi; all others measured at 20 psi, unless noted.

^fMeasured at 30°C.

^gMeasured at 20°C.

^hNatural resin (no carbon black).

ⁱThis sample is NBS Standard material 1470. The determination was made at 15.0 psi, under which condition the NBS Certified CO₂ transmission rate can be calculated to be 338 mL(STP)/m²·d·atm.

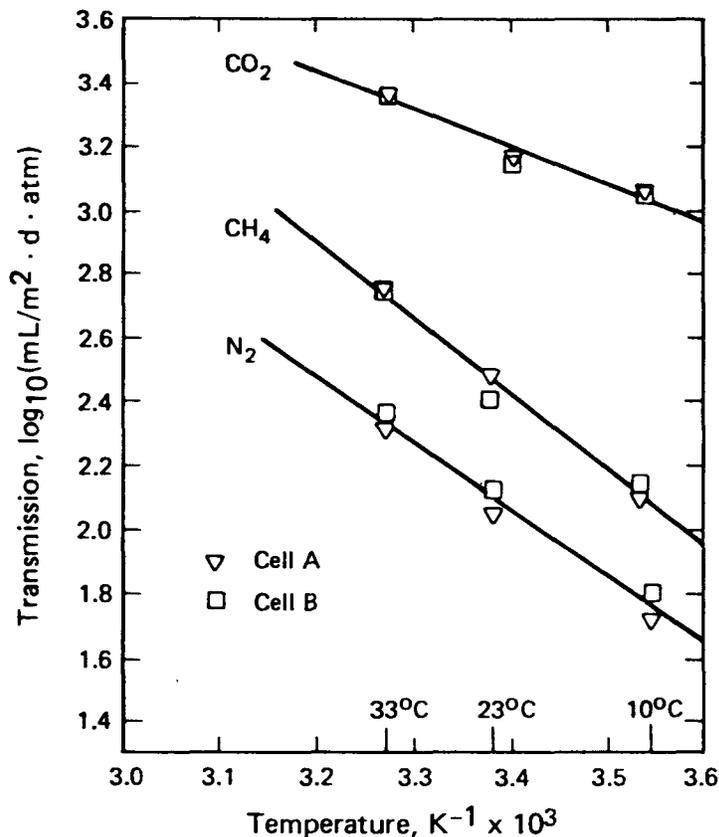


Figure 4-14. Permeability of ELPO to CO₂, CH₄, and N₂ as a function of temperature.

The water vapor transmission (WVT) rate of an FML is the time rate of water vapor flow normal to its surfaces under steady conditions through a unit area under the conditions of test and is reported in grams per square meter per day ($\text{g m}^{-2} \text{d}^{-1}$). Transmission of $1 \text{ g m}^{-2} \text{d}^{-1}$ of water is equal in practical units to 1.07 gal per acre per day. The water vapor permeance of a material is the ratio of its WVT to the vapor pressure difference across the two surfaces. The pressure difference is the saturation vapor pressure of water at a specific temperature multiplied by the difference in the relative humidity (expressed as a fraction) across the two surfaces. The unit of permeance used is metric perm, or $\text{g m}^{-2} \text{d}^{-1} (\text{mm Hg})^{-1}$. The permeance value of a sheet is a rational basis for evaluating its performance and comparing various FMLs of different thicknesses for a given application. The permeability of an FML is the product of its permeance and its thickness. The unit used in this report is the metric perm·cm or $\text{g m}^{-2} \text{d}^{-1} (\text{mm Hg})^{-1} \cdot \text{cm}$. The water vapor permeability of a homogeneous FML is a property of the composition which may vary with exposure conditions. Both permeance and permeability may vary with exposure conditions.

To assess this characteristic of FMLs, the WVT rates of a range of FMLs were determined in accordance with ASTM E96-80, Inverted Water Method (Procedure BW). In this procedure, a circular specimen of FML is sealed with

molten wax into the mouth of an aluminum cup partially filled with deionized water. The test cup is illustrated in Figure 4-15. The entire assembly is kept in an inverted position so that water is in contact with the FML surface, and stored in a cabinet maintained at 23°C and a relative humidity (RH) of 50±5%. This cabinet is equipped with a small fan to ensure uniform air velocity over the surfaces of the specimens as required by the procedure. Thus, the WVT occurs across a water vapor pressure gradient of 100% RH (inside the cup) to 50% RH in the cabinet.

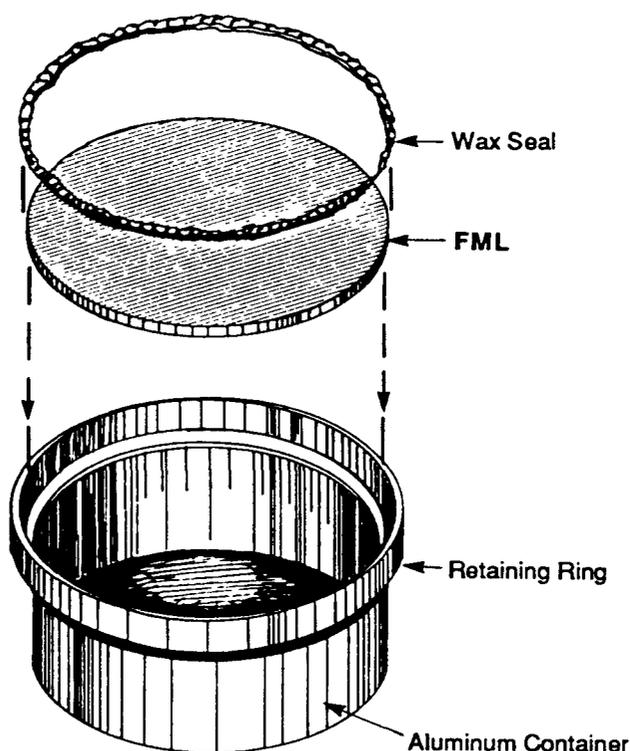


Figure 4-15. Exploded view of water vapor transmission cup used in ASTM E96-80. In the test procedure, the cup is kept in an inverted position so that water sealed in the cup contacts the FML surface.

The test cups are periodically weighed, and the resulting data (7 to 14 data points in the straight line portion of the weight-time curve) are reduced using linear regression to yield a loss rate which can be converted to a WVT value in units of $\text{g m}^{-2} \text{d}^{-1}$. WVT data for a series of FMLs, representing different material types and materials produced by different manufacturers, are presented in Table 4-8 by polymer and increasing thickness. The calculated values of water vapor permeance and water vapor permeability are also presented.

TABLE 4-8. PERMEABILITY OF POLYMERIC FMLS TO WATER VAPOR^a

Polymer	FML description			Water vapor transmission rate, $\text{g m}^{-2} \text{d}^{-1}$	Water vapor permeance, 10^{-2} metric perm	Water vapor permeability, 10^{-2} metric perm $\cdot\text{cm}$
	Serial number ^b	Thickness, mm	Compound type			
Butyl rubber	164	1.15	XL	0.053	0.503	0.0579
	57	0.85	XL	0.020	0.190	0.0161
	22	1.85	XL	0.097	0.921	0.170
CPE	86	0.53	TP	0.643	6.10	0.324
	142	0.76	TP	0.36-0.063	3.42-5.98	0.260-0.454
	135	0.79	TP	1.400	13.3	1.05
	145	0.79	TP	0.294	2.79	0.220
	77	0.79	TP	0.320	3.04	0.240
	38	0.82	TP	0.361	3.43	0.281
	12	0.85	TP	0.264	2.51	0.213
	136R	0.91 ^c	TP	1.470	14.0	1.27
	147R	0.94 ^c	TP	0.305	2.90	0.272
	152R	0.97 ^c	TP	0.557	5.29	0.513
	165	0.97	TP	0.643	6.10	0.592
	CSPE	169R	0.74 ^c	TP	0.333	3.16	0.234
148		0.76	TP	0.663	6.29	0.478
3		0.79	TP	0.634	6.02	0.475
55		0.89	TP	0.438	9.49	0.845
151R		0.91 ^c	TP	0.748	7.10	0.646
173R		0.94 ^c	TP	0.481	4.57	0.429
6R		0.94 ^c	TP	0.422	4.01	0.377
149R		0.97 ^c	TP	0.397	3.77	0.366
174R		0.99 ^c	TP	0.523	4.96	0.492
170R		1.07 ^c	TP	0.252	2.39	0.256
ELPO	172	0.61	CX	0.144	1.37	0.083
	36	0.72	CX	0.142	1.35	0.097
ECO ^d	178	1.16	XL	20.18	192	22.2
	178	1.65	XL	14.30	136	22.4
EPDM	41	0.51	XL	0.270	2.56	0.131
	83	0.94	XL	0.190	1.80	0.170
	26	0.97	XL	0.327	3.10	0.301
	163R	0.85 ^c	XL	0.384	3.64	0.310
	18	1.23	XL	0.314	2.98	0.367
	8	1.70	XL	0.172	1.63	0.278
EVA	308	0.53	TP	1.57	14.3	0.760

Continued . . .

TABLE 4-8. (Continued)

Polymer	FML description		Compound type	Water vapor transmission rate, $\text{g m}^{-2} \text{d}^{-1}$	Water vapor permeance, 10^{-2} metric perm	Water vapor permeability, 10^{-2} metric perm $\cdot\text{cm}$
	Serial number ^b	Thickness, mm				
Neoprene	42	0.51	XL	0.304	2.89	0.147
	43	0.80	XL	0.448	4.25	0.340
	168	0.91	XL	0.473	4.49	0.409
	167R	1.27 ^c	XL	0.429	4.07	0.517
	82	1.55	XL	0.240	2.28	0.353
	9	1.59	XL	0.237	2.25	0.358
Nitrile rubber	171R	0.76 ^c	TP	5.51	52.3	3.98
PB ^e	220	0.19	CX	0.401	3.81	0.0723
	221	0.69	CX	0.084	0.797	0.0550
PEL ^f	75	0.20	CX	10.50	99.7	1.99
	314	0.25	CX	43.7	41.5	10.6
LDPE	108	0.76	CX	0.0573	0.544	0.0413
HDPE	184	0.80	CX	0.0172	0.163	0.0131
	179	2.44	CX	0.0062	0.059	0.0144
HDPE-A	181	0.86	CX	0.0472	0.448	0.0385
PVC	89	0.28	TP	4.42	42.0	1.17
	17	0.51	TP	2.97	28.2	1.44
	88	0.52	TP	2.94	27.9	1.45
	19	0.54	TP	2.78	26.4	1.42
	137	0.74	TP	1.10	10.4	0.77
	146	0.76	TP	1.94	18.4	1.40
	11	0.76	TP	1.85	17.6	1.33
	143	0.79	TP	1.85	17.6	1.39
PVC-E9	176R	0.91 ^c	TP	2.78	26.4	2.40
	177R	0.97 ^c	TP	1.94	18.4	1.79
PVC-OR ^h	144	0.79	TP	3.47	32.9	2.60
	40	0.83	TP	4.17	39.6	3.28
	59	0.84	TP	4.20	39.9	3.35
Saran film (0.5 mil)	222	0.013	TP	0.563	5.34	0.00695
Teflon film (4 mil)	234	0.10	TP	0.217	2.06	0.00206

^aASTM E96-80, Procedure BW: Inverted water method at 23°C; 50% humidity on downstream side. Permeance in metric perms = $\text{g m}^{-2} \text{d}^{-1} (\text{mm Hg})^{-1} = \text{WVT}/\Delta p$ in mm Hg, where Δp = the vapor pressure difference = 10.53 mm Hg (at 23°C and 50% humidity on downstream side). Permeability in metric perms $\cdot\text{cm}$ = permeance x thickness of FML in cm.

^bMatrecon serial number; R = fabric-reinforced.

^cThickness is not corrected to exclude thickness of reinforcing fabric.

^dECO = epichlorohydrin rubber.

^ePB = polybutylene.

^fPEL = polyester elastomer.

^gElasticized PVC.

^hOil-resistant PVC.

As with the gas permeability data, permeability to water vapor varies considerably among the polymer types; for example, the rates are much lower through hydrocarbon types (e.g. butyl rubber, EPDM, and ELPO) than through polar types (e.g. ECO and nitrile rubber). Increased thickness and increased crystallinity, in the case of semicrystalline materials, reduce permeability rates. Also, within a polymer type there is considerable variation due to differences in composition. Thus, even though an FML may be thicker than another FML of the same generic polymer type, it does not necessarily have a reduced transmission rate. For example, the thinnest CSPE FML (169R) had the second lowest transmission rate of the 10 CSPE FMLs tested.

Solvent Vapor Permeability. Considerable data exist with respect to the transport of organics through polymeric films (Yasuda, 1966; Yasuda et al, 1968), but only a few data exist with respect to polymeric FMLs (Haxo et al, 1984a and 1984b; August and Tatzky, 1984). Preliminary experiments were performed with neat solvents to assess their transmission rates under controlled conditions through different FMLs. Solvent vapor transmission (SVT) rates were determined in accordance with a procedure based on ASTM E96-80, Inverted Water Method (Procedure BW). In this procedure, a circular specimen of an FML is mechanically clamped onto the mouth of an aluminum cup partially filled with the test solvent (Figure 4-16). The method differs from the procedure used to measure WVT described above in that the cups are stored in an upright position so that only solvent vapor contacts the FML specimen. SVT occurs as a result of the concentration gradient across the specimen by the presence of a saturated atmosphere within the cup and the essentially zero level outside the cup. Thus, the vapor pressure difference across the FML specimen is equal to the vapor pressure of the test solvent at the test temperature (i.e. at 23°C). The SVT rate is determined as described above for WVT.

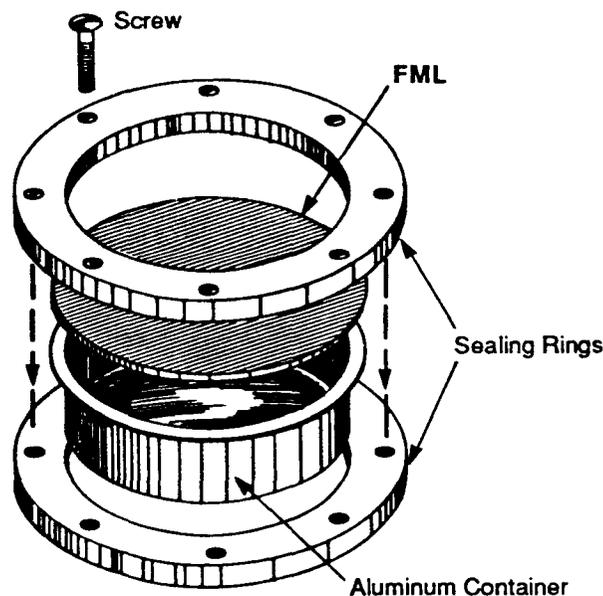


Figure 4-16. Exploded view of SVT cup with aluminum sealing rings.

SVT rates for a series of FMLs selected for test because of their good solvent resistance to five organic solvents (i.e. methanol, acetone, cyclohexane, xylene, and chloroform) are presented in Table 4-9. Also presented in Table 4-9 are the values for solvent vapor permeance (calculated by dividing the SVT by the vapor pressure difference) and solvent vapor permeability (calculated by multiplying the solvent vapor permeance by the thickness of the respective FML specimens). Although limited, the data show substantially different transmission rates among the FMLs and among the different solvents. Increased crystallinity among the polyethylene FMLs reduces transmission, as does increased thickness. HDPE that has been alloyed with another polymer to reduce environmental stress-cracking has significantly higher vapor transmission and permeability than the unalloyed HDPE.

Permeability to Organics and Organic Tracer Dyes. Using organic dyes as tracers has been suggested as a means of detecting the presence of holes in FMLs. The question arises whether an FML might allow a tracer to permeate a hole-free FML and thus falsely indicate the presence of a hole.

The pouch test appears to be an appropriate method to assess the permeability of selected FMLs to organics and organic tracer dyes. In this procedure, small quantities of a test liquid are sealed in pouches fabricated from FMLs. The pouches are immersed in deionized water (DI) or another liquid of known composition. Transmission through the pouch walls is monitored by changes in weight of the filled pouch, chemical analyses (including pH and conductivity measurements) of the liquid outside the pouch, and the appearance of the dyes in the outer liquid or on the pouch surface. The pouch procedure is presented in Appendix D.

Haxo and Nelson (1984a) reported on the use of the pouch test procedure to obtain data on the permeation of three semicrystalline FMLs (HDPE, HDPE-A, and PB) to selected organics and organic tracer dyes. The procedure used in these tests differs from that presented in Appendix D. The pouch size was reduced so that the pouches could fit into wide-mouth glass quart jars which were used to contain the pouches and the outer liquid. Jars were used instead of polybutylene bags to prevent the pouches from floating in the outer liquid. Specific FMLs were selected for test because of their low solubility in organics, because of their low extractables contents, and because they could be fabricated into leak-proof pouches relatively easily by heat-sealing of the seams. The two organics selected for this study were xylene and acetone. Five different solutions were prepared at 1% dye concentration. These solutions were:

- Automate Red in acetone.
- Automate Red in xylene.
- Methyl Violet in 50:50 solution of acetone and water.
- Fluorescent Yellow in acetone.
- Fluorescent Yellow in xylene.

TABLE 4-9. PERMEABILITY OF POLYMERIC FMLS TO VARIOUS SOLVENTS,
MEASURED IN ACCORDANCE WITH ASTM E96, PROCEDURE BW (MODIFIED) TO TEST SOLVENTS

Polymer	CSPE	ELPO	HDPE		HDPE-A			LDPE	PB	Teflon
Liner number	170R	172	184	179	180	181	182	108	221	234
Thickness, mm	1.07-1.12	0.53-0.61	0.77-0.83	2.42-2.81	0.53	0.85-0.88	0.97	0.74-0.76	0.64-0.74	0.10
Type of compound	TP	CX	CX	CX	CX	CX	CX	CX	CX	CX
<u>SVT, g m⁻² d⁻¹</u>										
Methyl alcohol	...	2.10	0.16	...	...	0.50	...	0.74	0.35	0.34
Acetone	221	8.62	0.56	...	...	2.19	...	2.83	1.23	1.27
Cyclohexane	...	7.60	11.7	...	...	151	...	161	616	0.026
Xylene	...	359	21.6	6.86	295	212	220	116	178	0.16
Chloroform	...	3230	54.8	15.8	...	506	...	570	2120	20.6
<u>Solvent vapor permeance^a, 10⁻² metric perms (SVT/mm Hg)</u>										
Methyl alcohol	...	1.88	0.14	...	...	0.45	...	0.66	0.31	0.30
Acetone	104	4.07	0.26	...	...	1.03	...	1.33	0.58	0.60
Cyclohexane	...	8.54	13.1	...	...	170	...	181	692	0.03
Xylene ^b	...	5130	308	97.9	4210	3020	3140	1650	2540	2.28
Chloroform	...	1810	30.8	8.88	...	284	...	320	1191	11.6
<u>Solvent vapor permeability^c, 10⁻² metric perms·cm</u>										
Methyl alcohol	...	0.11	0.01	...	...	0.04	...	0.05	0.02	0.003
Acetone	11.4	0.23	0.02	...	...	0.09	...	0.10	0.04	0.006
Cyclohexane	...	0.49	1.05	...	...	14.7	...	13.6	47.8	2.9 x 10 ⁻⁴
Xylene ^b	...	292	24.6	25.6	223	262	304	124	175	0.002
Chloroform	...	103	2.46	2.32	...	24.6	...	24.0	82.2	0.12

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^aVapor pressure of the solvents for permeance calculations was calculated by the Antoine equation using the variables from Table 10-8, Vapor Pressures of Various Organic Compounds, in Lange's Handbook of Chemistry (Dean, 1979). The vapor pressures in mm of Hg at a standard room temperature of 23°C are methyl alcohol 112, acetone 212, cyclohexane 89, and chloroform 178.

^bVapor pressure of 7 mm of Hg, which is the average of the individual values for o-xylene, m-xylene, and p-xylene (Dean, 1979), was used in the calculations since the solvent used was a mixture of the three isomers.

^cThe median thickness value was used to calculate the permeability.

Table 4-10 presents information on the dyes used in this study. The Automate Red B and Fluorescent Yellow were selected for this study to investigate the possibility of their permeation of an HDPE FML used to line a series of cells in which the permeability of various soils to waste liquids was being studied. These dyes, which are soluble in organics but not in water, were added to the organic wastes so that the flow of these liquids through soil liner specimens could be observed. During monitoring of the cell, leakage was observed outside the HDPE liner. It was desired to determine whether the leakage was by permeation or through holes in the liner. The Methyl Violet was selected because of its solubility in both water and acetone.

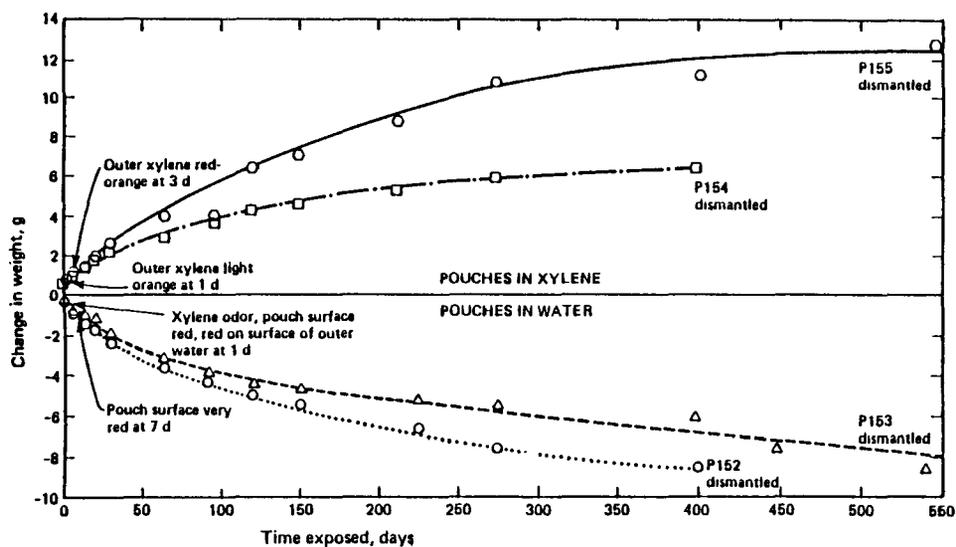
TABLE 4-10. ORGANIC DYES USED AS TRACERS IN POUCH EXPERIMENTS

Dye	Color index number	Color	Solubility	Description
Automate Red B	Solvent red 164	Red	Petroleum products	Proprietary AZO dye
Fluorescent Yellow	Solvent red 175	Brown oil	Xylene, acetone	Organic, proprietary yellow-green fluorescence
Methyl violet	680	Yellow at pH 2 to 3.1 Violet at pH >3.1	Water, alcohol, chloroform, acetone	C ₂₅ H ₃₀ ClN ₃

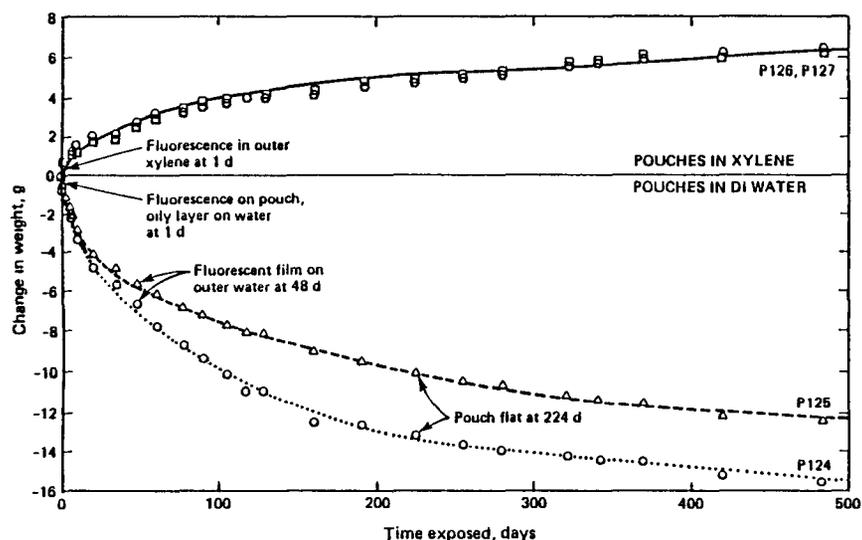
The 20-mil HDPE-A FML was selected for this study because it was semi-crystalline and resistant to the solvents, and because a leak-free pouch could be fabricated from it with the heat-sealing equipment available.

The filled pouches were placed in either distilled water or in the same solvent sealed in the respective pouch. Testing was performed in duplicate. By placing a pouch in the same solvent that was sealed in the pouch, permeation of the dye could be observed. The pouches were monitored principally for changes in weight. The odor of the outer liquids in the jars was also noted as well as any appearance of the dyes either on the surface of the pouches or in the outer liquid. Data on the HDPE-A pouches are discussed below.

The weight changes of the filled HDPE-A pouches are presented in Figures 4-17 and 4-18, as a function of time. The xylene and acetone with the dissolved organic dyes migrated through the walls of all of the HDPE-A pouches. The pouches which contained the xylene-dye solutions and which were placed in pure xylene increased in weight (Figure 4-17). This increase in weight is partially due to absorption of xylene by the pouch wall, but it is primarily due to the permeation of xylene into the pouch. The dye in the xylene in the pouch permeated the liner into the outer xylene, which was indicated by the red color in the outer xylene in the case of the Automate Red and by the fluorescence of the outer xylene in ultraviolet light in the case of the Fluorescent Yellow.

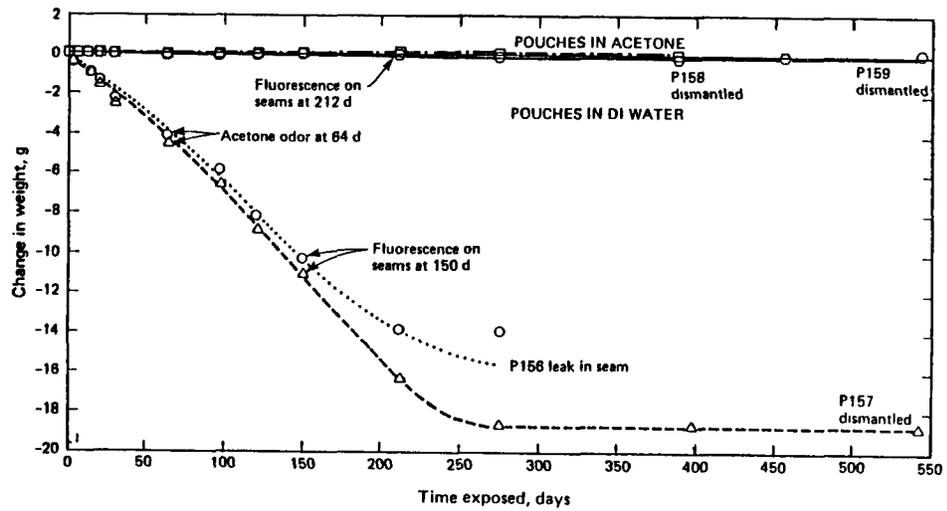


- a. Pouches of 20-mil HDPE-A 180 filled with xylene and 1% Automate Red. Pouches 154 (□) and 155 (○) were immersed in xylene. Note the movement of xylene into the pouch. Pouches 152 (○) and 153 (△) were immersed in DI water. Note the movement of xylene out of the pouch.

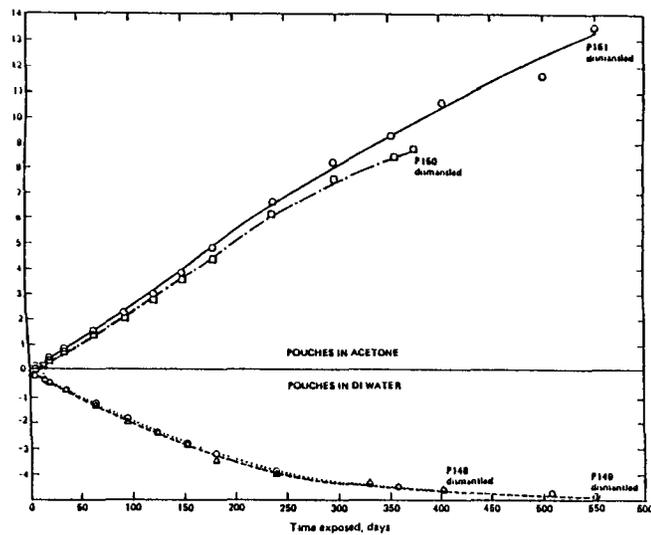


- b. Pouches of 20-mil HDPE-A 180 filled with xylene and 1% Fluorescent Yellow. Pouches 126 (□) and 127 (○) were immersed in xylene. Note the movement of xylene into the pouch. Pouches 124 (○) and 125 (△) were immersed in DI water. Note the movement of xylene out of the pouch.

Figure 4-17. Weight changes of HDPE-A pouches filled with xylene immersed in xylene or DI water.



- a. Pouches of 20-mil HDPE-A 180 filled with acetone and 1% Fluorescent Yellow. Pouches 158 (□) and 159 (○) were immersed in acetone. Note lack of movement of acetone. Pouches 156 (○) and 157 (△) were immersed in DI water. Note the movement of acetone out of the pouch.



- b. Pouches of 20-mil HDPE-A 180 filled with 50:50 acetone: DI water and 1% methyl violet. Pouches 150 (□) and 151 (○) were immersed in acetone. Note the movement of acetone into the pouch. Pouches 148 (○) and 149 (△) were immersed in DI water. Note the movement of acetone out of the pouch.

Figure 4-18. Weight changes of HDPE-A pouches filled with acetone or 50:50 acetone:DI water immersed in acetone or DI water.

In the case of the HDPE-A pouches containing xylene and which were placed in water, the xylene migrated out of the pouch into the water but, because xylene is sparingly soluble in water, it floated to the top of the outer water. The Fluorescent Yellow dye permeated the pouch wall and, because it is a solid and insoluble in water, it precipitated on the outside surface of the pouch. The outer water did not fluoresce in UV light.

In the case of the HDPE-A pouches containing acetone with Fluorescent Yellow dye and which were placed in water (Figure 4-18a), the acetone also permeated the pouch wall; but, because acetone is totally miscible with the water, it dissolved in the water to form a dilute solution. The dye also permeated the pouch wall, but precipitated on the outer surface causing it to fluoresce under UV light. When acetone was the outer liquid, the dye permeated into the outer acetone but the pouches did not change in weight. This behavior indicates that the pouch walls did not absorb acetone, which was verified when the pouches were dismantled.

The 20-mil HDPE-A pouches containing a 50:50 mixture of acetone and water were placed in both acetone and DI water to assess the effects on concentration on transmission rates. Changes in weight of the pouches up to 300 days are shown in Figure 4-18b. The pouches in water lost weight, leveling off as the acetone concentration in the pouch dropped and that in the outer water increased. The pouches placed in the acetone as the outer liquid gained weight as the acetone permeated into the pouch. However, the rate of transmission did not appear to change significantly as the concentration of acetone in the pouch increased. No sign of Methyl Violet was noted in the outer liquid for the pouches in acetone or in water.

The initial rate at which the acetone in the 50:50 mixture permeated through the HDPE-A membrane into the outer water was less than half that of the acetone in the pouch with the 100% acetone (compare Figures 4-18a and 4-18b). Calculated rates are, respectively, 1.68 vs 5.68 g m⁻² d⁻¹ for the losses of acetone from the pouch. These results show how a concentration gradient can affect rates of transmission through an FML.

The transmission rates of acetone and xylene through HDPE, HDPE-A, and PB FMLs resulting from the pouch test are compared with solvent vapor and water vapor transmission data in Table 4-11. These results show a correlation between the pouch data and the SVT data, particularly for acetone. The xylene transmission data resulting from the pouch test may be low, possibly due to the low solubility of xylene in water.

This pouch method appears to be a useful method for assessing the permeability of FMLs to various organic liquids that may be stored underground and require secondary containment.

Permeability to Ions and Water-Soluble Tracer Dyes. The permeability of FMLs to inorganic ions and water-soluble organic dyes has been reported by Haxo and Nelson (1984a). These materials may find use as tracers in testing the watertightness of a liner system. The pouch procedure appears to be a means of determining whether tracers could permeate a specific FML. Brown et al (1983) used tracer dyes to follow flow through soils.

TABLE 4-11. TRANSMISSION RATES OF ACETONE AND XYLENE THROUGH FMLS OBTAINED BY THE POUCH TEST COMPARED WITH SVT AND WVT

Polymer	HDPE	HDPE-A	PB
FML number	184	180	221
Nominal thickness, mil	30	20	30
<u>Analytical properties</u>			
Specific gravity	0.951	0.949	0.907
Extractables ^a , %	0.73	2.09	3.68
<u>Pouch test^b</u>			
Acetone, g m ⁻² d ⁻¹	-0.866 ^c -A	-6.53 ^c -A -5.68 ^d -A	-1.316 ^c -A
50:50, acetone: water, g m ⁻² d ⁻¹	...	-1.68 ^e -A +2.09 ^{e,f} -A	...
Xylene, g m ⁻² d ⁻¹	-1.788 ^d -X	-16.84 ^d -X -8.48 ^c -X	-4.40 ^d -X
<u>SVT (ASTM E96-66, Procedure BW, modified)</u>			
Xylene, g m ⁻² d ⁻¹	21.6	295	178
Acetone, g m ⁻² d ⁻¹	0.56	2.19 ^g	1.23
<u>WVT (ASTM E96-66, Procedure BW)</u>			
WVT, g m ⁻² d ⁻¹	0.0172 (32 mil)	0.0472 (34 mil)	0.084 (30 mil)

^aIn accordance with Matrecon Test Method 2 (Appendix E) using methyl ethyl ketone as the solvent.

^bTransmission rates from pouch into outer liquid indicated by negative sign, i.e. loss of weight by the pouch. Transmission values were determined graphically from data in the early portion of the pouch weight-time curves. The liquids permeating the pouch walls are represented by the following symbols: A = acetone; X = xylene. Except where indicated otherwise, pouches were immersed in deionized water.

^cWith Automate Red (1%).

^dWith Fluorescent Yellow (1%).

^eWith Methyl Violet (1%).

^fAcetone was outer liquid.

^gData for HDPE-A 181, a 30-mil nominal thickness sheeting of the same composition as FML-180.

Three water-soluble tracers were tested in FML pouches in accordance with the procedure presented in Appendix D. The tracers included one inorganic salt (lithium chloride) and two water-soluble organic dyes (Fluorescein and Sevron Red). Lithium chloride is generally found only in trace amounts in soil and has been suggested as a tracer to detect leaks in waste impoundments. The dyes have been used for tracing water flow. Information on the dyes included in this study is given in Table 4-12. The combinations of pouches that were tested and the liquids loaded into them are listed in Table 4-13. All the pouches were placed in individual containers filled with DI water.

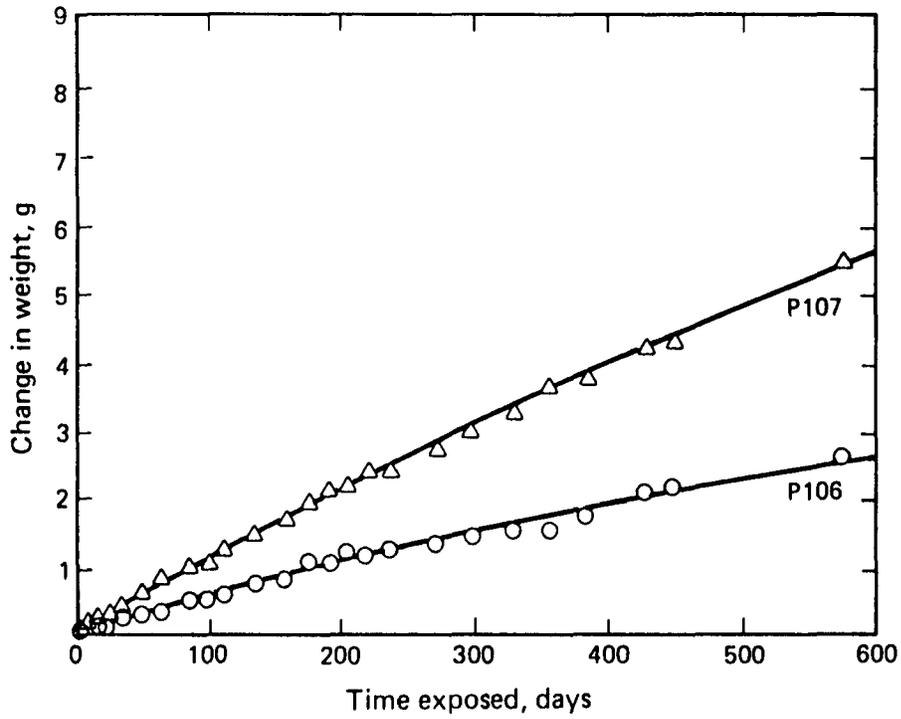
TABLE 4-12. WATER-SOLUBLE TRACER DYES USED IN POUCH EXPERIMENTS

Dye	Color index number	Color	Solubility	Description
Fluorescein-sodium	Acid yellow 73	Yellow-red	Water	C ₂₀ H ₁₀ O ₅ Na ₂ -yellow-green fluorescence in neutral or alkaline solutions
Sevron Red	...	Red	Water	Proprietary cationic dye

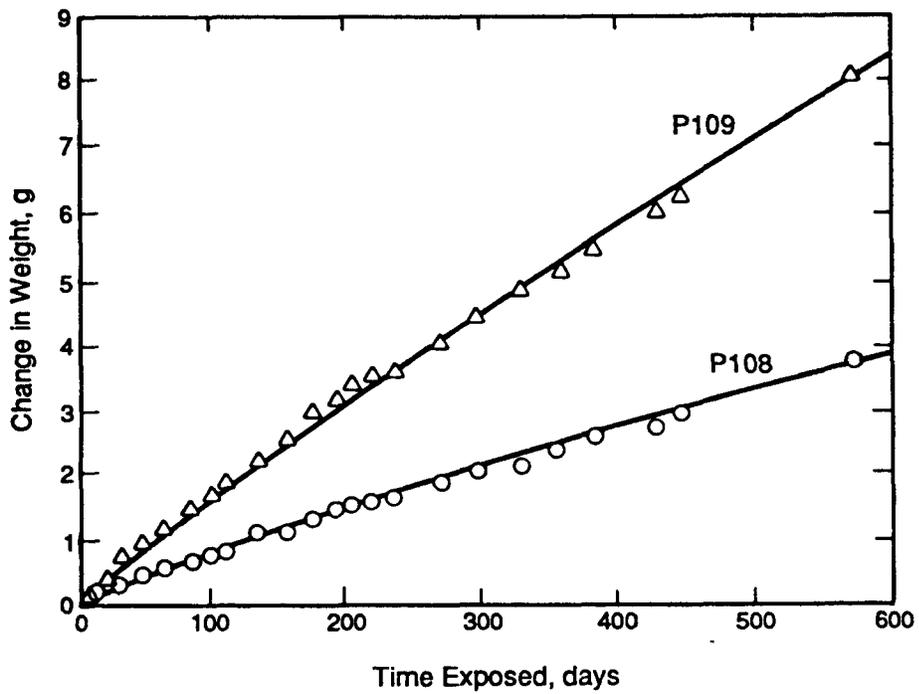
TABLE 4-13. COMBINATIONS OF AQUEOUS TEST LIQUIDS CONTAINING WATER-SOLUBLE TRACERS AND FMLS IN POUCH EXPERIMENTS

Polymer	FML		Tracer			
	Number	Nominal thickness, mil	Lithium chloride		Fluorescein	Sevron Red
			5%	10%	1%	1%
PVC	137	30	X	X	X	...
PVC	146	30	X	X	X	...
HDPE-A	180	20	...	...	X	X
PB	221	30	...	...	X	X

The pouch assemblies were monitored regularly by measuring the weight of the pouches, measuring the pH and electrical conductivity of the outer liquids, and by visual observation with normal and UV light for the permeation of the dyes. The weight changes of the PVC pouches containing 5 and 10% solutions of LiCl are shown in Figure 4-19.



a. Pouches of PVC 137. Pouch 106 contains 5% LiCl, and Pouch 107 contains 10% LiCl.



b. Pouches of PVC 146. Pouch 108 contains 5% LiCl, and Pouch 109 contains 10% LiCl.

Figure 4-19. Weight changes of PVC pouches containing 5 and 10% aqueous solutions of LiCl during immersion in DI water.

After 573 days of exposure, the pouches of PVC with the LiCl solutions had increased in weight in differing amounts depending on the concentration of the LiCl in the pouch and the specific PVC FML. The pouches with a 10% concentration of LiCl increased in weight at twice the rate of the pouches with the 5% LiCl solution. These results show how a concentration gradient can affect the rate of transmission. On the other hand, the electrical conductivity of the outer water exhibited almost no change during this period (up to a maximum of $23 \mu\text{mho cm}^{-1}$ against a background conductivity of $7 \mu\text{mho cm}^{-1}$). These results indicate that water passed through the pouch walls into the pouches, but little if any lithium chloride passed through the pouch walls into the outer water. These results indicate that ions do not permeate this FML in spite of their solubility in water which does permeate.

All six pouches with 1% aqueous solution of sodium fluorescein showed indications of transmission of the dye through the pouch walls, particularly in the case of the PVC 146 pouch. Under UV light, fluorescent specks showed on the surface of some pouches, in scratches, and at corners where the sheeting had been thinned during heat-sealing. Observation under UV light also indicated that a small amount of the organic dye permeated the PVC 146 wall since there was distinct fluorescence of the outer water. When the pH of the outer water was increased, traces of fluorescence appeared under UV light for all pouches. The gains in weight of the filled pouches were very small.

In the case of the HDPE-A and PB pouches that contained 1% aqueous solution of Sevron Red, no signs of dye appeared in the outer water or on the outside of the pouches after 440 days of test. The weight gains of the pouches were small, i.e. 0.20 g for HDPE-A pouches and 0.32 g for the PB pouches. Based on the weights of pouches that were dismantled, it appeared that the weight gains were in the pouch walls, presumably by absorption of outer DI water. Overall, the results indicate that Sevron Red probably does not permeate the walls or does so at a very slow rate.

Effect of Thickness on Permeability. In calculating the permeability of an FML, a value for permeability is usually obtained for a unit thickness, e.g. 1 cm of sheeting. This calculation assumes that the transmission is inversely proportional to the thickness of the sheeting as indicated by Fick's law for diffusion. In a study of the permeability of various FMLs to organics, August and Tatzky (1984) observed that the transmission of neat organics through a series of HDPE FMLs of different thicknesses deviated from this relationship, as is shown in Figure 4-20. Consequently, extrapolating from permeability data for a thin film to obtain data on a thicker film would lead to transmission values higher than those that would result from testing of the thicker film. A similar effect was observed in the methane permeability of HDPE FMLs of different thicknesses on measurements made at 23°C by Matrecon, as is shown in Figure 4-21.

4.2.2.4.2 Mechanical properties--The mechanical properties of an FML indicate its physical characteristics. The most important of these properties include tensile properties, both uniaxial and multiaxial, and the

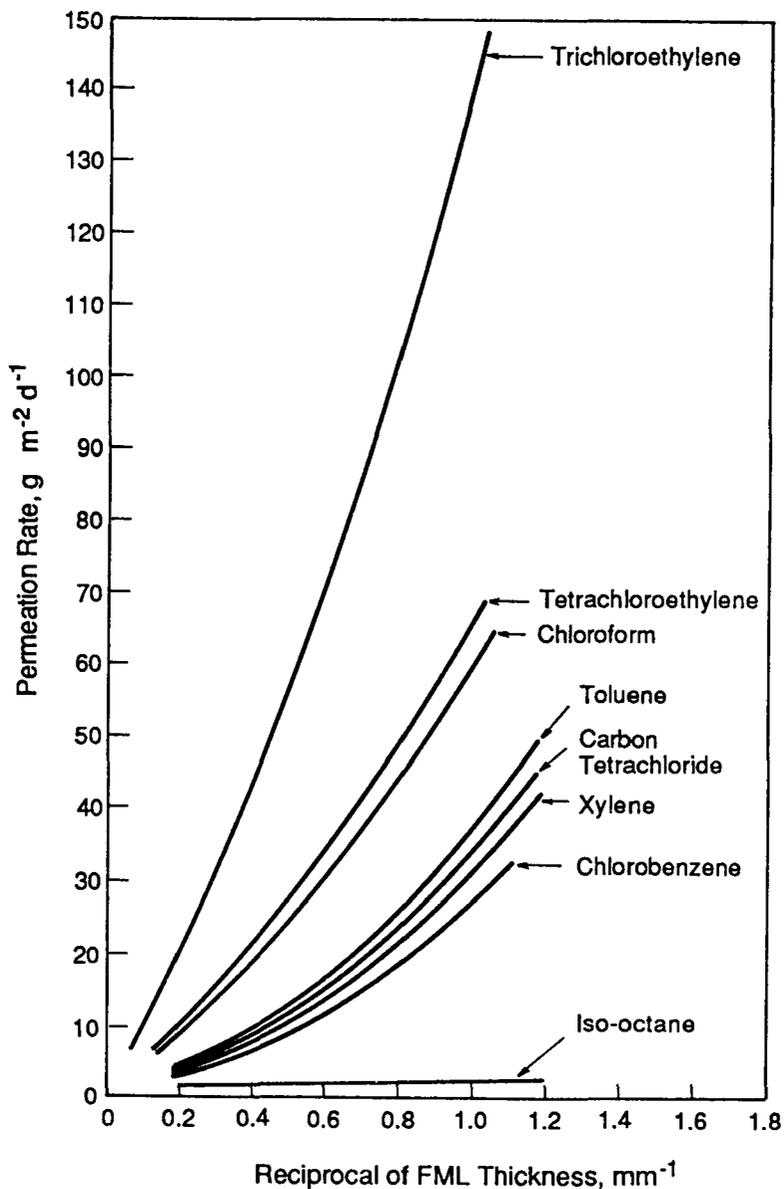


Figure 4-20. Transmission rates of various hydrocarbons as a function of the reciprocal of the thickness of HDPE FMLs. (Based on August and Tatsky, 1984, p 166).

ability to resist puncture and tearing. These properties are involved in an FML's use in the design of an installation and are important in meeting the installation's engineering requirements. The test methods used to measure these properties are discussed in detail in Section 4.2.2.5, "Testing and Laboratory Evaluation of FMLs." However, it should be noted that, at present, there is no correlation between the results of these tests and actual field performance. This subsection discusses how service conditions can

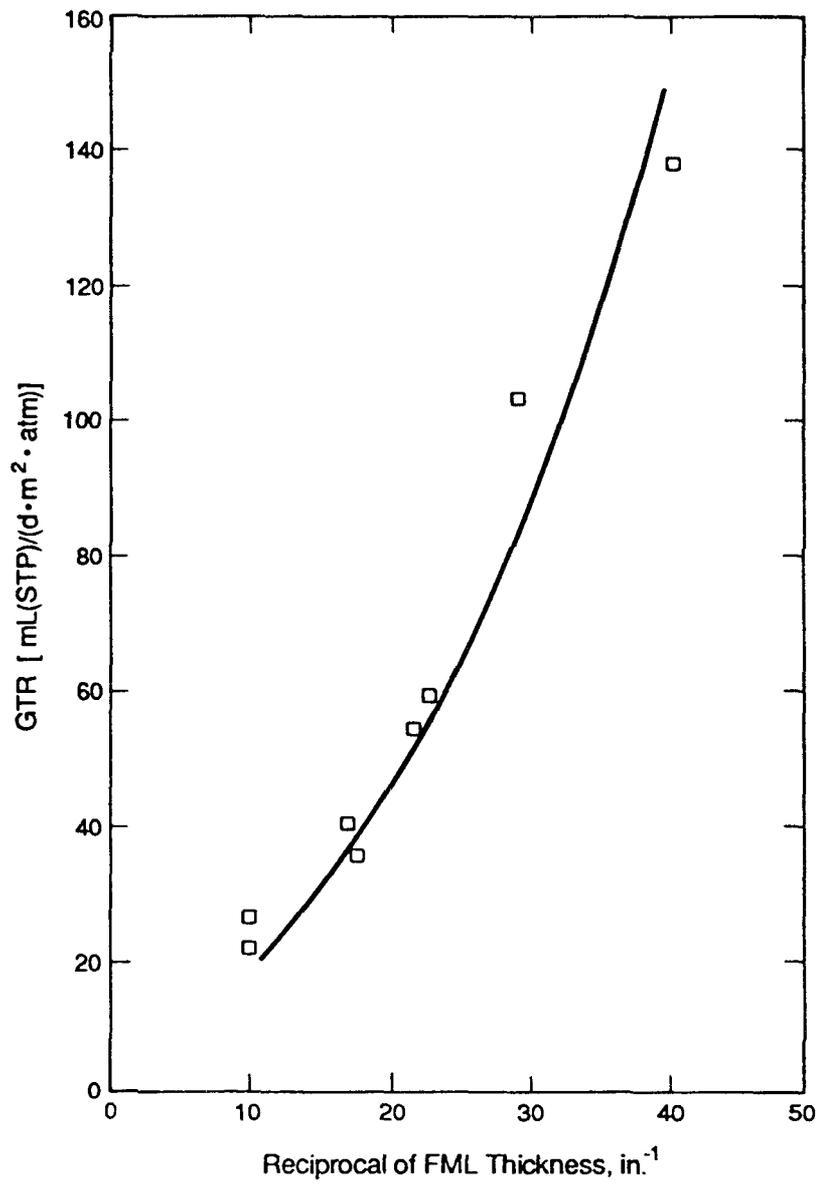


Figure 4-21. Gas transmission rate of methane at 23°C through HDPE vs reciprocal of FML thickness.

affect certain mechanical properties as measured by specific test methods. Specifically, this subsection discusses:

- The effect of temperature on properties.
- The effect of rate of deformation on puncture resistance.
- The effect of thickness on puncture resistance.
- The effect of lubrication on puncture resistance.
- Multiaxial stress-strain behavior of FMLs and comparison with uniaxial stress-strain behavior.

Effect of Temperature on Properties. As indicated in the general discussion on polymers, the characteristics of these materials are generally more sensitive to temperature than the more conventional materials of construction. The flexible type of polymeric compositions, such as the FMLs used in the construction of waste storage and disposal facilities, are particularly sensitive to temperature. FMLs, which generally contain carbon black as protection to UV light, can often reach 60-80°C (140°-160°F) in hot weather during installation and service. Furthermore, most polymeric FMLs are thermoplastic and, consequently, can lose considerable strength and stiffness at such temperatures. With FMLs of some polymers, particularly those of CSPE, the loss of strength and modulus is so great that it is necessary to use fabric reinforcement. At elevated temperatures and during direct exposure to sunlight, there can be considerable creep in an FML and thinning where it is stretched over sharp points, e.g. rocks and stones. Care must be taken through proper design to minimize the occurrence of such damage during installation and in service. The strength and other properties of an FML at these temperatures can be important factors in its proper installation.

In two separate studies performed by Matrecon, the tear resistance and tensile properties of 15 FMLs were tested at elevated temperatures. In the first study, five different HDPE FMLs were tested at room temperature and at 40°, 60°, and 80°C. In the second study, 10 unreinforced thermoplastic FMLs were tested at room temperature and at 60°C. These 10 FMLs included three CPE, one CSPE, four PVC, and two PVC-OR FMLs.

In the first study, five HDPE FMLs were tested at room temperature and at three elevated temperatures. Three of these FMLs were received from one supplier and two from a second supplier. FMLs from foreign and domestic productions were received from both suppliers, as is shown below:

<u>Nominal thickness, mil</u>	<u>Matrecon liner number</u>	<u>Supplier</u>	<u>Source</u>
30	269	A	Domestic
60	185	A	Foreign
70	266	A	Domestic
90	262	B	Domestic
100	288	B	Foreign

Tensile properties of the HDPE FMLs were measured in accordance with ASTM D638 at a jaw separation speed of 2 ipm using ASTM D638 Type IV dumbbells. Modulus of elasticity was measured in accordance with ASTM D882 using 1/2-in. wide strips at an initial jaw separation of 2 in. and a speed of 0.2 ipm (inches per minute), i.e. with an initial strain rate of 0.1 in. in.⁻¹ min.⁻¹, which is specified in the test method. Using specimens of sufficient size to be tested with an initial jaw separation of 10.0 in. as specified by ASTM D882, would have resulted in higher test values. The smaller test specimen size was used because it was easier to handle in the high temperature chamber. Tear resistance was measured in accordance with ASTM D1004, which specifies a specimen size identical to Die C from ASTM D624, at 2 ipm.

The results of the tests are presented in Table 4-14. The tensile and elongation at yield, the modulus of elasticity, and the elongation at break are presented graphically, as a function of temperature, in Figures 4-22 and 4-23.

The tensile strength at yield, tear resistance, and modulus of elasticity values of all five HDPE FMLs decreased in a similar fashion as the test temperature increased. The differences in thickness of the five FMLs did not affect the rates of change with temperature. Of the properties tested, the modulus of elasticity was affected the most, decreasing the most with the temperature increase up to 60°C (140°F). At 80°C (176°F), the rates of change appeared to decrease and to level off between 60° and 80°C (140° and 176°F). The values would all approach zero as the temperature approaches the respective melting points of the HDPE FMLs.

In the second study, 10 unreinforced thermoplastic FMLs were tested at room temperature and at 60°C. These FMLs included:

<u>Polymer</u>	<u>Matrecon FML number</u>	<u>Nominal thickness, mil</u>
CPE	142	30
	145	30
	154	27
CSPE	148	30
PVC	143	30
	146	30
	153	30
	155	30
PVC-OR	144	30
	150	30

Tensile testing was performed in accordance with ASTM D638 at a jaw separation rate of 20 ipm using a dumbbell specimen size that featured smaller tab ends and a shorter overall length than the ASTM D638 Type IV specimen. Tear resistance was measured in accordance with ASTM D1004 at 20 ipm.

TABLE 4-14. PROPERTIES OF HDPE FMLS OF VARIOUS NOMINAL THICKNESSES AT DIFFERENT TEMPERATURES

Property	Direction of test	Thickness and test temperature																			
		30 mil, No. 269 ^a				60 mil, No. 185 ^a				70 mil, No. 266 ^a				90 mil, No. 262 ^a				100 mil, No. 288 ^a			
		23°C	40°C	60°C	80°C ^b	23°C	40°C	60°C	80°C ^b	23°C	40°C	60°C	80°C ^b	23°C	40°C	60°C	80°C ^b	23°C	40°C	60°C	80°C ^b
Tensile at yield, psi	Machine	2650	2095	1355	1285	3045	2740	1855	1505	2675	2170	1355	1175	3080	2445	1580	1550	2705	2270	1625	1290
	Transverse	2875	2305	1575	1175	3225	2835	1990	1490	2690	2160	1325	1185	3175	2435	1630	1510	2700	2235	1660	1245
Elongation at yield, %	Machine	20	20	24	^c	15	17	21	24	20	19	21	25	18	19	18	23	17	18	19	19
	Transverse	10	18	22	28	15	16	19	22	20	18	20	24	18	20	19	24	15	17	21	21
Tensile at break, psi	Machine	4065	4510	3810	...	3405	3475	2540	...	4365	4235	3620	...	3920	3865	3195	...	3530	3465	2625	...
	Transverse	4225	5080	3985	...	2940	3270	2560	...	4285	4285	3635	...	3845	3765	3275	...	4065	3905	2660	...
Elongation at break, %	Machine	760	930	1080	...	885	1050	1240	...	815	965	1110	...	845	955	1160	...	785	930	1170	...
	Transverse	755	945	1035	...	760	965	1140	...	785	890	1075	...	815	950	1145	...	860	1045	1235	...
Set after break, %	Machine	660	825	935	...	785	960	1150	...	690	855	975	...	750	855	1030	...	680	800	1035	...
	Transverse	650	840	915	...	665	865	1065	...	695	790	910	...	720	840	1035	...	750	925	1095	...
Stress at 100% elongation, psi	Machine	2065	1890	1340	1240	1945	1835	1360	1185	1875	1625	1180	1140	1995	1695	1220	1260	1930	1665	1290	1095
	Transverse	2005	1675	1250	1130	1990	1800	1380	1130	1880	1565	1205	1115	2080	1645	1270	1185	1945	1645	1285	1105
Stress at 200% elongation, psi	Machine	2120	1720	1290	1190	1950	1825	1260	1165	1875	1620	1175	1080	1995	1675	1205	1225	1930	1660	1260	1080
	Transverse	2065	1720	1225	1050	1970	1825	1335	1110	1880	1570	1150	1105	2050	1645	1260	1180	1940	1635	1275	1085
Modulus of elasticity, 10 ⁴ psi	Machine	8.01	5.80	3.05	2.17	11.8	7.95	3.76	3.17	9.89	5.40	3.04	2.68	11.2	6.34	4.15	3.04	8.69	5.74	3.34	3.20
	Transverse	8.97	5.92	3.18	2.60	11.8	8.89	3.62	3.44	9.57	6.16	3.13	2.36	10.9	5.58	3.30	2.43	8.20	5.91	3.09	2.90
Tear resistance, ppi	Machine	790	675	555	...	855	770	595	...	785	685	565	...	900	765	610	...	900	765	615	...
	Transverse	795	655	540	...	890	770	610	...	780	680	540	...	895	750	600	...	885	755	605	...

^aMatrecon liner number.^bSpecimens tested at 80°C were extended only to 200% elongation due to the limited size of the temperature chamber which prevented the specimens from being extended all the way to break.^cExact point of yield difficult to determine because stress-strain curve revealed a plateau and not a peak.

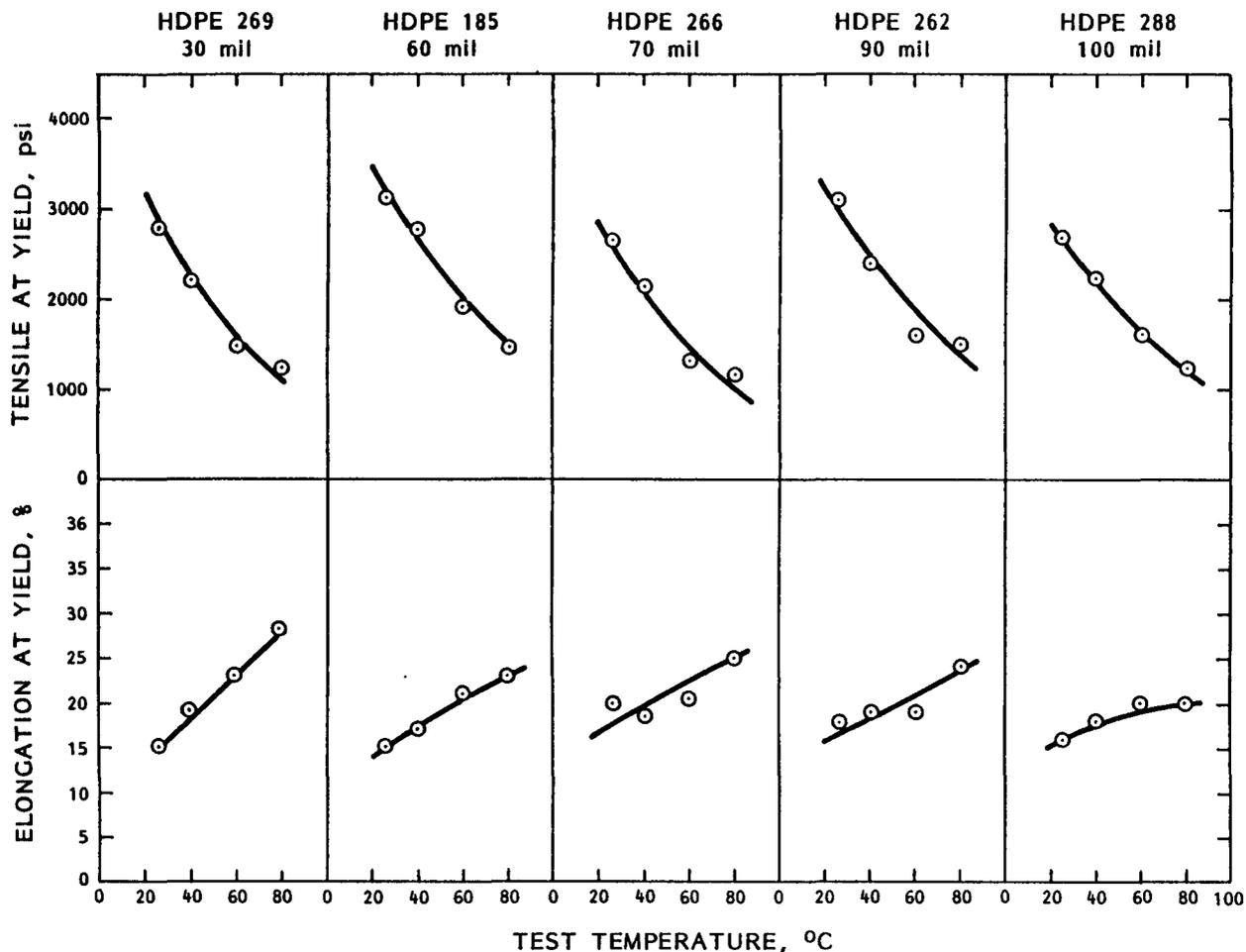


Figure 4-22. Tensile at yield and elongation at yield of five HDPE FMLs of 30 to 100 mil thickness tested at 23° to 80°C (73° to 176°F). Specific gravity of respective HDPE FMLs, not corrected for carbon black content, were 30 mil (269) 0.953; 60 mil (185) 0.961; 70 mil (266) 0.955; 90 mil (262) 0.954; 100 mil (288) 0.943.

Data from testing the unreinforced thermoplastic FMLs at 23°C (73°F) and 60°C (140°F) are presented in Table 4-15.

The CPE and CSPE FMLs were severely affected by the elevated temperature; at 60°C, they retained approximately 10-25% of their room temperature strength. During extension at 60°C, the CPE and CSPE FMLs underwent plastic flow and thinning. At 60°C, the PVC and PVC-OR FMLs retained, 60-70% of their respective room temperature strength.

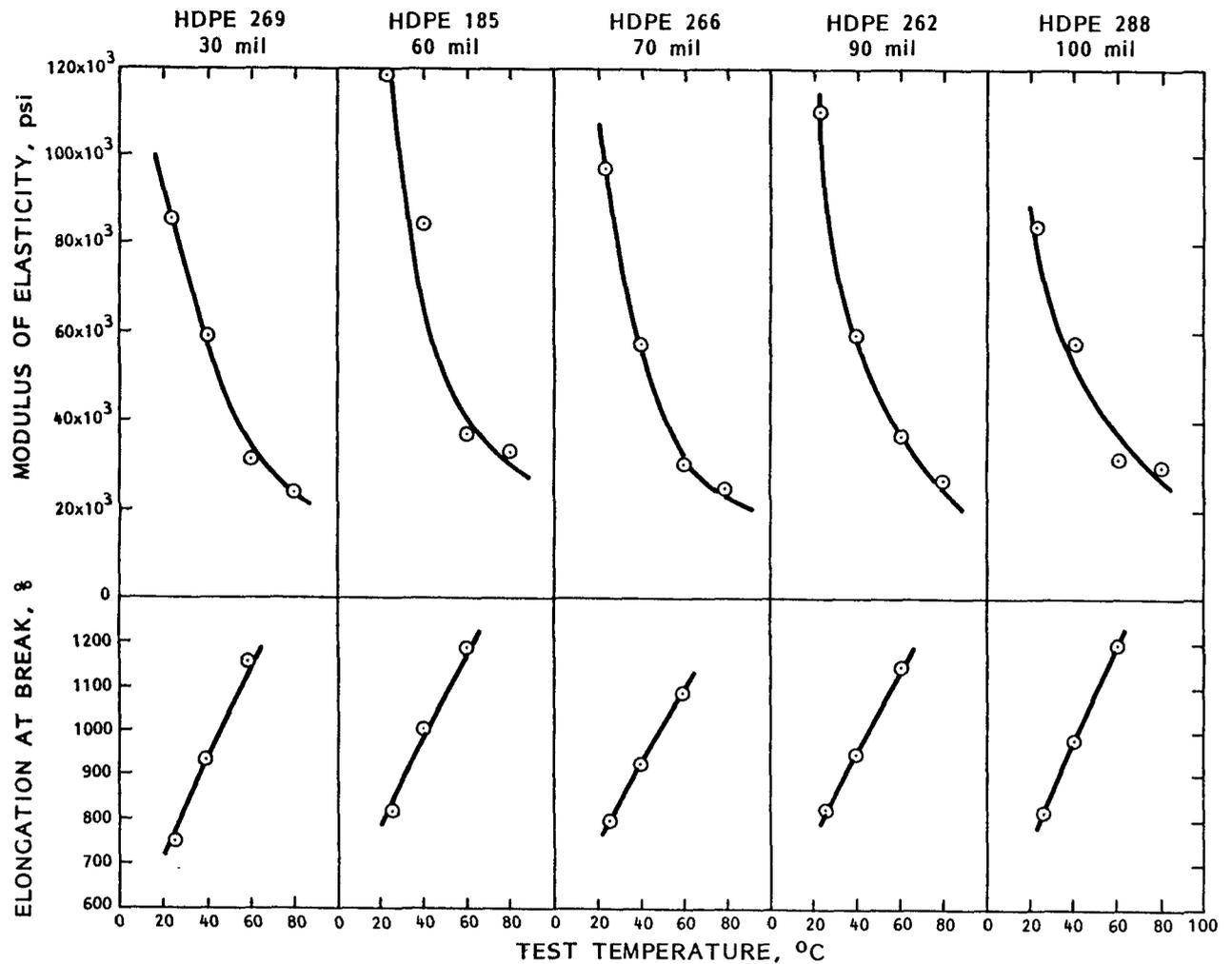


Figure 4-23. Modulus of elasticity and elongation at break of five HDPE FMLs of 30 to 100 mil thickness tested at 23° to 80°C (73° to 176°F).

The elongation at break of these FMLs were substantially higher at 60°C (140°F) than they were at room temperature. With the exception of the CPE FMLs, which showed approximately 200% retention of the values for elongation at break at 23°C (73°F), the elongation at break retention values for the thermoplastics were similar to the retention values for the HDPE FMLs, i.e. in the order of 140-150%.

Effect of Rate of Deformation on Puncture Resistance. Maintaining the integrity of an FML during installation and in service is essential for the proper functioning of a liner. During installation the FML can be punctured

TABLE 4-15. PROPERTIES OF THERMOPLASTIC FMLS AT DIFFERENT TEMPERATURES

Property	Direction of test	CPE				CSPE				PVC						PVC-OR					
		27 mil, No. 154 ^a		30 mil, No. 142 ^a		30 mil, No. 145 ^a		30 mil, No. 148 ^a		30 mil, No. 143 ^a		30 mil, No. 146 ^a		30 mil, No. 153 ^a		34 mil, No. 155 ^a		30 mil, No. 144 ^a		30-mil, No. 150 ^a	
		23°C	60°C	23°C	60°C	23°C	60°C	23°C	60°C	23°C	60°C	23°C	60°C	23°C	60°C	23°C	60°C	23°C	60°C	23°C	60°C
Tensile at break, psi	Machine	2395	b,c	2165	285 ^c	2350	315 ^c	1275	335 ^c	2865	1770	3240	1980	2765	1740	2860	1835	2655	1625	3425	1905
	Transverse	2200	b,c	1990	b,c	2250	b,c	1210	190	2620	1585	2990	1980	274	1980	2540	1740	2275	1340	3090	2110
Elongation at break, %	Machine	440	>900 ^b	350	800	410	835	360	410	340	510	320	440	290	410	315	460	365	490	275	365
	Transverse	485	>900 ^b	470	>900 ^b	515	>900 ^b	585	900	360	550	360	585	350	510	335	515	355	550	395	540
Set after break, %	Machine	220	b	125	215	215	285	135	55	95	115	75	90	65	70	75	95	75	105	30	50
	Transverse	200	b	120	b	190	...	250	200	110	135	95	135	105	115	80	120	70	115	75	145
Stress at 100% elongation, psi	Machine	905	305	1040	305	1340	365	1120	360	1470	540	1680	660	1600	665	1495	585	1235	480	2110	885
	Transverse	605	210	465	140	670	190	620	150	1315	470	1490	500	2410	570	1315	520	1085	385	1515	540
Stress at 200% elongation, psi	Machine	1240	350	1445	340	1620	380	1240	355	2065	815	2405	1040	1800	735	2250	1055	2120	915	2975	1405
	Transverse	875	205	710	130	990	170	745	165	1820	675	2080	755	1560	570	1965	870	1835	735	2080	840
Tear resistance, ppi	Machine	230	130	190	130	245	150	295	115	370	195	380	235	325	175	375	205	345	190	420	220
	Transverse	215	100	195	80	230	115	255	100	335	205	350	225	275	170	345	205	345	190	350	205

^aMatrecon liner number.

^bThe limited size of the elevated-temperature chamber prevented the test specimens from being stretched all the way to break.

^cIn the process of being extended at 60°C, the thermoplastic CPE and CSPE FMLs underwent plastic flow and thinning. Consequently, maximum tensile strength occurred before break. Maximum tensile strength values and the recorded elongation values at the maximum tensile values are as follows:

		Maximum tensile strength, psi	Elongation at maximum tensile strength, %
CPE (154)	Machine	440	ca 400
	Transverse	>245	>900
CPE (142)	Machine	420	ca 400
	Transverse	195	ca 100
CPE (145)	Machine	390	ca 425
	Transverse	145	<100
CSPE (148)	Machine	360	ca 125
	Transverse	<-----same as break----->	

Note: CPE Liner No. 154 went through a maximum at approximately 100% elongation.

by the accidental dropping of tools, by machinery, or by other equipment. Once a hole is made, it is difficult to detect as the FML is often black and may be soiled during installation. Puncturing may also take place during placement of a soil cover on the FML because of falling rocks and other sharp objects and, once the FML is covered, the holes are not visible. Once in service, the FML may be penetrated or punctured slowly from the load placed on the FML or from hydraulic pressure when the FML bridges a small cavity. Uncovered FMLs may be subjected to traffic damage and possibly to damage by animals, such as from deer hooves, rodent burrows, and birds. Consequently, high resistance to puncture is an important property of FMLs, especially because of the difficulties involved in detecting holes and repairing in-place liners.

Since FMLs are viscoelastic, the rate of deformation can have a significant effect on the force required to puncture them. The effect of the rate of deformation on puncture resistance test results was studied by Matrecon. Testing was performed in accordance with FTMS 101C, Method 2065, which is described in Section 4.2.2.5.2. In this procedure, a 0.5-in. diameter probe with one end tapered to a 0.125-in. radius penetrates a 2-in.-sq test specimen that is confined between two plates through which a 1-in. diameter hole has been drilled.

Figure 4-24 presents the results of testing both an unreinforced thermo-plastic FML (30-mil PVC 137) and an unreinforced crosslinked FML (45-mil EPDM 166) at 0.2, 0.5, 1.0, 2.0, and 20 ipm. The range of the test results at each speed of deformation is indicated by the use of bars. These results show that a slower rate of puncture will result in a slightly lower puncture resistance value for these types of FMLs.

Because of the known susceptibility of semicrystalline materials to test speed, two different HDPE FMLs produced by the same manufacturer at 0.2, 0.5, 1.0, 2.0, 5.0, and 20 ipm were also tested. One was 35 mils in thickness, and the second was 85 mils in thickness. These results are presented in Figure 4-25. The range of test results for each speed of test is indicated by the use of bars. The results show a somewhat greater susceptibility to speed in comparison with the results of testing the crosslinked and thermo-plastic sheetings, particularly with the thicker sheeting. It should be noted that the values reported for puncture testing are absolute values and no corrections for variations in thickness are made. Some of the variability in test results is caused by variations in the thickness of the tested specimen.

The results of this testing indicate that:

- The rate of deformation affects the amount of force required to puncture an FML.
- The crosslinked, the thermoplastic, and the semicrystalline FMLs tested had a log-linear relationship between rate of test and maximum force. The slope of this relationship was dependent on both the thickness and the composition of the FML.

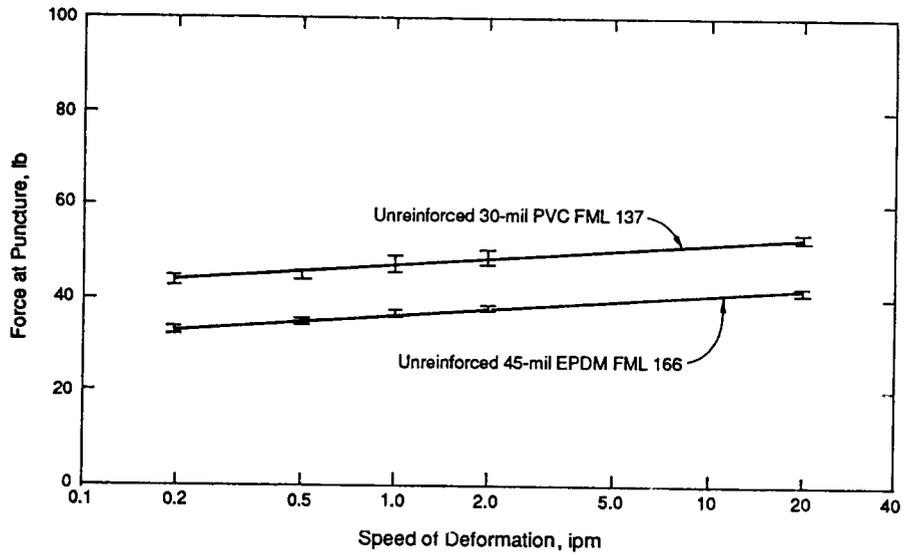


Figure 4-24. Force at puncture (FTMS 101C, Method 2065) vs speed of deformation of two unreinforced FMLs.

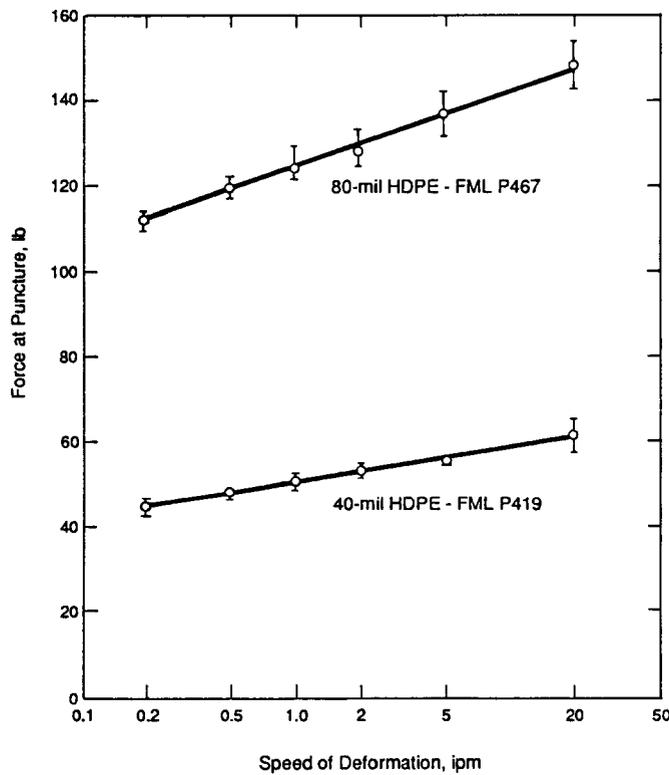


Figure 4-25. Force at puncture (FTMS 101C, Method 2065) vs speed of deformation for two different thicknesses of HDPE FML produced by the same manufacturer.

Effect of Thickness on Puncture Resistance. Another important variable that affects the puncture resistance of an FML is its thickness. This variable was investigated by determining the puncture resistance of a series of HDPE FMLs of different thicknesses that had been produced by the same manufacturer. These thicknesses ranged from 22 to 112 mils. The results are presented in Figure 4-26, which shows an almost linear relationship between force at puncture and thickness.

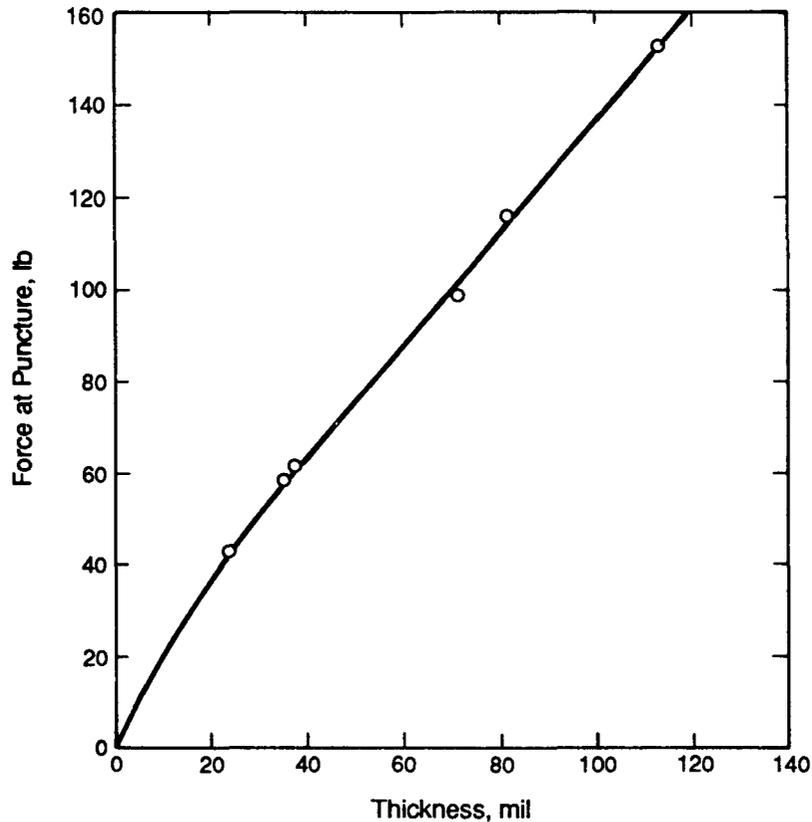


Figure 4-26. Force at puncture (FTMS 101C, Method 2065) vs thickness of test specimen for six different HDPE FMLs produced by the same manufacturer.

Effect of Lubrication on Puncture Resistance. FMLs in service are normally damp or wet on both surfaces, under which condition they are more likely to be punctured. Two studies of the effect of lubricating the probe used to puncture test specimens on puncture resistance, as measured in accordance with FTMS 101C, Method 2065, were performed by Matrecon. In the first study, two HDPE FMLs (Nos. 358 and 359) were tested. These FMLs were produced by different manufacturers and were of different thicknesses. The probe was lubricated with either SAE 30 oil or castor oil. The results of testing these FMLs with and without lubrication are compared in Table 4-16. The lubrication caused a 6-8% loss of maximum force, which in the case of these FMLs was the force at yield. Lubrication probably did not affect deformation at the initial yield. The force and deformation at puncture values showed somewhat more significant losses.

In the second study, the combined effect of lubrication and speed of test were investigated. A 40-mil FML (HDPE 419) was tested at two different speeds, 2 and 20 ipm, with the probe lubricated with either glycerine, castor oil, or SAE 30 oil. The results are presented in Table 4-17. As in the previous study, lubrication caused losses in maximum force and in force and deformation at puncture. In addition, deformation at initial yield appeared to be affected. Lubrication had more of an effect on the 20 ipm testing than the 2 ipm testing, as can be seen in Figure 4-27.

TABLE 4-16. THE EFFECT OF LUBRICATING THE TIP OF THE PROBE WITH SAE 30 OIL AND CASTOR OIL ON THE PUNCTURE RESISTANCE^a OF TWO HDPE FMLS

Measurement	FML number					
	358			359		
	None	SAE 30	Castor oil	None	SAE 30	Castor oil
Thickness, mil	89.3	89.4	89.6	102.2	101.5	101.8
Maximum force ^b , lb	141.0	133.2	129.2	170.2	157.7	157.4
Deformation at maximum force, in.	0.28	0.27	0.27	0.28	0.27	0.26
Force at puncture, lb	129.2	106.4	96.1	139.3	113.2	104.6
Deformation at puncture, in.	0.62	0.56	0.54	0.60	0.52	0.51

^aMeasured in accordance with FTMS 101C, Method 2065. All results are averages for five test specimens.

^bMaximum force occurred at initial yield.

Multiaxial Strain-Stress Behavior of FMLs. Tensile and tear property testing are often performed as if they can give some indication of the strength of an FML in the field where it is subjected to stresses in three dimensions. Data on tensile and tear properties that are usually reported and used in specifications for FMLs are obtained in tests run in only one direction at a time. If there is a grain introduced during manufacture, the FML is tested in both the machine and transverse directions. This type of test is satisfactory for amorphous thermoplastic materials. However, the stress-strain behavior of semicrystalline FMLs or FMLs which crystallize on stretching when deformed simultaneously in two or three directions is very different from the stress-strain behavior of these materials when deformed in only one direction.

To assess multiaxial tensile properties of FMLs, Steffen (1984) constructed the testing device shown in Figure 4-28. This device, which is a

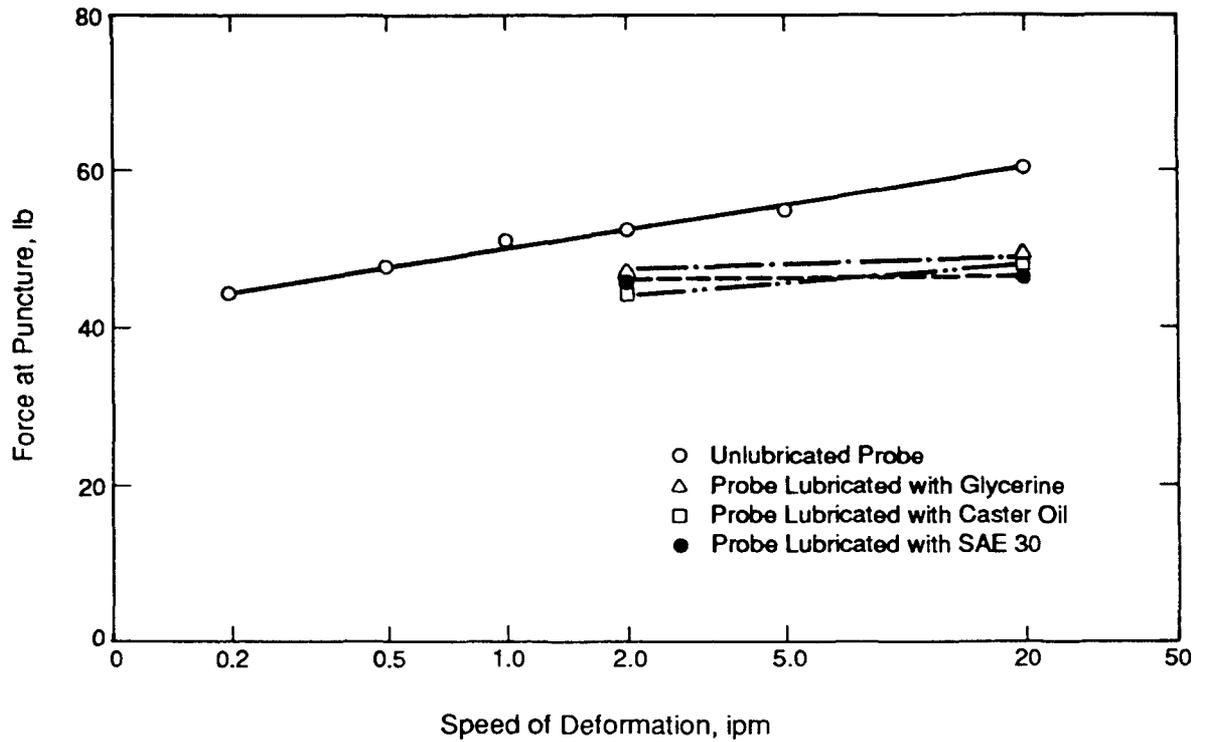


Figure 4-27. Effect of lubricating the probe on puncture resistance of 40-mil HDPE FML (No. 419) at different speeds of deformation. Puncture resistance measured in accordance with FTMS 101C, Method 2065.

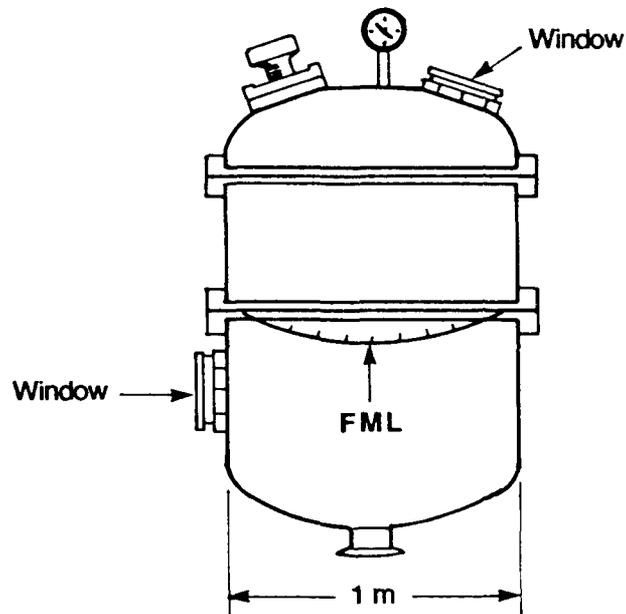


Figure 4-28. Pressure vessel device for three-dimensional stress-strain tests; diameter of vessel is 1 m. (Based on Steffen, 1984, p 181).

TABLE 4-17. COMBINED EFFECTS OF LUBRICATION OF THE PROBE AND THE SPEED OF DEFORMATION ON THE PUNCTURE RESISTANCE^a OF A 40-MIL PE FML (NO. 419)

Measurement	Test speed, ipm							
	2				20			
	None	Glyc- erine	Castor oil	SAE 50	None	Glyc- erine	Castor oil	SAE 50
Thickness, mil	34.8	34.8	35.3	36.0	35.7	36.0	36.3	35.8
Maximum force, lb	52.1 ^b	47.4 ^c	43.4 ^d	46.0 ^d	59.5 ^b	48.3 ^d	47.0 ^d	46.1 ^d
Deformation at initial yield, in.	0.29	0.24	0.23	0.24	0.27	0.23	0.23	0.24
Force at puncture, lb	47.5	47.4	35.1	40.5	54.9	43.9	37.9	42.1
Deformation at puncture, in.	0.72	0.63	0.44	0.52	0.78	0.54	0.45	0.53

^aMeasured in accordance with FTMS 101C, Method 2065. All results are averages.

^bMaximum force occurred at secondary yield, i.e. when a second area which was being deformed by the probe began to yield.

^cMaximum force occurred at puncture.

^dMaximum force occurred at initial yield.

1 m diameter pressure vessel, can perform bursting tests on circular specimens 1 m in diameter which may or may not include a seam. The FML specimen is fixed in the pressure vessel between the lower and the middle section. The specimen is loaded with pressure from the upper side, and deformation of the specimen and pressure are measured. It was found that the deformation line approximates the form of a section of a ball. The strain and stress for the different stages of the tests are calculated. Normally the test is continued up to the bursting point.

Figure 4-29 presents the results of testing 9 different FMLs. The thicknesses of the FMLs are included in the figure so that the stress values for these materials can be corrected for thickness. The materials tested included two HDPE FMLs, one PVC, one EPDM, two rubber-modified bitumens [i.e. one standard ethylene copolymer with bitumen (ECB) material and one modified ECB], a bituminous FML reinforced with both a net and polyester film (BIT), and one butyl (IIR) FML.

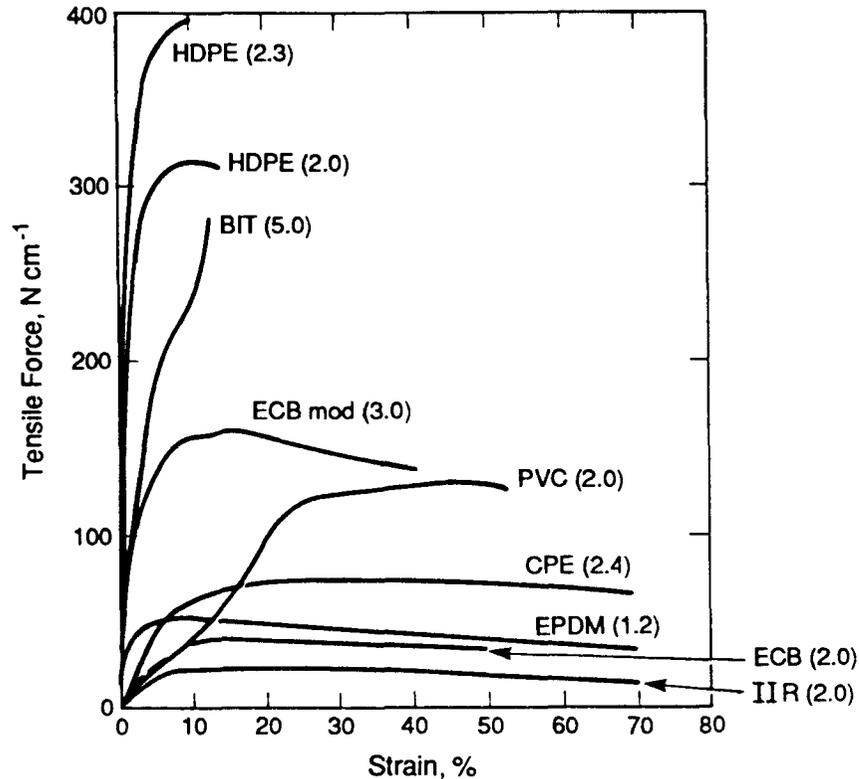


Figure 4-29. Results of three-dimensional stress-strain testing of nine FMLs. Numbers in parentheses indicate FML thickness in mm. (Based on Steffen, 1984, p 182).

The results presented in Figure 4-29 show that the two PE FMLs failed at a strain of 9 and 15%, respectively. Note: Some reviewers indicated that these values are abnormally low for HDPE. These strain results are approximately 1 to 2% of the strain at breaks that are usually obtained in uniaxial stress-strain tests and approximately 50% of the strain at the tensile yield point results. These results differ greatly from the strain at break values reported by manufacturers of HDPE FMLs. These low values for strain at failure resulting from multiaxial testing seem to be at least one of the reasons for failure of some HDPE FMLs in practice. However, the differences between the breaking loads in uniaxial tests and in triaxial tests are not so great.

FMLs that did not contain any crystallinity failed at a lower load and at a higher strain than the HDPE FMLs. For these materials, the difference between the strain at failure in uniaxial testing and those in triaxial testing is not as large. The strain values in the triaxial tests are approximately 10% of those in the uniaxial tests.

Failure of the HDPE FMLs occurred in a small area either after a high elongation in this area or with a spontaneous break. The FMLs without any

crystallinity usually failed after a high elongation in wide areas of the test specimen. To find the correlation between the thickness of an FML and the strain at failure, tests were made of three different thicknesses of HDPE FMLs, all of which were of the same composition. Thicknesses ranged from 1.6 mm to 2.7 mm (63 to 106 mils). The results are shown in Figure 4-30. The 1.68-mm FML has a strain at failure of 7.4%, the 2.10-mm FML a strain at failure of 10.2%, and the 2.70-mm FML a strain at failure of 12.4%. These results show that the thickness of an HDPE FML affects how much it can deform without failure.

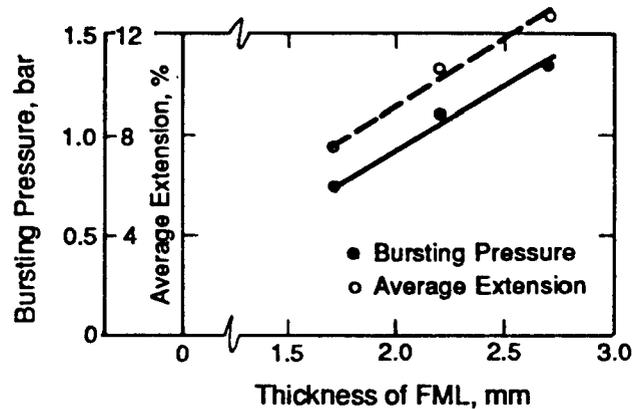


Figure 4-30. Relationship between thickness of FML and pressure and strain at failure for three different FMLs of the same composition. (Based on Steffen, 1984, p 183).

4.2.2.4.3 Chemical properties--The resistance of an FML to various chemicals determines how the FML will interact with a waste liquid. Most FMLs will absorb constituents of waste liquids and swell during exposure to liquids containing organics, though some shrink; for example, highly plasticized FML compositions, such as PVC FMLs, can lose plasticizer and other components and shrink. These two processes can take place simultaneously so that, in the case of plasticized compositions, the plasticizer can be extracted and, simultaneously, the organic constituents in a waste liquid can be absorbed and result in either a net swelling or loss.

Absorption of water and organics in the waste liquid by an FML and the resultant swelling can cause deterioration of many physical properties. When the physical properties of an FML have deteriorated on exposure to a waste liquid, it is likely that there has also been swelling. However, physical properties of FMLs other than tensile strength, elongation at break, tear resistance, puncture resistance, and permeability can be affected by organics and waste liquids without showing much swelling. Of particular importance are the effects on semicrystalline FMLs which can, under simultaneous exposure to waste liquids and mechanical stress, be subject to environmental stress-cracking (ESC) and rupture. This type of failure can be minimized by controlling molecular weight (MW) and MW distribution.

The chemical properties of an FML that affect the magnitude of its swelling in a liquid include the following:

- Solubility parameters of the polymer with respect to those of constituents of the liquid.
- Crosslinking of the polymer.
- Crystallinity content of the polymer.
- Filler content of the compound.
- Plasticizer content of the compound.
- Soluble constituents in the compound.
- Molecular weight and MW distribution.

Due to differences in polymers and in compounding, some of these properties do not apply or are not important for every FML.

For rubber and noncrystalline or amorphous polymers, the solubility parameters are probably the most important factor in swelling and are used by polymer scientists to measure the compatibility of an amorphous polymeric composition with a liquid with which it may be in contact.

Crosslinking of a noncrystalline polymer or a rubber reduces its ability to swell in a liquid which has solubility parameters similar to those of the polymer. The amount of swelling of a crosslinked polymer in a good solvent for the raw polymer can be used as a measure of the degree of crosslinking: the greater the crosslinking, the less the swelling.

Crystallinity of a polymer acts much like crosslinking to reduce the ability of a polymer to dissolve. The crystalline domains of most polymers do not readily absorb organics at normal ambient temperatures. Highly crystalline polymers, such as HDPE, will swell slightly in gasoline but will not dissolve, even though they are both hydrocarbons.

Two additional factors in FML compositions that also can affect the magnitude of swelling of noncrystalline polymers are the amount of particulate filler used in the compound recipe, e.g. carbon black, silica, or clay, and the amount of plasticizer. As with the crystalline domains in semi-crystalline polymers, nonporous particulate fillers such as those listed do not absorb organics. In the case of plasticizers, they are generally extractable by organic solvents, and most are only slightly extractable by water.

Rubber and plastic compounds may contain minor amounts of water-soluble inorganic salts which enter the compound via the polymer itself, e.g. catalyst traces, salt used in flocculation, etc., and via small amounts in the various compounding ingredients, e.g. many of the non-black fillers contain

small amounts of water-soluble constituents. These water-soluble salts can cause swelling by diffusion of water into the mass by the driving force of osmosis.

Solubility parameters have found wide use in determining the solubility of polymeric materials in various organics. Some of the many applications are reviewed by Barton (1975). Also of particular interest are the uses of these parameters in studying the plasticization of polymers, in preparing rubber blends, and in designing rubber and plastic compositions for contact with various oils, hydraulic fluids, and gasoline (Beerbower et al, 1963 and 1967).

The Hildebrand solubility parameter (δ_0) and cohesive energy density (CED) are concepts related by the following equation (Hildebrand and Scott, 1950, p 56):

$$\delta_0 = (\text{CED})^{1/2} = (\Delta E/V_m)^{1/2} , \quad (4-3)$$

where

ΔE = the energy required to vaporize one mole of material, and

V_m = the molar volume.

Thus, δ_0 is a measure of the potential energy of any material with respect to its energy in an entirely disassociated form and is free of any intermolecular interactions. Intuitively, two different organics of exactly equal potential energies should be mutually miscible in all proportions with no loss or gain of energy. This model of solubility, termed the solubility parameter model, was developed by Hildebrand (Hildebrand and Scott, 1950, p 119) and may be expressed by the equation:

$$\Delta E_{\text{mix}} = X_1 X_2 (\delta_1 - \delta_2)^2 , \quad (4-4)$$

where

ΔE_{mix} = the energy of mixing,

$X_{1,2}$ = the volume fractions of components 1 and 2, and

$\delta_{1,2}$ = the solubility parameters of components 1 and 2.

Clearly, the mathematical model agrees with intuition in concluding that equal solubility parameters imply no energy change on mixing.

The potential energy of organics may be simply expressed as δ , but is in fact a sum of energies due to several different types of molecular interaction. These include dipole-dipole interactions, London dispersion forces,

hydrogen-bonding effects, and at very close distances, repulsive effects. These energies are approximately additive (Hildebrand and Scott, 1950, p 56; Gardon and Teas, 1976, p 428; Hansen, 1967, p 104):

$$E_{\text{total}} = E_1 + E_2 + E_3 + \dots \quad (4-5)$$

From the relationship between δ and ΔE , it follows that:

$$\delta_{\text{total}}^2 = \delta_1^2 + \delta_2^2 + \delta_3^2 + \dots \quad (4-6)$$

Consideration of the individual contributions of the solubility parameter components becomes quite important in determining the solubility of complex systems such as polymers. These do not behave in the "ideal" manner assumed in construction of the solubility parameter model and consequently solubility is sensitive to variations in the component solubility parameters, not just the overall solubility parameters.

In order to properly describe the solubility of polymers, models more complex than Hildebrand's solubility parameter model are required. The most important model of this general form was proposed by Hansen (1967) and is termed the three-dimensional solubility parameter model. It is written as:

$$\delta_{\text{total}}^2 = \delta_d^2 + \delta_p^2 + \delta_h^2 \quad (4-7)$$

where

δ_{total} = total Hansen solubility parameter,

δ_d = the contribution to the total solubility parameter due to intermolecular London dispersion forces,

δ_p = the contribution due to intermolecular dipole interactions, and

δ_h = the contribution due to intermolecular hydrogen-bonding.

Approaches taken by various researchers are described in Beerbower et al (1963), Gardon and Teas (1976), and Van Krevelen and Hoftyzer (1976). Comprehensive tabulations of solubility parameters for common solvents and other organic chemicals have been made by Barton (1975 and 1983). A generally useful model will probably require parameters defining polymer crosslinking and crystallinity as well as polymer solubility parameters, and may well not be amenable to a simple graphic presentation.

To determine the solubility parameters of FMLs and the effect of various chemical properties on swelling, Haxo et al (1987b) determined equilibrium swelling of 28 FML-related polymeric compositions in 30 organics and DI

water. These 28 polymeric materials included thermoplastic, crosslinked, and semicrystalline compositions, of which 22 were commercial FMLs or sheetings and six were laboratory-prepared compositions. Within these 28 compositions, basic polymer and compound variations (such as polymer types, level of crystallinity, crosslink density, filler level, and amount and type of plasticizer) were included.

The 30 organics covered a wide range of Hildebrand solubility parameters as well as the component solubility parameters, i.e. the dispersive (δ_d), polarity (δ_p), and hydrogen-bonding (δ_h) components. The organics were selected by a computer program to cover the ranges of the component solubility parameters. Selection was made from a list of 131 organics for which solubility parameter data were available.

Equilibrium swelling was measured by weighing specimens of the polymeric compositions that had been immersed in the individual neat organics until there was essentially no change in weight. Each of the solubility parameters, including the Hildebrand and component parameters, were then calculated from the swelling data for each of the polymeric compositions through a computer program which generated the curve that best fit the data for that parameter. The results of these solubility parameter determinations are presented in Table 4-18.

The most significant results of this study were:

- The crystallinity of the polymer appeared to be the dominant factor in reducing the swelling of a polymeric composition in all of the organics and appeared to override both the crosslinking and the proximity of the solubility parameters.
- The crosslinking of an amorphous polymer reduced swelling in all of the organics compared with the uncrosslinked polymer. Increasing the crosslinking density reduced the swelling.

Note: The crystallinity and crosslinking factors are not additive. The introduction of crosslinking in semicrystalline polymeric compositions tends to reduce the amount of crystallinity.

Though the magnitude of swelling of amorphous polymers can, in many instances, be estimated from the proximity of the values of the component solubility parameters of the polymer and those of the organic, the swelling of the FML in many combinations can only be roughly estimated based on the type of organic. The matching of the Hildebrand solubility parameter values remains a necessary, but not sufficient condition for swelling. Swelling tests should be performed to ensure that an amorphous FML does not swell in a particular organic. Thus, empirically derived data are still needed for untested combinations of organics and FMLs.

TABLE 4-18. SOLUBILITY PARAMETER VALUES FOR FMLS AND OTHER POLYMERIC COMPOSITIONS^a

Polymer	Matrecon identification number	(cal/cm ³) ^{1/2}					
		δ_o^b	δ_d	δ_p	δ_h	δ_t^c	Δ^d
Chlorinated polyethylene	195	9.27	7.99	3.23	3.15	9.18	-0.09
	335R	9.39	9.23	2.06	2.50	9.78	+0.39
	378R	8.91	9.23	2.84	3.15	10.2	+1.29
Chlorosulfonated polyethylene	169R	9.52	9.13	0.93	2.60	9.54	-0.02
	174R	9.39	8.91	1.76	1.52	9.21	-0.18
	DOY-3 ^e	9.39	9.07	1.03	1.19	9.21	-0.18
	DOZ-2 ^e	9.27	9.18	1.91	1.38	9.48	+0.21
	DPO ^e	9.39	9.13	1.91	0.53	9.34	-0.05
	DPPE	9.39	9.13	1.96	1.09	9.40	+0.01
Epichlorohydrin rubber	178	11.35	9.23	5.00	4.56	11.45	+0.10
		11.35	9.23	5.54	4.56	11.69	+0.34
Ethylene propylene rubber	232	8.91	9.07	0.64	0.65	9.12	+0.21
Ethylene vinyl acetate	308A	9.39	8.96	0.88	0.98	9.06	-0.33
Neoprene	168	9.52	9.29	1.72	1.95	9.65	+0.13
Nitrile rubber	DPN ^e	10.49	9.02	2.50	3.58	10.02	-0.47
Polyester elastomer	316	10.61	8.91	2.06	5.32	10.58	-0.03
	323	11.35	8.91	4.02	4.12	10.61	-0.74
Polybutylene	221A	7.69	7.49	0.05	0.43	7.50	-0.18
Polyethylene: Low-density Linear low-density High-density	309A	7.81	9.45	0.05	0.11	9.45	+1.64
	284	8.17	9.02	0.05	0.43	9.03	+0.86
	184	7.44	9.29	0.05	0.65	9.31	+1.87
	263	7.93	8.05	0.05	0.98	8.11	+0.18
	305	7.56	8.50	0.05	0.54	8.52	+0.96
	181	7.69	9.07	0.15	0.76	9.10	+1.41
HDPE/EPDM-alloy	181	7.69	9.07	0.15	0.76	9.10	+1.41
Polyurethane	351	11.59	8.86	3.82	5.64	11.18	-1.63
Polyvinyl chloride	153	10.13	7.99	5.39	3.91	10.40	+0.27
	DPQ ^e	9.64	7.83	5.64	4.34	10.58	+0.94
Elasticized polyvinyl chloride	176R	9.76	9.34	4.26	3.47	10.84	+1.09
Polyvinyl chloride (oil-resistant)	144	9.64	7.88	4.41	4.23	9.97	+0.33

^aMore data for these FMLs are presented in Appendix F.

^b δ_o = Hildebrand solubility parameter.

^c δ_t = total Hansen solubility parameter = $\sqrt{\delta_d^2 + \delta_p^2 + \delta_h^2}$.

^d Δ = $\delta_t - \delta_o$.

^eLaboratory-prepared compound (see Appendix F, Tables F-11 and F-12).

Source: Haxo et al, 1987b, p 41.

4.2.2.4.4 Durability--Polymeric FMLs used to line hazardous waste storage and disposal facilities must be durable and maintain their integrity and performance characteristics over the designed life of the specific facility. Since the principal function of an FML is to prevent leakage and migration of the wastes and their constituents, low permeability to the contained materials must be maintained throughout the service life of the FML. Also, resistance to physical damage and the integrity of the seams must be maintained so that breaks, tears, and other holes in the liner system do not develop. Durability is important even during installation so that an effective barrier to waste migration can be achieved.

Ultimately, the service life of a given FML will depend on the intrinsic durability of the material and on the conditions under which it is exposed during service. Differences in composition and construction will cause FMLs to vary in their response to the exposure conditions which, even within a given facility, can differ greatly.

This subsection describes the ways in which polymeric compositions in FMLs can degrade, and the environmental factors that can cause degradation in these materials. These environmental factors are discussed in more detail in Chapter 5 by the specific type of impoundment. This subsection also briefly discusses ways of testing durability.

Intrinsic Durability of Polymeric FMLs. The intrinsic durability of an FML depends on the polymer, the auxiliary compounding ingredients, and the construction and manufacture of the sheeting.

All materials of construction are prone to deteriorate in service in some way and eventually become unserviceable. The mode of deterioration varies with the individual material and with the environment in which the material is exposed. The deterioration of polymeric compositions becomes apparent in one or more of the following ways:

- Softening and loss of physical properties due to polymer degradation by depolymerization and molecular scission. Some polymers can gel and crosslink to yield brittle materials.
- Stiffening, and embrittlement due to loss of plasticizer and other auxiliary ingredients.
- Loss of physical properties and increase in permeability due to swelling which, in the extreme case, results in dissolution.
- Failure of FML seams due to interaction with the waste liquids and due to stress on the seams.

Table 4-19 outlines the various degradation processes that might occur with FMLs in a service environment.

The principal agents aggressive to polymeric compositions are heat, oxygen, light, ozone, moisture, atmospheric NO₂ and SO₂, solvents, low temperatures, stress and strain, and enzymes and bacteria. All of these

TABLE 4-19. POTENTIAL DEGRADATION PROCESSES IN POLYMERIC FMLS DURING SERVICE

Process	Effect on FMLs
<u>In weather exposure^a</u>	
Oxidation	Stiffening, chalking, and crazing, causing losses in mechanical properties, e.g. tensile strength, elongation, tear; crosslinking and chain scission
Elevated temperature	Reduces mechanical strength and accelerates degradation, generally by stiffening on prolonged exposure; sometimes softens
Ozone	Cracks at points of strain
UV light	Stiffens and cracks
Loss of volatile plasticizer	Stiffens and can become brittle
High humidity	Water absorption, leaching of antidegradant resulting in greater susceptibility to oxidation and UV
<u>In waste exposure^b</u>	
Swelling	Softens and loses properties; increases in permeability
Dissolution (if solubility parameter of waste constituent equal that of FML)	Hole or general loss of barrier function
Extraction of plasticizer	May stiffen and lose elongation
Extraction of antidegradant	Make more susceptible to degradation
Mechanical stress	Creep of liner; cracking and breaking
<u>Interface of waste and weather</u>	Combination of weather and waste exposure often more severe than either alone
<u>Biodegradation, particularly if oxygen is present</u>	Plasticizers, oils, and monomeric organic molecules can be degraded

^aLiner exposed on either a berm or a slope.

^bLiner is either buried, covered, or below the waste/weather interface area.

Source: Haxo and Nelson, 1984b.

agents can be operative in the exposure of FMLs in service. In most situations two or more of these agents act together.

FMLs rarely encounter the temperatures that would cause polymer decomposition. Sometimes, however, the elevated temperatures involved in weathering and possibly in handling the impoundment contents might cause oxidative thermal degradation in the presence of oxygen.

Photodegradation is only encountered on weather-exposed surfaces. Most polymers are susceptible to degradation on exposure to ultraviolet light; however, the introduction of UV absorbers, such as carbon black and UV stabilizers, can greatly reduce and essentially eliminate this effect for extended periods of time.

Ozone can be particularly damaging and cause cracking in polymers that have unsaturation in their main chains. Ozone-cracking can only occur at points of strain of 15-25% or more. Of the polymers that have been used in FMLs, only butyl rubber and neoprene have unsaturation in their main chains and can crack due to ozone attack.

Polymeric compositions under constant or cyclic stress and strain can fatigue, lose mechanical strength, and crack. Cracks and breaks can occur in an FML under biaxial strain at significantly lower stress values than those encountered in uniaxial tensile tests. As is characteristic of all materials, polymers creep under stress, which can result in thinning and puncturing or rupturing of an FML. Environmental stress-cracking, a type of failure of some PEs, involves the cracking of a strained material in the presence of aggressive chemicals or such chemicals as detergents, silicone oils, petroleum oils, linseed oils, or organic acids (Howard, 1959).

Polymers are generally considered to be resistant to biodegradation, although some types are known to degrade (Schnabel, 1981). Oils, plasticizers, and possibly other monomeric type ingredients in compounds, however, are biodegradable in the presence of air and humidity. Their loss can result in stiffening and embrittlement of some compounds.

Though the mechanism is primarily physical, the swelling of a polymeric material by a solvent, including water, is considered a chemical attack on the material. Polymeric materials can vary greatly in their interaction with solvents. The solvents are absorbed without affecting the molecular weight of the polymer. They generally extract plasticizers and other ingredients that are soluble in the particular solvents. Also, it is possible that solvents can dissolve some of the polymers.

Environmental Factors Affecting FMLs in Service. The environment in which an FML must exist will ultimately determine its service life. Table 4-20 enumerates environmental factors that can affect the durability of polymeric liners in service. These environmental factors are discussed in detail in Chapter 5.

TABLE 4-20. ENVIRONMENTAL FACTORS AFFECTING
DURABILITY AND SERVICE LIFE

Compatibility factors with waste liquids:
Chemical
Physical
Combination of chemical and physical
Weathering factors - geographic location:
Solar radiation
Temperature
Elevated
Depressed
Cycles and fluctuations
Water -- solid, liquid and vapor
Normal air constituents, e.g. oxygen and ozone
Freeze-thaw and wind
Stress factors:
Mechanical stress, sustained and periodic
Stress, random
Physical action of rain, hail, sleet, and snow
Physical action of wind
Movement due to other factors, e.g. settlement
Discontinuity at penetrations
Burden, hydraulic head
Use and operational factors:
Design of system, groundwork and installation
Operational practice
Biological factors

Source: Haxo and Nelson, 1984b.

Service Life and Durability Testing. At the present time information exists on the outdoor exposure of polymeric materials (Strong, 1980) and methodologies are being developed for durability testing of materials that are exposed to weather, such as on the berms and slopes of uncovered impoundments and reservoirs. Rossiter and Mathey (1983) describe a methodology for predicting the service life of single ply roofing materials which, in many respects, may be applicable to FMLs exposed to the weather on berms and

slopes. Durability testing of materials by immersion or intermittent immersion in waste liquids for predicting service life, however, has not been fully developed.

Laboratory tests that do exist for assessing the durability of FMLs under different environmental conditions range from chemical analyses to tests of mechanical properties (e.g. tensile properties, tear resistance, puncture resistance, and impact resistance) after exposure to high and low temperatures, to ozone while under strain, to UV light, and to stress and strain for extended periods of time. Some of these tests are discussed below in the subsection, "Testing and Evaluation of FMLs."

A chemical compatibility-type test, EPA Method 9090, in which samples of lining materials are immersed has been developed (EPA, 1986). This test is discussed in more detail in Chapter 5. In this test the retention of selected properties are observed as a function of immersion time. This test, however, does not indicate the effect of immersion under strain and other mechanical stresses due to temperature cycling, soil settlement, etc.

Maximum changes in properties that can take place without affecting overall performance have not been established. Nevertheless, laboratory testing of several properties can yield data indicative of durability.

For the development of realistic laboratory tests that can predict the performance and durability of FMLs and components of liner systems in service knowledge is needed regarding actual performance and durability of these materials in service. Information with respect to the type of distresses and failures that these materials encounter in service is necessary to develop and select tests that correlate with service. However, comparatively little information of this type has become available in the public domain. Much dependence has been and is still being placed on the knowledge of the performance of FMLs and other components in applications and under service conditions that may be similar to those encountered in waste containment.

4.2.2.5 Testing and Laboratory Evaluation of FMLs--

Because of the wide range of compositions and differences in the construction of polymeric FMLs, different groups of index tests have been developed for different polymeric FMLs.

The methods used for testing a specific FML will depend on the type of FML being tested. Because sheetings used as FMLs have been developed by three different industries (rubber, plastics, and textile), there are three groups of standard index test methods. Some methods used to test one type of FML are inappropriate for other types; for example, using a dumbbell with a 1/4-in. restricted area, which is used to test rubber vulcanizates, is unsatisfactory for measuring the tensile properties of fabric-reinforced FMLs. From the point of view of testing, there are four types of polymeric FMLs:

- Thermoplastic or uncrosslinked polymeric FMLs (TP).
- Vulcanized or crosslinked elastomeric FMLs (XL).

- Semicrystalline thermoplastic polymeric FMLs (CX).
- Fabric-reinforced FMLs manufactured with either crosslinked or thermoplastic polymers.

The types of testing performed on an FML may depend on the reason for the testing. Before an FML is selected and purchased, the designer and/or site owner tests various FMLs to determine whether any meet the design requirements of the facility. These tests include a determination of the compatibility of the FMLs with the waste to be contained and assess their potential performance in service. Sheeting may also be tested to characterize or to "fingerprint" the material. The concept of fingerprinting is discussed in more detail in the following subsection. Testing a polymeric FML at the time of installation has three uses: (1) to assess the quality of the specific sheeting being placed at a site, (2) to determine if it is the same material that was prequalified during initial selection, and (3) to provide a baseline for assessing the effects of exposure on the FML. Testing samples during service can be performed to assess the performance or the condition of the FML and the seams. Eventually, correlations may be developed between simulation tests and field performance to yield tests that can effectively predict the field performance of an FML in a given situation.

During an exposure, a change in one property is usually accompanied by changes in other properties. No single property of an FML, however, has been correlated with the performance or failure of an FML in the field. Thus, a group of test methods is necessary to evaluate and characterize FMLs, especially in assessing the effects of exposure or service. These methods can be categorized into five groups:

- Analyses to fingerprint and assess composition.
- Tests of physical properties, including information regarding construction and dimensions of the membrane.
- Tests to assess permeability characteristics.
- Tests to determine properties in stress environments, including accelerated aging tests, tests in specific exposures, and compatibility tests; these include tests that assess the durability of FMLs under conditions that simulate actual field service.
- Performance tests to determine actual engineering properties of an FML that are needed for designing a liner system.

These analyses and tests can include measurements of the following properties:

- Analytical properties:
 - Volatiles.
 - Ash.

- Extractables.
- Gas chromatography.
- Pyrolysis gas chromatography.
- Infrared spectroscopy.
- Specific gravity.
- Thermogravimetric analysis.
- Differential scanning calorimetry (if FML is semicrystalline).
- Melt index (if FML is semicrystalline).
- Molecular weight (average) and molecular weight distribution.
- Physical properties:
 - Thickness.
 - Tensile properties.
 - Modulus of elasticity (if FML is semicrystalline).
 - Hardness.
 - Tear resistance.
 - Puncture resistance.
 - Hydrostatic resistance.
 - Strength of factory and field-prepared seams.
- Permeability characteristics:
 - Water vapor transmission (WVT).
 - Solvent vapor transmission (SVT).
 - Gas permeability.
 - Pouch test.
- Tests that measure environmental and aging effects:
 - Resistance to ozone-cracking.
 - Resistance to environmental stress-cracking (if FML is semi-crystalline).

- Low-temperature properties.
- High-temperature properties.
- Air-oven aging.
- Dimensional stability.
- Water absorption.
- Liner-waste compatibility testing.
- Soil burial.
- Pouch test.
- Outdoor exposure:
 - Exposure of test slabs.
 - Bent loops.
 - Exposure in tubs filled with a waste liquid.
 - Accelerated outdoor weathering using concentrated natural sunlight (ASTM Methods D4364 and G-90-EMMAQUA).
- Performance tests:
 - In-soil stress-strain tests.
 - In-soil creep tests.
 - Shear strength between FMLs and soils.
 - Anchorage or embedment depth of an FML.
 - Puncture (hydrostatic) resistance.

Performance of these tests are the basis of a testing protocol that can be used to characterize the properties of an FML and to assess the effects of environmental exposure. The subsequent paragraphs discuss these tests and how they can be used to evaluate polymeric FMLs. Selected properties of unexposed polymeric FMLs are presented in Appendix F.

4.2.2.5.1 Analytical properties of polymeric FMLs--Table 4-21 lists appropriate or applicable test methods for determining the analytical properties of FMLs. The results of determining the volatiles, extractables, ash content, and specific gravity of a group of unexposed polymeric FMLs are presented in Table 4-22.

TABLE 4-21. APPROPRIATE OR APPLICABLE METHODS FOR TESTING ANALYTICAL PROPERTIES OF POLYMERIC FMLS

Property	FML without fabric reinforcement			Fabric reinforced
	Thermoplastic	Crosslinked	Semicrystalline	
Volatiles	Appendix G	Appendix G	Appendix G	Appendix G (on selvage and reinforced sheeting)
Extractables	Appendix E	Appendix E	Appendix E	Appendix E (on selvage and reinforced sheeting)
Ash	ASTM D297, Section 34	ASTM D297, Section 34	ASTM D297, Section 34	ASTM D297, Section 34 (on selvage)
Specific gravity	ASTM D792, Method A	ASTM D297, Section 15	ASTM D792, Method A	ASTM D792, Method A (on selvage)
Thermal analysis:				
Differential scanning calorimetry (DSC)	na	na	yes	na
Thermogravimetry (TGA)	yes	yes	yes	yes
Melt index	na	na	ASTM D1238	na

na = Not applicable.

TABLE 4-22. ANALYSIS OF UNEXPOSED POLYMERIC FMLSA, b

Polymer	Base polymer, specific gravity ^c	Property			
		Specific gravity	Volatiles, %	Extract- ables, %	Ash, %
Butyl rubber	0.92	1.206	0.45	10.96	5.25
		1.176	0.46	11.79	4.28
Chlorinated polyethylene	1.16-1.26	1.360	0.10	7.47	14.40
		1.362	0.00	9.13	12.56
		1.377	0.05	6.02	17.37
Chlorosulfonated polyethylene	1.08	1.433	0.84	1.49	33.95
		1.343	0.51	3.77	3.28
Elasticized polyolefin	0.92	0.938	0.15	5.50	0.90
Epichlorohydrin rubber	1.27-1.36	1.490	0.63	7.27	4.49
Ethylene propylene rubber	0.86	1.173	0.38	23.41	6.78
		1.122	0.50	31.77	5.42
		1.199	0.31	18.16	0.32
Neoprene	1.25	1.503	0.76	10.15	12.98
		1.480	0.19	13.43	13.43
		1.390	0.37	21.46	4.67
Polybutylene	0.91	0.915	0.12	4.42	0.08
Polyester elastomer	1.17-1.25	1.236	0.26	2.74	0.38
Polyethylene (low-density)	0.92	0.921	0.18	2.07	0.13
Polyethylene (high-density)	0.96	0.961	0.12	≥0.60	0.46
Polyethylene (high- density) alloy	0.95	0.949	0.11	2.09	0.32
Polyvinyl chloride	1.40	1.275	0.11	33.90	6.20
		1.264	0.09	37.25	5.81
		1.231	0.05	38.91	3.65
		1.280	0.31	35.86	6.94
		1.308	0.03	25.17	5.67

^aSource of some of the data: Haxo et al, 1982.

^bEach line of data represents the results of testing one liner sample.
Multiple lines of data for a specific polymer type represents the
results of analyzing samples from different manufacturers.

^cBased on information supplied by the polymer manufacturers.

Volatiles. The volatile fraction is defined as the weight lost by an FML specimen on heating in a circulating air oven at 105°C for 2 hours. Polymeric compositions generally contain a small amount of volatiles (<1.0%), mostly absorbed moisture. A detailed description of the procedure for determining volatiles is presented in Appendix G. The recommended test specimen size is a 2-in. diameter disk.

Volatiles should be removed before determining ash, extractables, and specific gravity. Ash and extractables are reported on a dry basis (db). Volatiles contents of representative FMLs are presented in Table 4-22. Monomeric plasticizers, which are generally used in PVC liner compositions, are somewhat volatile and can slowly volatilize at 105°C. Thus, heating specimens to 105°C in an air oven to determine volatiles content must be limited to 2 hours to prevent plasticizer volatilization.

Determination of volatiles is generally the first test performed on an exposed FML sample and needs to be run as soon as possible after the sample has been removed from exposure. This test indicates the amount of volatile constituents that has been absorbed by the FML during exposure. In cases where it is not possible to measure the increase in weight of an exposed sample directly, the weight increase can be approximated using the following formula:

$$\text{Weight increase, \%} = \frac{V_E}{100 - V_E} \times 100\% , \quad (4-8)$$

where

V_E = percent volatiles of the sample after exposure.

This formula assumes that the volatiles content of the unexposed FML was equal to zero.

If the volatiles specimen from an exposed sample is to be used for measuring specific gravity, care must be taken to avoid causing a "skin" to form on the surface of the specimen, which is the result of trying to remove the volatiles too quickly at too high a temperature. For example, in measuring the volatiles of an exposed CPE FML, a disk specimen heated at 105°C developed blisters that were caused by the surface sealing in the volatiles in the center of the specimen. To prevent this from happening, specimens can be taken up to temperature very gradually. A procedure that has been used allows specimens to dehydrate for 1 week in moving air. The specimens are then heated in a circulating air oven for 20 h at 50°C over a desiccant and then for 2 h at 105°C. In the case of highly swollen samples, disk specimens can also be allowed to come to constant weight at 50°C before being placed in the 105°C oven. After the volatiles are removed, the exposed materials can be subjected to other tests, including specific gravity, extractables, ashing, etc.

Inasmuch as the volatiles contain both water and organic components, it may be desirable to distinguish between the two. The disk specimen can be heated at 50°C for 4 days in a small, individual desiccator containing calcium chloride to remove the moisture without removing the organic volatiles. The organic volatiles can then be removed by heating the specimen for 2 h at 105°C in a circulating air oven. The composition of the organic volatiles can be determined by headspace gas chromatographic analysis of vapors sampled from a sealed can in which a specimen has been heated.

Total volatiles can also be determined through the use of TGA which is discussed in the paragraphs on TGA. The composition of the volatiles can be determined by head space analysis, such as described under gas chromatography.

The volatiles test can also be used to determine the direction of the grain that has been introduced in an FML during manufacture. By identifying the orientation of the specimen with respect to the sheeting at the time the specimen was died out, the grain direction can be identified. The grain direction must be known so that tensile and tear properties can be determined in machine (grain) and transverse directions. Upon heating in the oven at 105°C, sheeting with a grain will shrink more in the grain direction than in the transverse direction (Figure 4-31). With semicrystalline FMLs, such as HDPE, which have higher softening or melting points, it may be necessary to heat the disk to higher temperatures to observe the shrinkage.

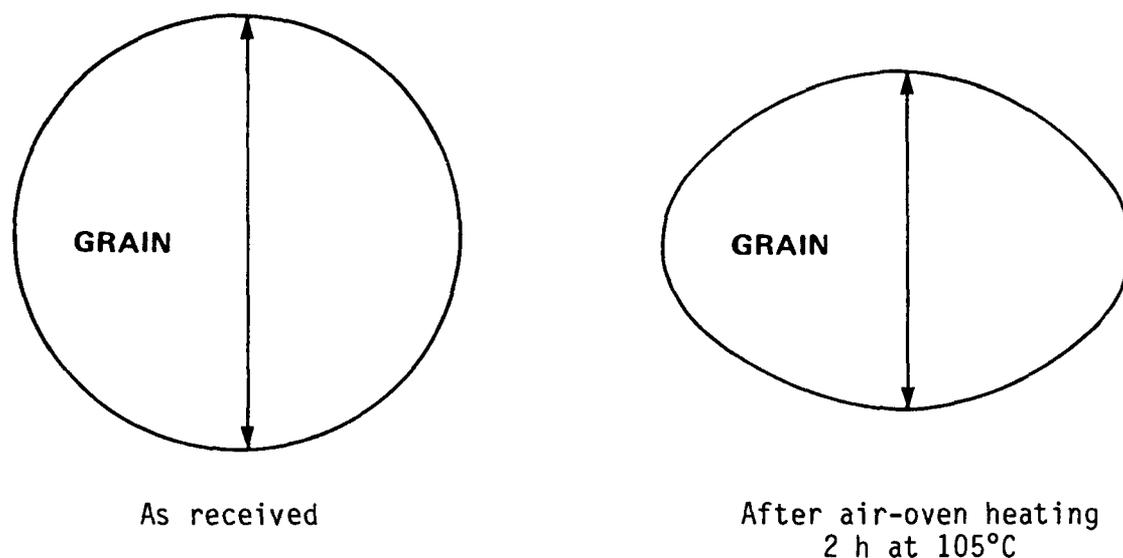


Figure 4-31. Determination of grain or machine direction.

Testing the volatility of plasticizers in PVC compositions can also be performed in accordance with ASTM D1203. In this test, activated charcoal is used to absorb volatilized plasticizer under a controlled set of conditions.

Ash. The ash content of an FML is the inorganic fraction that remains after a sample, from which the volatiles have been removed, is thoroughly burned at $550 \pm 25^\circ\text{C}$ in a muffle furnace. The ash consists of the inorganic ingredients that have been used as fillers and components of the curative system in the liner compound, and the ash residues from the polymer. Different FML manufacturers formulate their compounds differently, and the ash content is part of the "fingerprint" of a polymeric FML compound. The residue obtained by ashing can be retained for other analyses (such as trace metals analyses) needed for further identification. The test method described in ASTM D297 is generally followed in performing this analysis. Ash contents of representative FMLs are presented in Table 4-22. Ash content can also be determined by TGA.

The ash content of an exposed FML sample can differ from that of the unexposed FML, depending on how many nonvolatile organics were lost or gained during the exposure period. For example, if plasticizer is lost, the ash content will increase because of the decrease in nonash content, i.e., the plasticizer, in the dried specimen. Also, if any organic metal compounds are absorbed by the FML, they will increase the ash content. A comparison of the elemental analysis of the ash with that of the original FML will determine whether any absorption of metal species occurred during the exposure. No such absorption, however, has been observed in work performed by Matrecon, even though organic metals can be absorbed.

Extractables. The extractable content of a polymeric FML is the fraction of the compound that can be extracted from a devolatilized sample of the FML with a suitably selected solvent that neither decomposes nor dissolves the base polymer. Extractables consist of plasticizers, oils, or other solvent-soluble constituents that impart or help maintain specific properties, such as flexibility and processibility. Measuring the extractable content is important in fingerprinting an FML. The extract and the extracted specimen obtained by this procedure can be used for further analytical testing (e.g. gas chromatography, infrared spectroscopy, ash, thermogravimetry, etc.) and fingerprinting of the FML. A detailed description of the procedure for determining extractables is presented in Appendix E. This procedure generally follows ASTM D3421 and D297.

Extractables of exposed FMLs may differ from the original values because of the loss of extractable components to the waste liquid and because of absorption of nonvolatile organics, e.g. oils. For example, if the FML has been in contact with wastes containing nonvolatile constituents, the extractables recovered may be greater than the original values. The extracts can be analyzed by gas chromatography and infrared analysis to study the nonvolatile organics that were absorbed, thus indicating which constituents of the waste are aggressive to the FML, because they are the constituents that were absorbed. Even though these constituents may show up in only minor amounts in a waste analysis, they may be scavenged by an FML because of their chemical characteristics, e.g. their solubility parameters.

Because of the differences between the polymers used in FML manufacture, a variety of extracting media must be used. The solvents found to be the

most suited for determining the extractables of FMLs of each polymer type are listed in Appendix E. However, because FMLs can be based on polymeric alloys marketed under a trade name or under the name of only one of the polymers, this list has only served as a guideline for choosing a suitable solvent for determining the extractables. When extractables determinations are being used to assess the effects of exposure in an exposure study, and once a suitable solvent has been found, it is important that the same solvent be used for determining the extractables across the range of exposure periods. Typical values for the extractables in FMLs are given in Table 4-22.

Gas Chromatography. Gas chromatography (GC) can be used to find the level of a specific plasticizer that has been compounded into an FML, e.g. the level of diethylhexyl phthalate (DEHP), a dioctyl phthalate (DOP), in a PVC FML. Gas chromatography separates organic compounds from a mixture based on their boiling points and polarities. A small sample of mixture is injected into a gas chromatograph and the components of the mixture are separated in a column through which an inert gas, such as helium or nitrogen, is flowing. The compounds that are most volatile and least polar elute first and are detected by ionization in a hydrogen/oxygen flame. Organic compounds can be characterized by their retention time on the column at a certain temperature. Thus, small amounts of a complex mixture can be tentatively identified or compared to other mixtures based on similar retention times. For positive identification, additional corroborative analysis, such as mass spectrometry, would be necessary.

A typical gas chromatographic procedure for determining the type and amount of plasticizer involves measuring the level of a plasticizer in the redissolved extract from an FML. A weighed sample of FML is extracted with an appropriate solvent. The extract is evaporated to dryness over a steam bath to determine its weight. The dry residue is redissolved in solvent and brought to an accurately known volume. Following the development of appropriate chromatographic conditions, the solution is injected into the gas chromatograph. Using predetermined retention times of specific plasticizers, the unknown plasticizer constituents can be identified. Comparing peak-height (or area-under-the-curve) data obtained from the injection of equal volumes of the extract solution and quantitatively prepared standard solutions of the identified plasticizer constituents allows the concentration of the identified plasticizer in the extract solution to be determined by interpolation. Figure 4-32 shows the quantification of DEHP (about 0.7 g L^{-1}) in the solvent extract of a PVC FML. Assuming that the extraction was 100% efficient, the percent, by weight, of DEHP in the FML can then be calculated.

GC can also be used by headspace analysis to analyze the volatile organics absorbed by an FML during an exposure. In the headspace gas chromatography (HSGC) procedure, an exposed FML specimen is placed in a small vapor-tight can provided with a septum through which vapors from the specimen can be sampled. The can is placed in an oven at 105°C and heated for approximately one hour. A sample of the vapors is drawn from the can and injected into the GC. The FML specimen is removed from the sample can and

placed in a new can which is then heated in a 105°C oven for approximately one hour. Once again, the vapors inside the can are sampled and injected into the GC. The process of heating, sampling, and injecting is repeated until no organics are detected in the sampled vapors by the GC. The concentrations of the organics in the injected samples can be calculated by comparing peak height values with calibration curves prepared by analyzing a specific volume of vapor (e.g. 100 μ L or 400 μ L) from headspace cans injected with different volumes of a standard solution of organics.

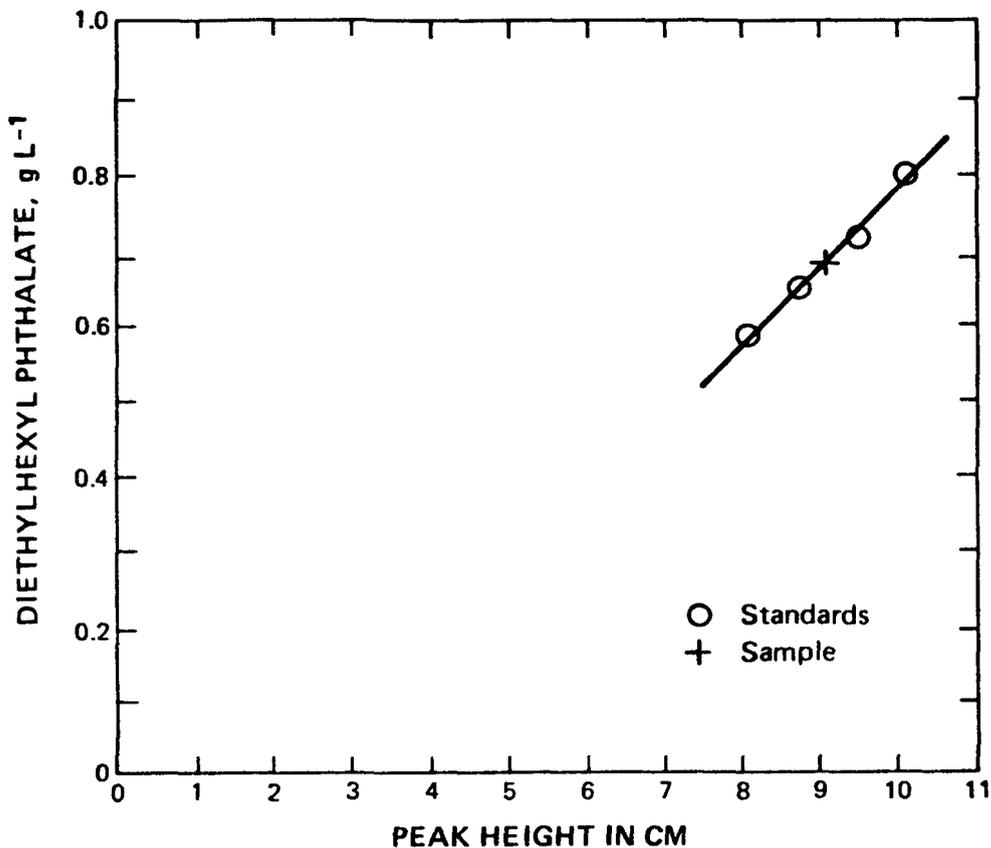


Figure 4-32. Gas chromatographic determination of the diethylhexyl phthalate content in an extract of a PVC FML. Column: 6 ft x 1/8 in., 3% methyl silicone (OV 101) on Chromosorb WHP, mesh size 100-120. Temperature: 200-300°C at 8°C/min. Helium carrier gas: at 30 mL/min.

Pyrolysis Gas Chromatography. Pyrolysis gas chromatography is an alternative method for measuring the plasticizer content of FMLs. In this

technique, a small, weighed FML sample is heated very rapidly to a temperature sufficient to volatilize all of its organic components. The plasticizer and other lower-molecular weight organics will be driven off as chemically unchanged vapors. The polymer will undergo pyrolysis, or high-temperature decomposition, and will volatilize as lower-molecular-weight organic compounds. The resulting volatiles can be separated and quantified by gas chromatography as previously described, and the plasticizer content of the liner can be calculated.

This method has the strong advantage of not requiring extraction of the liner sample, but it may not be as reliable a means of quantification because of the very small sample size and the large number of components that must be separated by the gas chromatograph.

Infrared Spectroscopy. Infrared spectroscopy is the analysis of organic molecules/mixtures by their absorbance of infrared radiation. Each molecule contains a unique set of functional groups which absorb radiation at a precise frequency. The intensity of radiation absorption at that frequency by an individual molecule is dependent on the amount of that functional group present in that particular molecule. Each molecule will have a unique spectrum based on the combination of functional groups in the molecule. The use of the IR spectrophotometer on FML extracts provides information on the composition of an FML and can be used in fingerprinting. It can also be used to indicate compositional changes in formulations of antioxidants and the decomposition of antioxidants with time and exposure to environmental conditions. An example of an infrared scan of the dried film from an n-hexane extract of an unexposed HDPE FML is presented in Figure 4-33.

Although only a fraction of a percent of material was extracted from the polyethylene, this example of an extract showed by the absorption at 1710 cm^{-1} that the extracted solids consisted essentially of hydrocarbons and small amounts of other ingredients, possibly esters or phenols which may be associated with antioxidants. This type of curve functions primarily as a fingerprint. Further analysis by other means would be needed to identify all constituents. The IR curves of the extracts of exposed PE FMLs indicate whether organics have been absorbed by the PE and give an indication of the general character of the absorbed organics.

Specific Gravity. Specific gravity is an important characteristic of a material and is generally easy to determine. Determinations are often made on devolatilized specimens. Because of differences in the specific gravities of the base polymers, specific gravity of the FML compound can give an indication of the composition and identification of the polymer. Specific gravities of base polymers and of selected FMLs are presented in Table 4-22. These results show the differences among polymers and the variations in compounds from one manufacturer to another.

ASTM Method D792, Method A-1, and ASTM Method D297, Hydrostatic Method, both of which are displacement methods, are generally used in determining specific gravity. These two methods are essentially the same procedure.

ASTM D792 covers solid plastics, whereas ASTM D297 covers rubber products. A density-gradient column can also be used to determine density (ASTM D1505). The specific gravity of a material at a stated temperature can be obtained by multiplying the density by the appropriate factor.

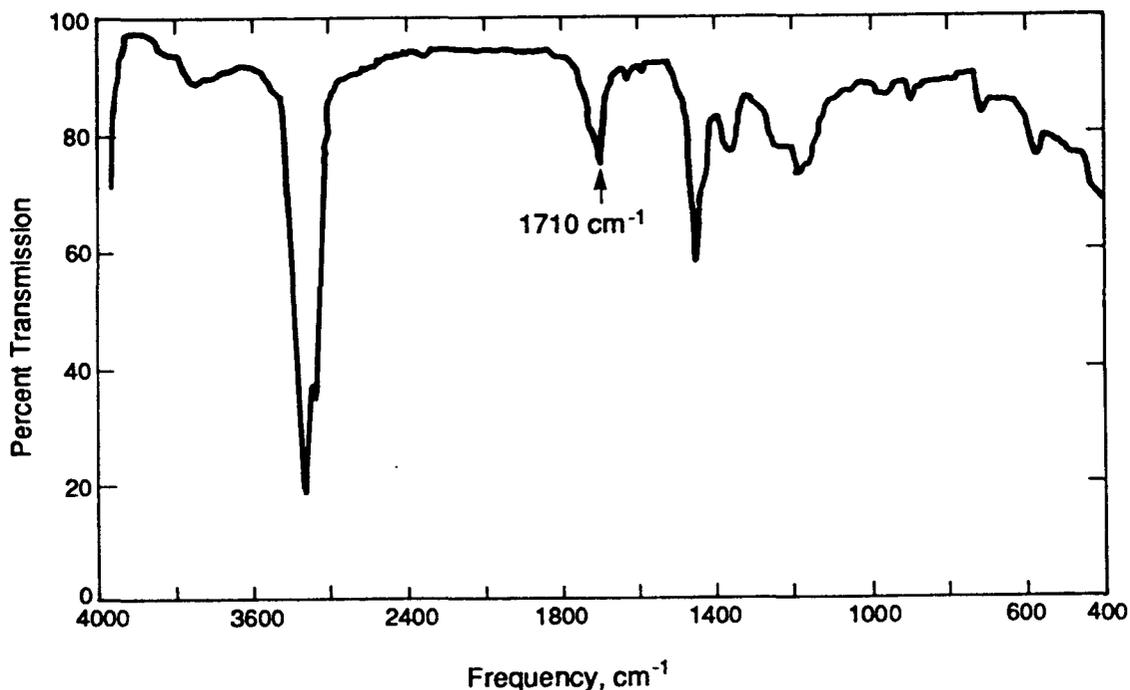


Figure 4-33. Infrared scan of a dried film from an n-hexane extract of an HDPE FML. Note: the absorption at 1710 cm^{-1} may be related to an antioxidant or to possible oxidation of the low molecular weight PE.

The specific gravity of an exposed FML can differ from that of the unexposed FML depending on how much of the original extractable material was lost and how much material was absorbed from the waste during exposure.

The specific gravity of an exposed FML is determined on a test specimen that has been thoroughly devolatilized. To prevent the formation of bubbles in the FML mass during a direct devolatilizing process (which would affect the specific gravity results), specimens may need to be devolatilized relatively slowly. A procedure that has been used allows specimens to dehydrate for one week at room temperature in an air stream in a hood; they are then heated in a circulating air oven for 20 h at 50°C ; lastly, they are heated for 2 h at 105°C . In the case of highly swollen FML samples, specimens can also be allowed to come to constant weight before being placed in the 105°C oven.

Thermogravimetric Analysis. Thermogravimetric analysis (TGA) is a thermal technique for assessing the composition of a material by its loss in weight on heating at a controlled rate in an inert or oxidizing atmosphere.

For example, when a material is heated in an inert atmosphere from room temperature to 600°C at a controlled rate, it will volatilize at different temperatures until only carbon black, char, and ash remain. The introduction of oxygen into the system will burn off the char and carbon black. The weight-time curve, which can be related to the weight of the sample remaining and temperature, can be used to calculate the volatiles, plasticizer, polymer, carbon black, and ash contents. In some cases, TGA can replace the methods used to measure the volatiles, ash, and extractables contents discussed above. The TGA curve and the derivative of the TGA curve can thus be used as part of a fingerprint of a polymeric composition. This technique is described by Reich and Levi (1971), Turi (1981), Earnest (1984), and Matrecon (1986).

In the work performed by Matrecon, a Perkin-Elmer TGS-2 thermogravimetric system, consisting of an analyzer unit, balance control unit, heater control unit, and first derivative computer, was used. Temperature control was supplied by the temperature controller on the Perkin-Elmer DSC-2 (Differential Scanning Calorimeter). A double side-arm furnace tube was used to allow rapid changing of the atmosphere from inert (N₂) to oxidative (N₂/O₂ mixture). For the oxidative atmosphere, N₂-purity was maintained through the analyzer unit head, and O₂ was introduced at the upper side arm where it mixed with the N₂ to burn the carbon black and any carbonaceous residue that forms during the pyrolysis of the polymer. Use of the double side-arm furnace tube shortened the turnaround time because it eliminated the need to flush the analyzer head completely to remove O₂ between runs, as would be necessary if O₂ were introduced through the head. A dual pen recorder, Perkin-Elmer Model 56 allowed a simultaneous display of thermocouple temperature in the furnace and the change in weight of the specimen or the first derivative of the change in weight.

A TGA procedure followed by Matrecon for analyzing an FML is as follows: a 5-mg specimen of the FML is placed in the balance pan and weighed in a nitrogen flow of 40 mL/min. The instrument is adjusted to give a 100% full-scale deflection for the weight of the sample so that the percent of weight change can be read directly from the chart. The specimen is heated to 110°C and held there for 5 min. to determine whether measurable volatiles are present; the specimen is then heated from 110° to 650°C at a rate of 20°C/min. in a nitrogen atmosphere. The specimen is held at 650°C until no additional weight loss has occurred, usually 2 to 3 minutes, after which it is cooled to 500°C and O₂ is introduced at a rate of 10 mL/min. with an N₂ flow rate of 30 mL/minute.

Typical thermograms for HDPE and EPDM FMLs appear in Figures 4-34 and 4-35, respectively. Analyses of a variety of polymeric FMLs are presented in Table 4-23.

TGA can also be used to give a quick analysis of the composition of an exposed FML. Testing an exposed FML follows the same procedure as testing an unexposed FML, except that care must be taken in handling the small specimens of exposed FMLs that contain volatiles. These volatiles can be easily lost.

Figure 4-36 presents a thermogram of an exposed PVC FML which had increased in weight by more than 7% due to absorption of the waste liquid which was predominantly water. The thermogram shows four weight losses. These weight losses are as follows:

- Weight loss A = 7.0% = volatiles = moisture + possible organics.
- Weight loss B = 60.2% = plasticizer + HCl from the polymer (PVC).
- Weight loss C = 16.0% = residual polymer.
- Weight loss D = 10.0% = carbonaceous polymer residue.

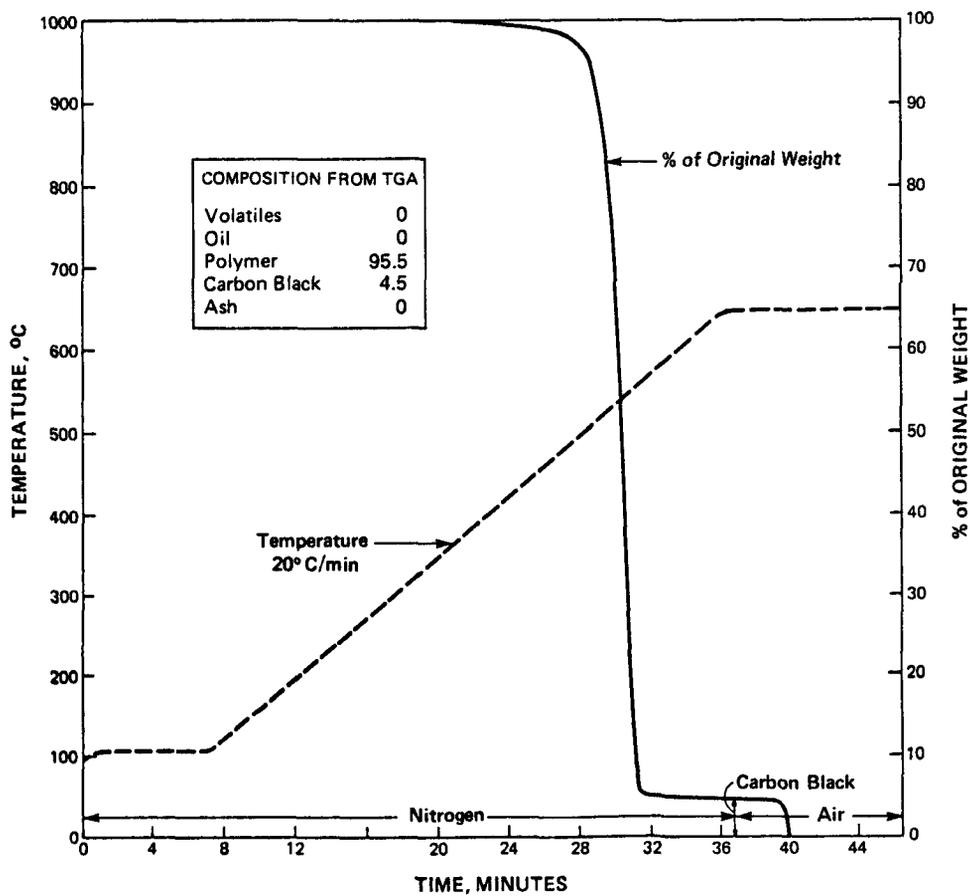


Figure 4-34. TGA of an unexposed black HDPE FML. The plots of sample weight and temperature as a function of time are shown. Under an N₂ atmosphere, the black HDPE sample lost approximately 95.5% of its mass as hydrocarbons were evolved. The carbon black added as an UV light absorber remained as a carbonaceous residue and was not volatilized until it was oxidized when oxygen was allowed into the system.

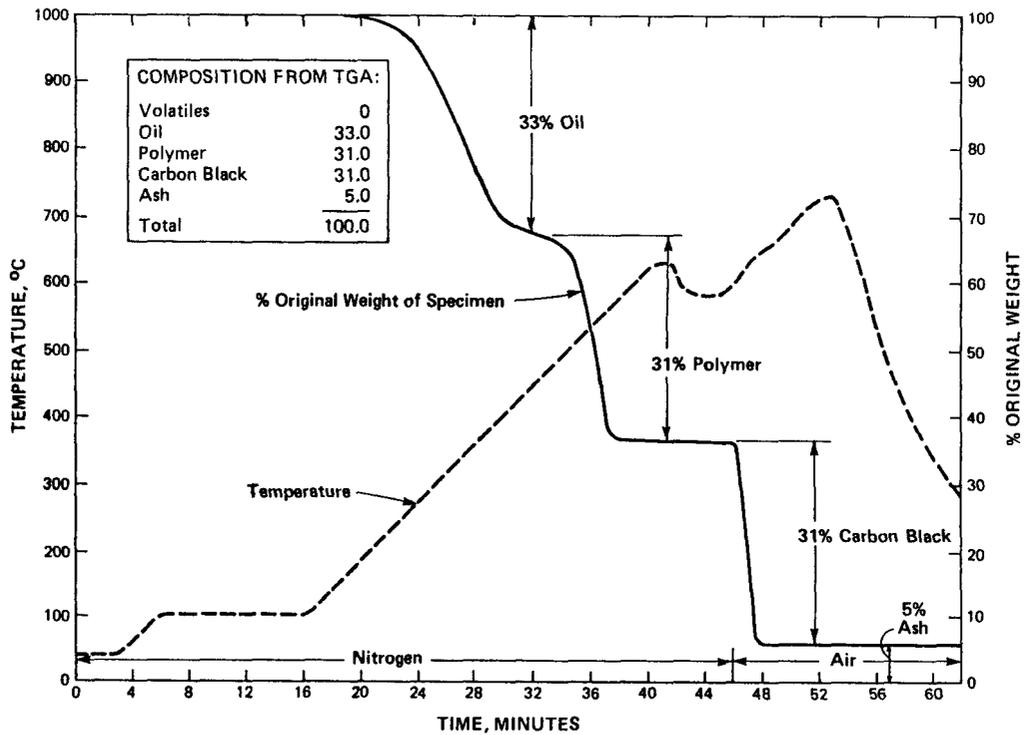


Figure 4-35. TGA of an unexposed EPDM FML. The dotted line shows the temperature program and the solid line shows the percent of the original specimen weight. At 46 minutes the atmosphere was changed from nitrogen to air to burn the carbon black.

The residue, E, which is the ash, is 6.8%. The losses show the effect of the char formation of the PVC when it is heated in a nitrogen atmosphere. Chlorinated polymers lose HCl and leave a char which must be corrected for in calculating the polymer content. The results of calculating the composition of the exposed FML specimen in comparison with the results of direct analyses of the same FML, are as follows:

<u>Constituent</u>	<u>By TGA</u>	<u>By direct analysis</u>
Volatiles, %	7.0	7.9
Polymer (PVC), %	52.1	...
Plasticizer, %	34.1	32.2 (as extractables)
Carbon black, %	~0	...
Ash, %	6.8	6.4

The results obtained by TGA and those obtained by direct analysis are comparable. The differences in the results indicate that some of the volatiles may have been lost in preparing the TGA specimen, that the extraction may not have been 100% efficient, that a small amount of plasticizer may have been driven off in the process of removing the extraction solvent from the extract, or that in devolatilizing the ash specimen, some of the plasticizer may have been driven off. A large difference between the plasticizer content

as determined by TGA and the extractables content as determined by direct analysis would indicate that an unsuitable solvent was probably being used in the extraction.

TABLE 4-23. THERMOGRAVIMETRIC ANALYSIS OF UNEXPOSED POLYMERIC FMLs

Polymer type	Volatiles, %	Polymer, %	Oil or plas- ticizer, %	Carbon black, %	Ash, %
Butyl rubber	~0	45.0	12.2	37.1	5.7
CPE	~0	72.2	7.6	5.3	14.9
	~0	71.3	9.1	6.5	13.1
	0.4	53.9	13.9	21.0	10.8
CSPE	1.0	49.3	1.5	45.6	2.6
	0.9	47.7	3.2	45.2	3.0
	0.1	58.1	5.5	9.8	26.5
ELPO	~0	93.1	1.7	4.0	1.2
ECO	~0	49.3	8.2	37.7	4.8
EPDM	0.1	30.8	32.9	30.9	5.3
	0.2	33.5	23.2	35.5	7.6
Neoprene	1.0	42.3	10.7	34.9	11.1
	~0	44.0	10.7	33.8	11.5
HDPE	~0	97.9	~0	2.1	~0
	~0	95.6	~0	4.2	0.2
	~0	97.0	~0	1.8	1.2
PVC	~0	54.9	38.2	~0	6.9
	~0	53.8	42.1	~0	4.1
	~0	58.0	35.0	~0	7.0

Differential Scanning Calorimetry. Differential Scanning Calorimetry (DSC) is a thermal technique that has a variety of applications in the testing and evaluation of FMLs, other geosynthetics, and pipe. Among these applications are its use for measuring the melting point, the amount of crystallinity in semicrystalline polymers, i.e. PE, PP, and PB, and the measurement of the thermal stability and the OIT of polymeric compositions. This technique measures the heat of fusion and the oxidative induction time of a crystalline structure; it can also give an indication of the modification of semicrystalline compositions with other polymers by alloying. Thus, this type of analysis can be used as a means of fingerprinting semicrystalline

FMLs (particularly HDPE) and of assessing the effects of aging and exposure to wastes. This technique is described by Boyer (1977), Ke (1966), Turi (1981), and Haxo (1983).

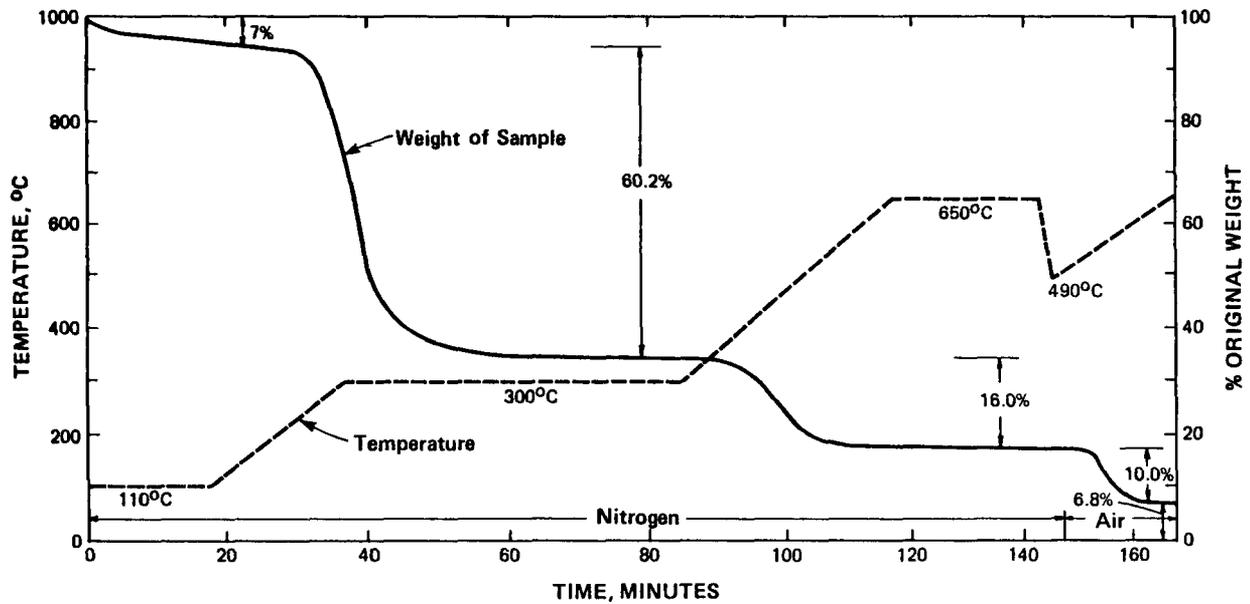


Figure 4-36. TGA of an exposed plasticized PVC FML.

The differential scanning calorimeter used in the work performed by Matrecon was the Perkin-Elmer Model DSC-2C, equipped with an Intracooler I subambient temperature accessory to provide an operating temperature range of -40 to 725°C.

The instrument can characterize the thermal transitions, e.g. melting, boiling, and changes in crystalline structure, of a material. When a sample undergoes a thermal transition, an endothermic or exothermic reaction will occur. These transitions are characterized by comparing the effects of heating on the thermal characteristics of two cells that are simultaneously heated or cooled so that the average cell temperature follows a preset program. A weighed sample is placed in one cell and the other cell is a reference cell, which is generally run empty so that all of the thermal transitions in the tested material can be identified. The change in power required to maintain the sample cell at the same temperature as the reference cell is recorded as a deflection of the recorder pen. The recorder plots the temperature (°C) versus the differential energy flow (mcal/sec) required to maintain the sample cell temperature. An endothermic transition, such as melting, is shown as a positive peak; an exothermic reaction, such as crystallization, is shown as a negative peak. The amount of energy absorbed during the melting process may be determined by calculating the peak area and relating it to the peak area resulting from the melting of an indium standard of known weight. The energy absorbed is termed the "heat of fusion" (ΔH_f). Assuming that ΔH_f for the fully crystalline polymer is

known, the degree of crystallinity of the sample can be determined as a simple ratio. The magnitudes of these peaks and the temperatures at which they occur are characteristic of the analyzed material. An example of a DSC determination of PE crystallinity in an HDPE FML is shown in Figure 4-37.

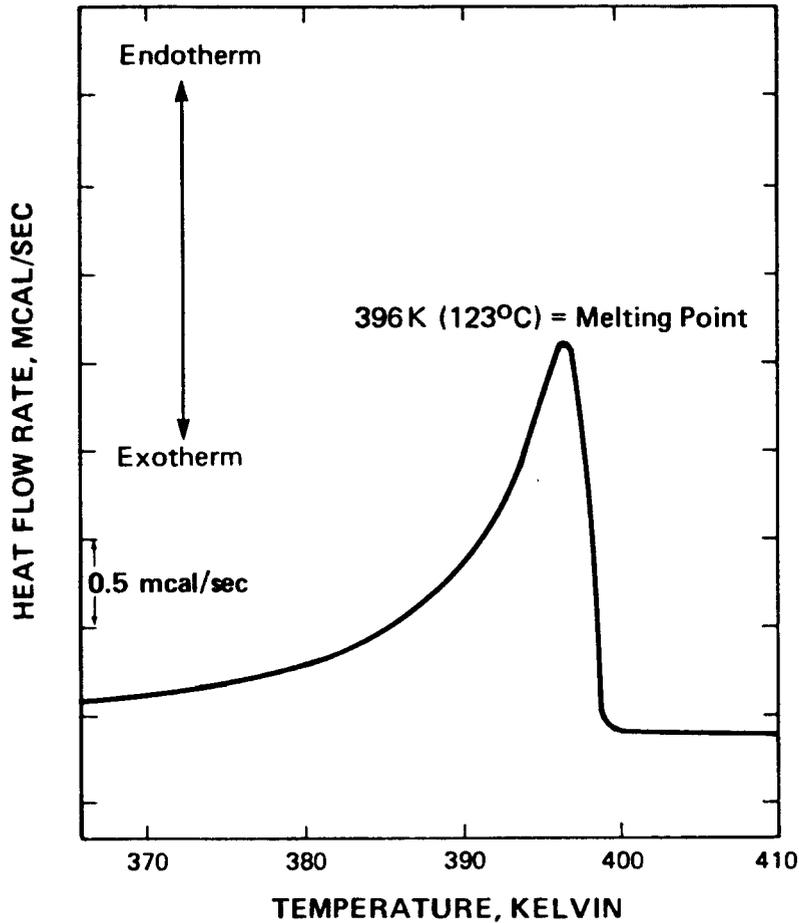


Figure 4-37. DSC determination of the melting point and PE crystallinity in an HDPE FML. The x-axis is the temperature which was raised at 5°C/min. The y-axis is calibrated in mcal/sec, or rate of energy flow. A positive deflection of the plot indicates that the sample is absorbing energy (e.g. during melting).

To study the effect of the rate at which a material is cooled on crystallinity content, Matrecon determined the crystallinity of specimens of the same PE which were cooled at different rates. The material tested was a sample of National Bureau of Standards' Standard Reference Liner Polyethylene (NBS 1475), an HDPE. Crystallinity was determined using the method described by Gray (1970a). Crystallinity contents were calculated from calorimetric data obtained on specimens that had been heated to 157°C, then crystallized

at cooling rates of 0.3125°, 10°, and 320°C per minute; the crystallinity was also calculated from the density specifications for this material. The DSC results are presented in Table 4-24. This reference PE is certified to have a density of 0.97844 g/cm³ with a standard deviation from the mean of 0.00004 g/cm³ following conditioning as described in ASTM D1928. Using the data of Brandrup and Immergut (1966), the conditioned reference material is calculated to be 80.9% crystalline after having been cooled at rate of 0.083°C/min. As is shown in Figure 4-38, sample crystallinity is linearly related to the logarithm of the cooling rate up to a cooling rate of 10°C/min. where it appears to level off. Thus, the percent crystallinity calculated from the differential scanning calorimetric data is in good agreement with the value calculated from the density. The samples cooled at 320°C/min. are displaced from the regression because inadequate thermal conductivity and the sample heat capacity effectively put an upper limit on the cooling rate. The results indicate that cooling rate inversely affects the degree of crystallinity achieved.

TABLE 4-24. PERCENT CRYSTALLINITY AND MELTING TEMPERATURE OF NBS STANDARD POLYETHYLENE 1475 WITH VARYING THERMAL HISTORY

Sample	Weight, mg	Cooling rate, °C/min.	Melting temperature, °C	ΔH _f , cal/g	Crystallinity ^a , %
A	6.0	0.3125	136 ^b	50-52 ^c	73-75
		10	133	45	65
		320	131	43	62
B	6.6	0.3125	136	53	76
		10	133	46	67
		320	132	45	65

^aCrystallinity value assumes that ΔH_f = 69 cal/g for polyethylene in perfect single crystal form (Gray, 1970b).

^bTemperature at maximum endotherm.

^cPeak off-scale; lower bound is measured value, upper is best estimate.

The melting points and percent of crystallinity of a variety of PE FMLs and films as determined by DSC is presented in Table 4-25. These data show the pronounced differences between the different types of polyethylene and the correlation of density and crystallinity data. The standard reference material is shown for comparison. The similarity of the results of testing a sample of HDPE 307 that had been "quenched" at 160°/min. and an as-received sample indicate that HDPE 307 had been cooled relatively rapidly during manufacture.

The DSC can also be used to measure the oxidative induction time (OIT) of a polymeric composition to assess its thermal stability and to assess the various antioxidant packages that may be used in the preparation of the polyethylene.

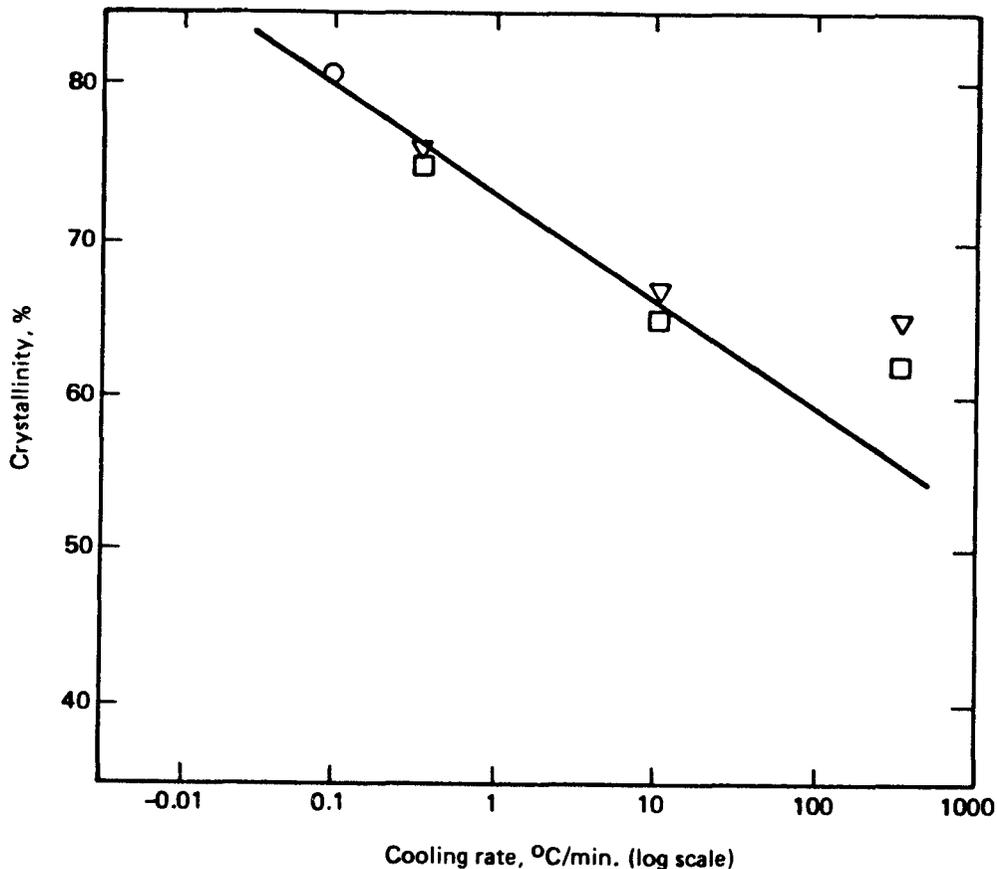


Figure 4-38. Crystallinity of NBS Standard Polyethylene 1475 as a function of cooling rate. ○ derived from published data for NBS 1475, □ from experimental data, Sample A; ▽ from experimental data, Sample B.

As is described in ASTM D3895, the material under test and the reference are heated at a constant rate in an inert gas. When the desired temperature has been reached, the gas is changed to oxygen at the same flow rate. The material is then held at constant temperature until the oxidative reaction is exhibited on the thermogram. The OIT is determined from data recorded during the isothermal test.

Correlation of OIT to FML durability is improved by incorporating high pressure oxygen to help accelerate testing at temperatures closer to the actual high temperature stresses expected in the field (e.g. antioxidant activity can change from very high-temperature testing to lower high-temperature testing) and to prevent loss of antioxidants which would occur at the high temperatures.

This test is useful in assessing the thermal stability of the PE resin in the FML or other PE product because of the several heatings and meltings

TABLE 4-25. DIFFERENTIAL SCANNING CALORIMETRY OF SELECTED POLYETHYLENES
Melting Points and Percent Crystallinity

Type	Liner number ^b	Thickness, mil	Density ^a , g/cm ³	Carbon black content ^c , %	Feature	Melting point, °C	Crystallinity, %
LDPE	21	10	0.935	0	Clear	97-100	29
LLDPE	284	30	0.931	2.4	Black	100-123	39
HDPE-alloy	181	30	0.948	4.0	Alloyed with EPDM	133	43
HDPE	99	100	0.943	d	Shiny side of sheeting	124-129	46-48
					Dull side of sheeting	124-125	47
HDPE	105	30	0.950	0	As received	130	66-67
					After drawing	131-133	62-64
HDPE	184	30	0.953	2.0	As received	134	69
					"Quenched" ^e	132	69
					"Annealed" ^f	135	<70
HDPE	288	100	0.945	1.8	European production	129	53
HDPE	307	80	0.947	2.6	As received	124	48
					"Quenched" ^e	123.5	48
					"Annealed" ^f	127	55
HDPE	...	Pellet	0.9789	0	Reference ^h	136	75

^aDetermined in accordance with ASTM D792.

^bMatrecon liner identification number.

^cBy thermogravimetric analysis.

^dShiny side of sheeting had a carbon black content of 1.9%; dull side had a carbon black content of 1.4%.

^eCooled at 160°C/min.

^fCooled at 10°C/min.

^gFrom NBS certificate.

^hNational Bureau of Standards' Standard Reference Material NBS 1475; cooled at 0.3125°C/min.

that the base resin goes through during fabrication and in welding of an FML or a pipe during installation in the field.

Melt Index. Melt index is the flow rate of a thermoplastic as determined by an extrusion plastometer specified in ASTM D1238. The rate of flow through a die of a specified length and diameter under prescribed conditions of temperature, load, and piston position in the barrel at the time of test is measured. Values are reported as the rate of extrusion in grams per 10 min. at the temperature and load at which the test is run. This test is used in the quality control of PE resins. The constancy of the melt index value within a narrow tolerance range ensures consistent molecular weight and rheological properties. Melt index values in flow rates are also helpful in indicating the process properties of a resin. It should be noted that the melt index of a PE FML will be equal or less than that of the PE resin from which it was manufactured due to slight changes in the PE caused by the processing.

4.2.2.5.2 Physical-mechanical properties--Appropriate or applicable test methods for testing the physical properties of polymeric FMLs are presented in Table 4-26.

Tensile Properties. Tensile tests are probably the most widely used tests in the rubber and plastics industries for evaluating polymeric compositions and products because tensile properties give a good indication of the quality of the compound of a specific polymer. Tensile properties of polymeric materials are generally measured in tension by a stress-strain test. The specific properties that are measured depend on the type of FML. They include:

- Tensile stress at yield (if a semicrystalline FML).
- Elongation at yield (if a semicrystalline FML).
- Tensile stress at fabric break (if fabric reinforced).
- Elongation at fabric break (if fabric reinforced).
- Stress at specified elongations (e.g. 100% and 200%).
- Tensile stress at break of FML.
- Elongation at break of FML.

The test method used, including the type of test specimen required and the rate at which a specimen is elongated, varies with the type of FML being tested (Table 4-26). The method used, particularly the type and size of the test specimen, may also depend on the purpose of the test. For instance, in the compatibility of a fabric-reinforced FML, 1-in.-wide strip specimens are preferred over 4-in. wide grab test specimens due to the limited size of the exposed sample. However, for quality control testing and specification testing, 4-in or even wider specimens are preferred.

TABLE 4-26. APPROPRIATE OR APPLICABLE METHODS FOR TESTING THE PHYSICAL PROPERTIES OF POLYMERIC FMLS

Property	FML without fabric reinforcement			Fabric reinforced
	Thermoplastic	Crosslinked	Semicrystalline	
Thickness (total)	ASTM D638	ASTM D412	ASTM D638/D374	ASTM D751, Section 6
Coating over fabric	na	na	na	Optical Method ^a
Tensile properties	ASTM D882/D638	ASTM D412	ASTM D638 (modified)	ASTM D751, Methods A & B (ASTM D638 on selvage)
Tear resistance	ASTM D1004 (modified)	ASTM D624, Die C	ASTM D1004	ASTM D751, Tongue Method (8 x 8-in. test specimen ^a)
Modulus of elasticity	na	na	ASTM D882, Method A	na
Hardness	ASTM D2240 Durometer A or D	ASTM D2240 Durometer A or D	ASTM D2240 Durometer A or D	ASTM D2240 Durometer A or D (selvage only)
Puncture resistance	FTMS 101C, Method 2065 ^b	FTMS 101C, Method 2065 ^b	FTMS 101C, Method 2065 ^b	FTMS 101C, Methods 2031 & 2065 ^b
Hydrostatic resistance	na	na	ASTM D751, Method A	ASTM D751, Method A
Seam strength: In shear	ASTM D4437/D882, Method A (modified)	ASTM D882, Method A (modified)	ASTM D4437/D882, Method A (modified)	ASTM D751, Grab Method (modified ^a) ASTM D882, Method A (modified)
In peel	ASTM D4437/D413	ASTM D413	ASTM D4437/D413	ASTM D413
Ply adhesion	na	na	na	ASTM D413 ASTM D751, Sections 39-42

^aNSF, 1985.

^bU.S. GSA, 1980.

na = Not applicable.

For a given polymeric FML, tensile properties will vary with speed of test, specimen size, direction of test with respect to the grain in the sheeting, temperature, and humidity. The sensitivity of the tensile properties of FMLs indicates the need for strict conformance to the specified procedure in specification testing. Semicrystalline FMLs are particularly sensitive to rate of test. The results of testing an HDPE FML at 20 ipm are significantly different from the results of testing the same FML at 2 ipm. Absolute values of the tensile strength of the compositions of different polymers should not be compared unless tensile strength is required in the performance of the product.

Changes in tensile properties can be used to monitor the effects on an FML of exposure to wastes. In many rubber and plastics applications, either a 50% loss in tensile strength or elongation or a 50% increase or decrease in modulus (i.e. stress at a specified elongation) is taken to indicate that the product is no longer serviceable in the specific application. These criteria are probably not applicable to FMLs; nevertheless, major changes of properties within a relatively short exposure period indicate the incompatibility of an FML with the specific waste.

Modulus of Elasticity. The modulus of elasticity is commonly used as a measure of the stiffness or rigidity of a semicrystalline FML, such as HDPE. It is defined as the ratio of stress to strain in the part of the stress-strain curve that is linear, particularly at low stresses. Over this range of stress, the material is said to follow Hooke's law, which says that stress is proportional to strain. The modulus is expressed as force per unit area. In tension, this property is also known as Young's modulus.

The modulus of elasticity of the semicrystalline FMLs is generally measured by one of two methods:

- ASTM D882, in which a standard-size strip specimen is extended in tension at a strain rate of 0.1 in./in.·min. The elongation is monitored by the jaw separation. The slope of the straight line portion of the stress-strain curve is taken as the modulus of elasticity.
- ASTM D638, in which a standard dumbbell specimen is extended at a standard rate, usually of 2 in./min. The elongation is monitored by following the bench marks using an extensometer. The slope of the straight line portion of the stress-strain curve is taken as the modulus of elasticity.

In view of the approximate relationship of the modulus of elasticity, Y , to the modulus of rigidity, G , i.e. $Y = 3G$, the modulus of rigidity can be measured in torsion, in accordance with ASTM D1043 and ASTM D1053, and the modulus of elasticity calculated using the equation. Modulus of elasticity also can be measured in flexure, in accordance with ASTM D797.

Due to the variations in test conditions and the speed of test, the values for the elastic modulus vary, but are reproducible for a given method. Regardless of the method of determining the modulus of elasticity,

the limitations of applying the term "modulus of elasticity" to polymeric materials must be recognized, as is indicated in "Note 4" of ASTM D638:

Since the existence of a true elastic limit in plastics (as in many other organic materials and in many metals) is debatable, the propriety of applying the term "elastic modulus" in its quoted generally accepted definition to describe the "stiffness" or "rigidity" of a plastic has been seriously questioned. The exact stress-strain characteristics of plastic materials are highly dependent on such factors as rate of application of stress, temperature, previous history of specimen, etc. However, stress-strain curves for plastics, determined as described in this test method, almost always show a linear region at low stresses, and a straight line drawn tangent to this portion of the curve permits calculation of an elastic modulus of the usually defined type. Such a constant is useful if its arbitrary nature and dependence on time, temperature, and similar factors are realized.

Nevertheless, the determination of modulus of elasticity serves as a good measure of the stiffness or rigidity of a polymeric material, and, if measured in a consistent and reproducible manner, it can be used to measure variability in a material and changes due to different aging effects.

In the present version of EPA Method 9090 (EPA, 1986), modulus of elasticity testing of semicrystalline FMLs is required in accordance with ASTM D882. However, because of the limited size of the samples that can be placed in exposure, a test specimen smaller than the D882 standard size is used. Even though the strain rate for the smaller specimens is equal to that of the standard specimen, the results of testing the smaller specimens are lower. Modulus of elasticity can also be measured in accordance with ASTM D638, which calls for a dumbbell specimen.

Hardness. Hardness is defined in terms of standard tests for hardness of polymeric materials; it is the ability of a material to resist indentation by a small probe of specified shape and dimensions. Although no simple relationship exists between hardness and other measured properties, hardness is related to the modulus of elasticity, Young's modulus (ASTM D1415). It is easily measured and can be used to assess changes in an FML during exposure to wastes and weather.

Hardness testing is usually performed in accordance with ASTM D2240. Test values are reported as a value followed by a letter which indicates the type of durometer that was used. The scales overlap somewhat; Duro A of 90 approximately equals a Duro D of 40. If a material has a value greater than 80 with the Type "A" durometer, it should also be tested with the Type "D" durometer.

Tear Resistance. Tear resistance is the force required to tear a specimen that has a controlled flaw. The value can indicate the mechanical strength of an FML, particularly with respect to the types of stresses

imposed during installation. Tear resistance can also be used to monitor the effects of an exposure on an FML. The tear value depends on both the rate of test, and the shape and size of the test specimens.

The tear resistance of fabric-reinforced FMLs is determined in accordance with a modified version of the Tongue Tear Method in ASTM D751, which calls for a 3 x 8-in. test specimen that tears along a line parallel to the 8-in. direction. However, because of the relatively low strength of the adhesive bond between the fabric and the polymeric coating in many fabric-reinforced FMLs, an 8 x 8-in. test specimen is generally used in testing fabric-reinforced FMLs (NSF, 1985). The low adhesion allows the fabric threads to bundle at the top of the tear and give false high values or to pullout of the coating matrix and yield false low values.

Puncture Resistance. Puncture resistance is the force required to puncture a sheeting with a standard probe. The value is an indication of the ability of a material to withstand puncture from above (i.e. by equipment, foot traffic, deer hooves, etc.) and from below (i.e. by irregularities in the substrate, etc.). Puncture resistance can be used to assess the effects on an FML of exposure to an environment.

Two methods frequently used for assessing the puncture resistance of polymeric FMLs are:

- Federal Test Method Standard (FTMS) 101C, Method 2031--Tetrahedral-Tip Probe Method (U.S. GSA, 1980).
- Federal Test Method Standard 101C, Method 2065--1/8-in. Radius-Tip Probe Method (U.S. GSA, 1980).

In FTMS 101C, Method 2031, a tetrahedral-tip probe punctures a 10 x 4-in. specimen which has been looped around the point of the probe. The test is presented schematically in Figure 4-39. This method has been used particularly for assessing the puncture resistance of fabric-reinforced FML because the probe is large enough to cut and break several cords during test.

In FTMS 101C, Method 2065, a 1/8-in. radius-tip probe punctures a 2 x 2-in. square test specimen that is confined between two plates in which a 1-in. diameter hole has been drilled. A drawing of the probe and sample holder is presented in Figure 4-40. Method 2065 is particularly useful for measuring the puncture resistance of unreinforced sheetings. The applicability of this test to fabric-reinforced FMLs is limited because of the openness of the weaves normally used in fabric reinforcement. The openness of the weave can result in the probe's passing between the threads or in the probe's breaking one or two threads when the FML is punctured.

The ASTM D35 Committee is reviewing the puncture test and is presently considering a 5/16-in. diameter probe with a flat tip beveled 1/32 in. around its circumference.

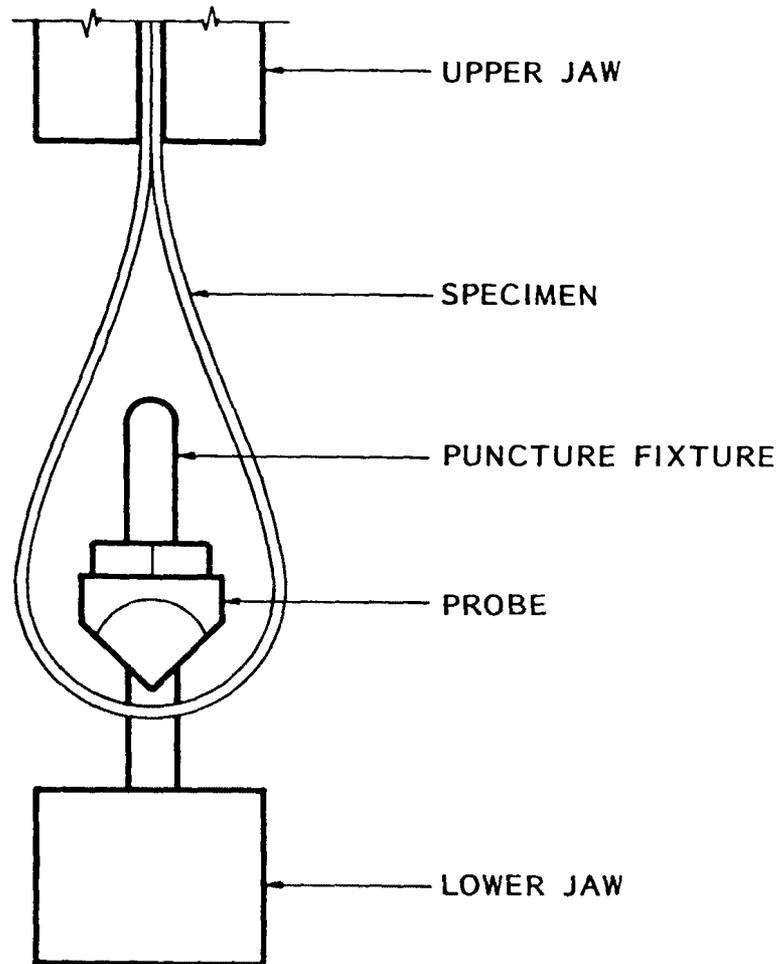


Figure 4-39. Puncture assembly for the tetrahedral tip probe, FTMS 101C, Method 2031 (not to scale) (Source: U.S. GSA, 1980).

Hydrostatic Resistance. In the hydrostatic resistance test a column of water is forced through a test specimen until the specimen bursts. The reported value is the maximum value before rupture of the specimen. The test is important because it can indicate the biaxial stress-strain behavior of a sheeted material. The machine required to perform this test is presented in Figure 4-41. The minimum size test specimen is a 4-in. diameter disk (ASTM D751). The specimen is held between two annular plane clamps which have coaxial apertures in their centers. When the clamps are closed together around the test specimen, a seal is formed. Hydrostatic pressure is applied to the underside of the clamped specimen, which is 1.75 in. in its unsupported diameter, until leakage of the specimen occurs, i.e. the specimen ruptures. This pressure is generated by means of a piston forcing water into the pressure chamber at a specified rate.

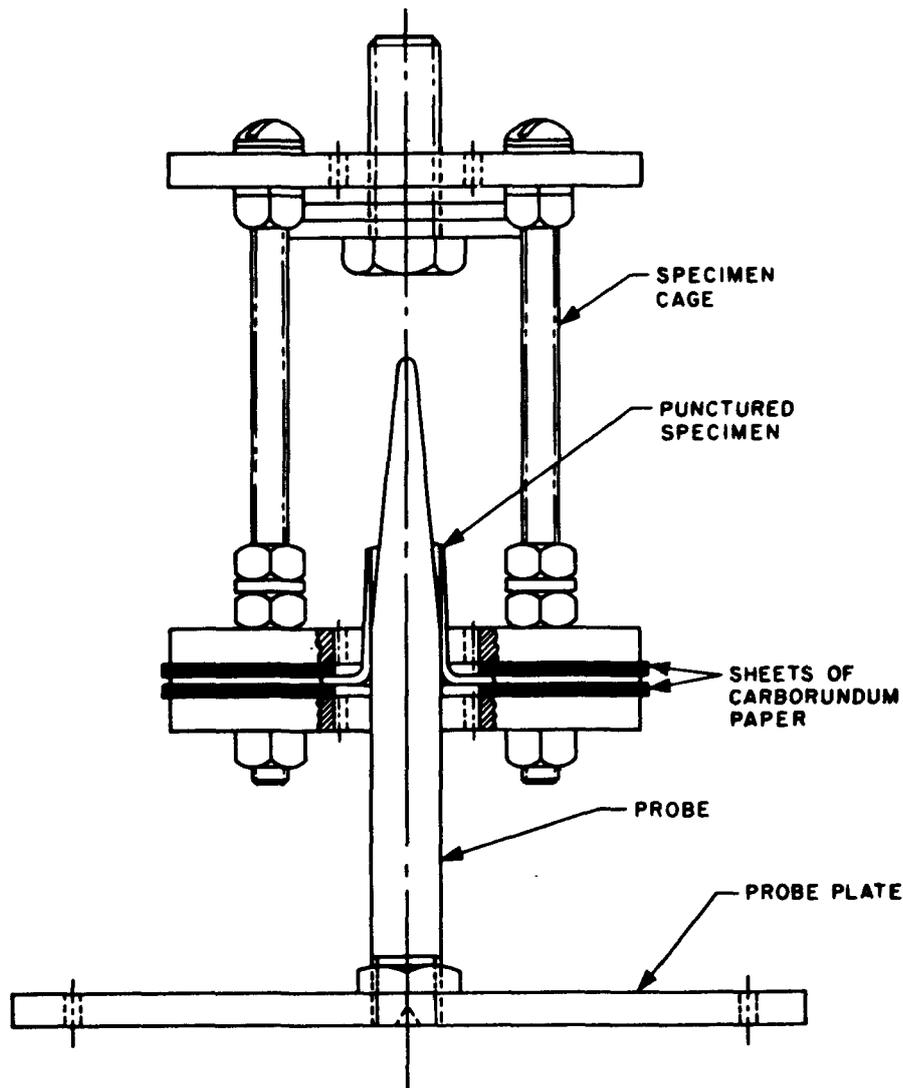


Figure 4-40. Jig for puncture resistance and elongation test, FTMS 101C, Method 2065. (Source: U.S. GSA, 1980)

This test is used primarily with coated fabrics, such as fabric-reinforced FMLs, but it can also be used to measure the hydraulic burst strength of semicrystalline FMLs. This method is not applicable to many unreinforced thermoplastic and crosslinked FMLs because the biaxial elongation of these materials exceeds the dimensions of the cavity above the test specimen in the testing machine. Used with a diaphragm to seal the water, the testing equipment is used to measure the bursting strength of fabrics, both woven and nonwoven.

Seam Strength of Factory and Field Systems. The integrity of the seams is a critical factor in the functioning and durability of an in-service FML. Seams are tested to ensure that the method of seaming a particular material

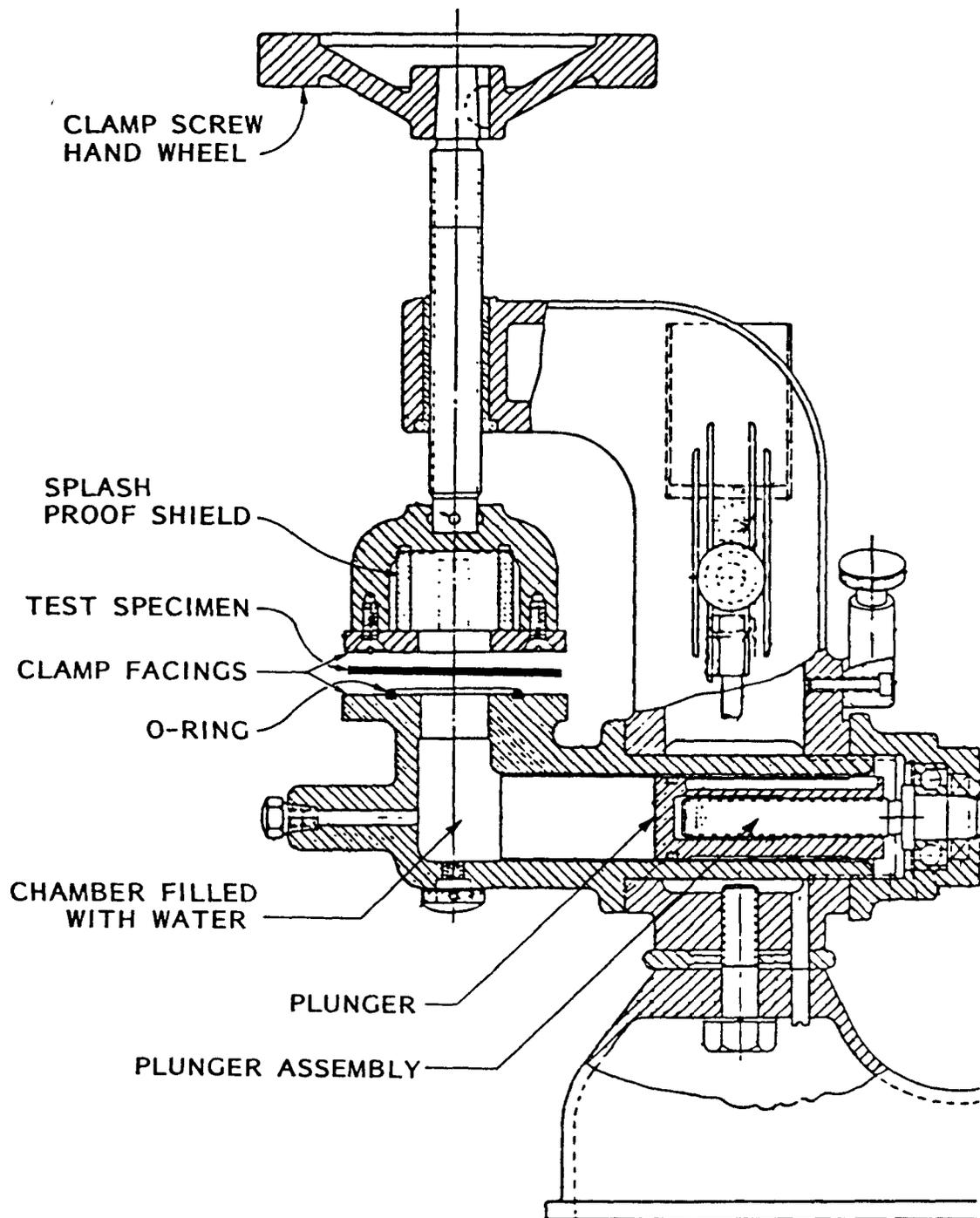


Figure 4-41. Schematic of hydrostatic resistance test machine.

is adequate. Tests are also performed as part of immersion and compatibility tests with waste liquids and with standard fluids, because the effects of various liquids on seams vary, particularly with seams fabricated with adhesives. Seams are tested in shear and peel modes, both using an increasing load and under a constant load until breakage.

Shear strength testing is performed by applying a force across the seam in a direction parallel to the plane of the bond, thus subjecting the bond interface to a shearing force. In most specification testing, a constant rate of extension testing machine is used; however, in some on-site testing during installation, manually powered screw-type devices have been used.

At present there is no standard test method intended specifically for testing FML seams in shear. One of the methods most frequently cited for the shear testing of seams made from unreinforced FMLs is ASTM D882, which is a strip tensile test method intended for determining the properties of plastic sheeting less than 0.04 in. in thickness. Also cited are ASTM D3083 and D638, either by themselves or in conjunction with ASTM D882. ASTM D3083 is a specification for PVC sheeting which specifies the use of ASTM D882 for seam testing with some modifications. ASTM D638 is a dumbbell tensile test method intended for determining the properties of plastic sheeting greater than 0.04 in. in thickness. All of these test methods need to be modified to be used for shear testing of seams.

The types of specimens that have been used for shear testing of seams fabricated from unreinforced FMLs have included strips 0.5-1.0 in. in width, ASTM D638 Type I dumbbells (which feature a 0.5 in. narrow width test area), and ASTM D638 Type IV dumbbells (which feature a 0.25 in. narrow width test area). The dumbbell test specimens have been used in cases where it was necessary to localize the tensile stress in the seam part of the sample and away from the grips, as in the case of seams fabricated from semicrystalline FMLs. Testing of seams made with reinforced FMLs is often performed in accordance with a modified version of ASTM D751 Grab Method. In the modification, the distance between the clamps at the start of test is 6 in. plus the seam width (Figure 4-42). Total length of the test specimen is 9 in. plus the seam width.

ASTM D4437, "Standard Practice for Determining the Integrity of Field Seams Used in Joining Flexible Polymeric Sheet Geomembranes," cites ASTM D816, Method B, as the procedure for testing shear strength. ASTM D4437 modifies ASTM D816 and recommends a minimum of five 1-in. wide specimens for unreinforced FMLs and a minimum of five 2-in. wide specimens for fabric-reinforced FMLs. Recommended initial grip separation is 2 in. plus the width of the seam and the recommended crosshead speed is 2 ipm. The test specimen should be fully supported within the grips across the width of the specimen.

Peel testing is performed by applying a load such that the bonded interface is subjected to a peeling force that attempts to separate the two FMLs that have been seamed together. The peel strength of seams, particularly for seams fabricated with adhesives, is more sensitive to the effects of aging and exposure than their shear strength. Laboratory peel testing of all

types of FMLs is often performed in accordance with ASTM D413 at a jaw separation rate of 2 ipm. Testing can be performed either in 90° or 180° peel (Figure 4-43). Peel testing of semicrystalline FMLs in 180° peel is difficult to perform because of their stiffness. In testing seams fabricated

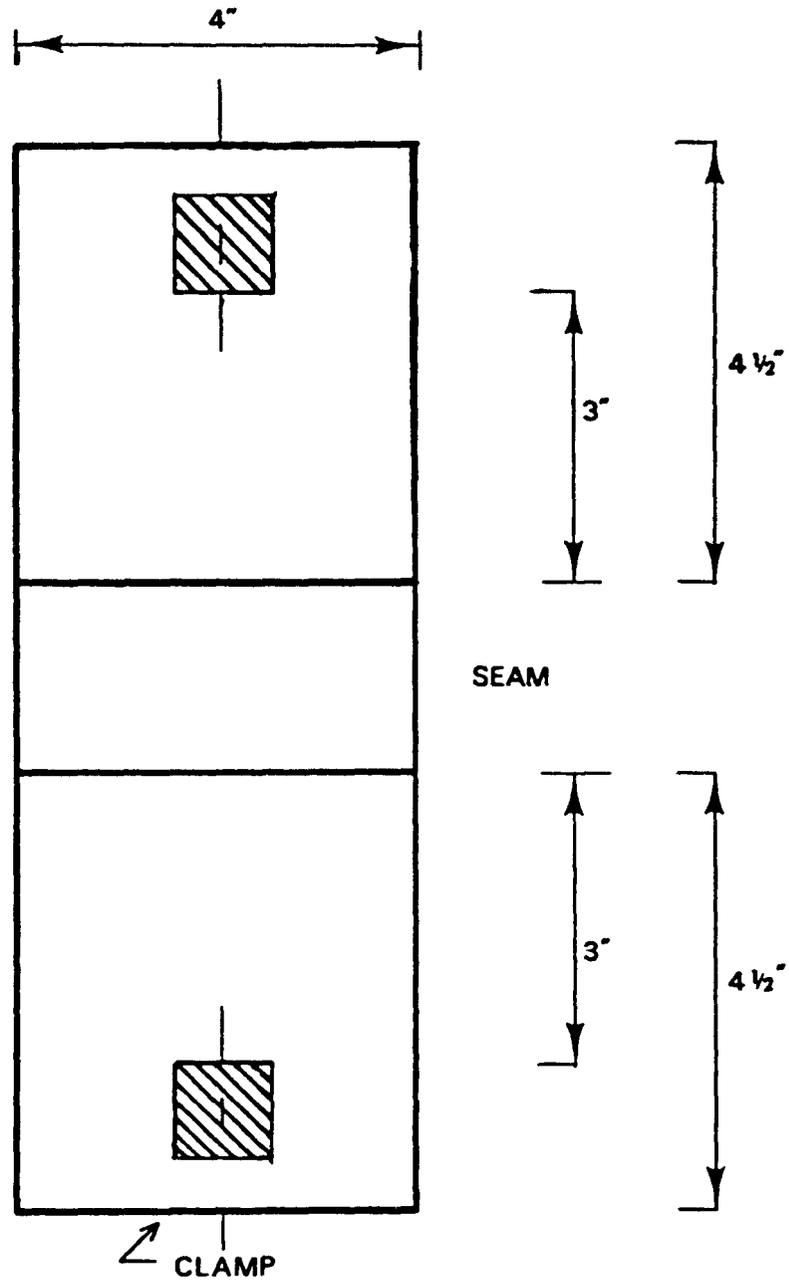
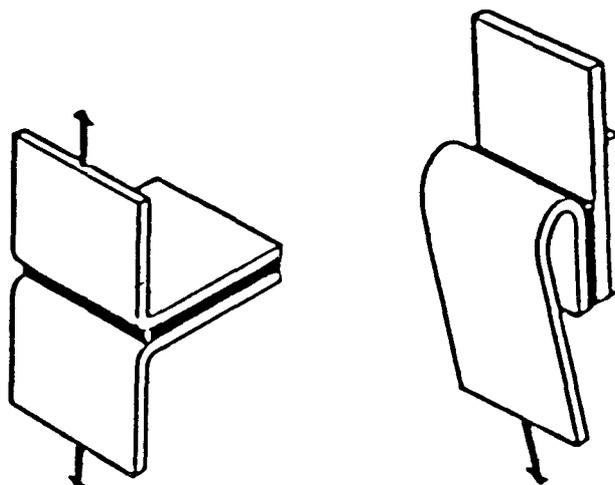


Figure 4-42. Seam strength specimen for testing seams of fabric-reinforced FMLs in accordance with ASTM D751, modified.

from fabric-reinforced FMLs 1-in. wide strip specimens are usually used. In testing seams fabricated from semicrystalline FMLs, ASTM D638 Type I and Type IV dumbbell specimens have sometimes been used to localize the peeling force in the seam test area. ASTM D4437 cites methods ASTM D413, Method A (Machine Method, Strip Specimens--Type A), which is a 180°-peel method, and ASTM D816, Method C, which can be either a 90°- or a 180°-peel method. Both methods are modified so that a minimum of five 1-in. wide specimens are tested with an initial grip separation of 1 inch. Testing is performed with a crosshead speed of 2 ipm.



(a) 90° peel

(b) 180° peel

Figure 4-43. Two configurations of peel testing.

Test results can be reported either as a *maximum* or an *average* peel value. ASTM D413 requires the average value over the seam test area, but in cases in which the seam test specimens break through one of the FML sheets or through a weld bead rather than delaminate along the contact interface between the two sheets, often only a maximum value can be reported. Care should be taken in noting how the reported peel values are calculated.

Peel testing using a static or "dead load" at room temperature and at elevated temperatures can provide a good indicator of time-dependent weaknesses that will not be observed under dynamic testing. Dead load testing at elevated temperatures can be used as a method of revealing the sensitivity of a seam system to long-term exposures on the FMLs and the seaming system.

Hessel and John (1987) suggest a quantitative factor for the long-term behavior of welded seams of PE FMLs by carrying out creep tests in a solution containing a wetting agent at 80°C and a load of 600 psi (4N/mm²). The welding factor is the ratio of the tension creep of the weld to the creep of the parent material.

4.2.2.5.3 Permeability characteristics--Liquids or gases per se do not permeate homogeneous nonporous FMLs but do permeate FMLs as vapors or gases on a molecular scale. The rate of permeation depends on the solubility of the liquid and the diffusibility of the dissolved molecule in the FML. The permeability of FMLs to different species can vary by orders of magnitude.

Tests to measure the permeability of FMLs to different species include the following:

- Water vapor transmission, ASTM E96, Inverted Water Method (Procedure BW).
- Solvent vapor transmission, ASTM E96, Inverted Water Method (Procedure BW), modified.
- Gas permeability, ASTM D1434, Procedure V--Volumetric.
- Pouch test, Appendix D.

These tests are discussed in Section 4.2.2.4.1, "Permeability." All of these tests can be used to determine the permeability characteristics of all types of FMLs with the exception of the pouch test. Because of the difficulty in forming seams of narrow widths in crosslinked FMLs, it is not possible to use the pouch procedure in testing crosslinked FMLs. The pouch test also functions as a long-term exposure to a waste or test liquid.

4.2.2.5.4 Tests to measure the effects of environmental or accelerated exposure--Appropriate or applicable methods for determining the effects of environmental or accelerated exposure are listed in Table 4-27. The following paragraphs discuss these tests.

Ozone-Cracking. FMLs must be resistant to ozone-cracking. Ozone can be particularly damaging to and cause severe cracking in polymers that have unsaturation in their main chains. Of the polymers that have been used in FMLs, only butyl and neoprene have unsaturation in their main chains. ASTM D1149 estimates the resistance of a sample to cracking when exposed to an atmosphere containing ozone. Specimens are kept under a surface tensile strain, and the ozone content or partial pressure in the test chamber is maintained at a fixed value.

Environmental Stress-Cracking. A stress-crack is defined as either an external or internal crack in a plastic that is caused by tensile stress less than its mechanical strength as measured at standard rates. Under conditions of simultaneous stress and exposure to chemicals (e.g. soaps, oils, detergents, or other surface-active agents), some plastics, such as PE, can fail mechanically by cracking. A test can be run that indicates the susceptibility of a PE sheeting to stress-cracking by exposing bent specimens with controlled imperfections to a designated surface-active agent. ASTM D1693, though commonly used to measure susceptibility to stress-cracking, has limitations for assessing the long-term resistance in service of FMLs to cracking. In this test 10 notched and bent strip specimens are

TABLE 4-27. APPROPRIATE OR APPLICABLE METHODS FOR DETERMINING EFFECTS OF ENVIRONMENTAL OR ACCELERATED EXPOSURES ON POLYMERIC FMLS

Property	FML without fabric reinforcement			Fabric reinforced
	Thermoplastic	Crosslinked	Semicrystalline	
Ozone-cracking	ASTM D1149	ASTM D1149	na	ASTM D1149
Environmental stress-cracking	na	na	ASTM D1693	na
Low-temperature testing	ASTM D1790	ASTM D746	ASTM D1790/D746	ASTM D2136
Tensile properties at elevated temperature	ASTM D638 (modified)	ASTM D412 (modified)	ASTM D638 (modified)	ASTM D751, Method B (modified)
Dimensional stability	ASTM D1204	ASTM D1204	ASTM D1204	ASTM D1204
Air-oven aging	ASTM D573 (modified)	ASTM D573 (modified)	ASTM D573 (modified)	ASTM D573 (modified)
Water absorption	ASTM D570	ASTM D471	ASTM D570	ASTM D570
Liner/waste compatibility	EPA 9090 ^a ASTM D471/D543	EPA 9090 ^a ASTM D471	EPA 9090 ^a ASTM D543	EPA 9090 ^a ASTM D471/D543
Soil burial	ASTM D3083	ASTM D3083	ASTM D3083	ASTM D3083
Pouch test	Appendix D	na	Appendix D	Appendix D
Outdoor exposure:				
Test slabs	ASTM D1435	ASTM D1435	ASTM D1435	ASTM D1435
Bent loops	ASTM D518	ASTM D518	ASTM D518	ASTM D518
Tub test	Appendix H	Appendix H	Appendix H	Appendix H
Accelerated outdoor weathering (EMMAQUA)	ASTM D4364	ASTM D4364	ASTM D4364	ASTM D4364

^aEPA, 1986.

na = Not applicable.

immersed in a detergent solution, and the time it takes before 5 of the 10 specimens break is determined. The test apparatus is shown schematically in Figure 4-44. This method is not suitable for testing PE seams.

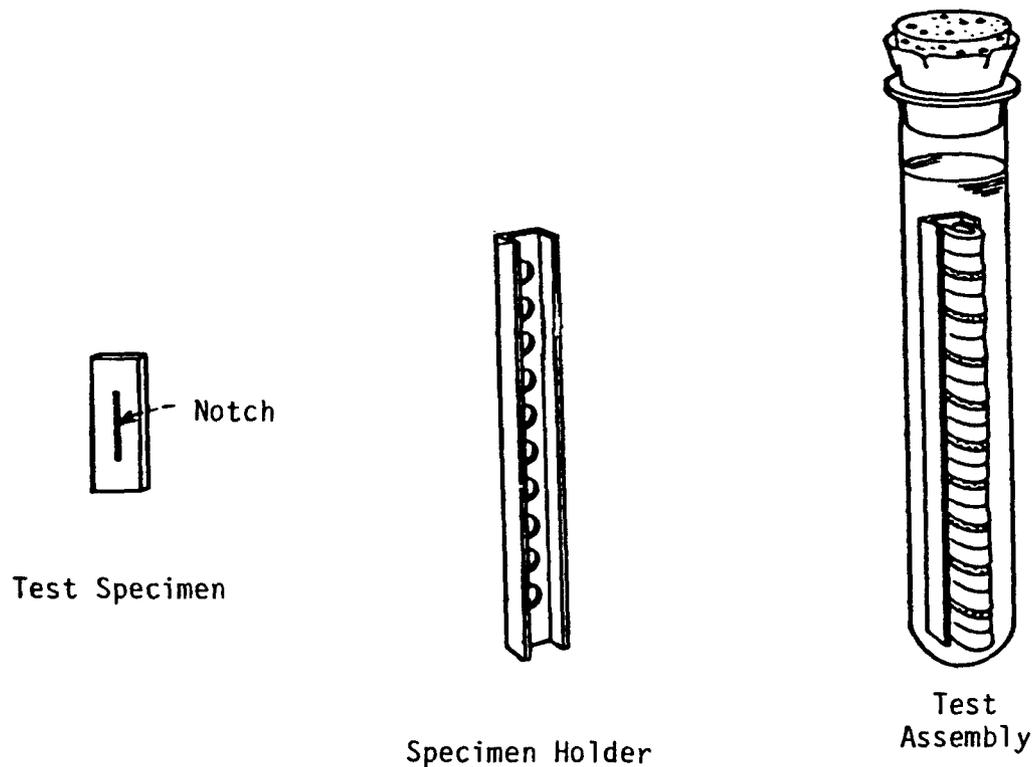


Figure 4-44. Specimen and equipment of ASTM D1693 for bent-strip test specimen is 0.5 ± 0.03 in x 1.5 ± 0.1 in. The holder is 6.5 in. in length and 0.463 ± 0.002 in. in inside width. It holds 10 specimens. The holder with specimens is placed in a 32 x 200 mm test tube fitted with an aluminum foil wrapped cover. The notch cut in the specimen is 0.750 ± 0.005 in. in length and varies in depth depending on the thickness of the sheeting. (Based on ASTM D1693).

Another method used to measure the tendency of a semicrystalline product to break when exposed simultaneously to stress and a detergent solution is ASTM D2552. In this test, 20 dumbbell specimens are placed under constant load, and the time it take before 10 of the 20 specimens break is determined. The test apparatus is shown schematically in Figure 4-45. This method has been used to test seams by selecting a dumbbell with a neck section of sufficient length to test the full width of the seam and by modifying the specimen holders accordingly.

Crissman (1983) has proposed another test where the specimen is constrained in a fixed geometry by binding it around a cylindrical metallic form and subjecting it to a constant applied stress, as is shown in Figure 4-46.

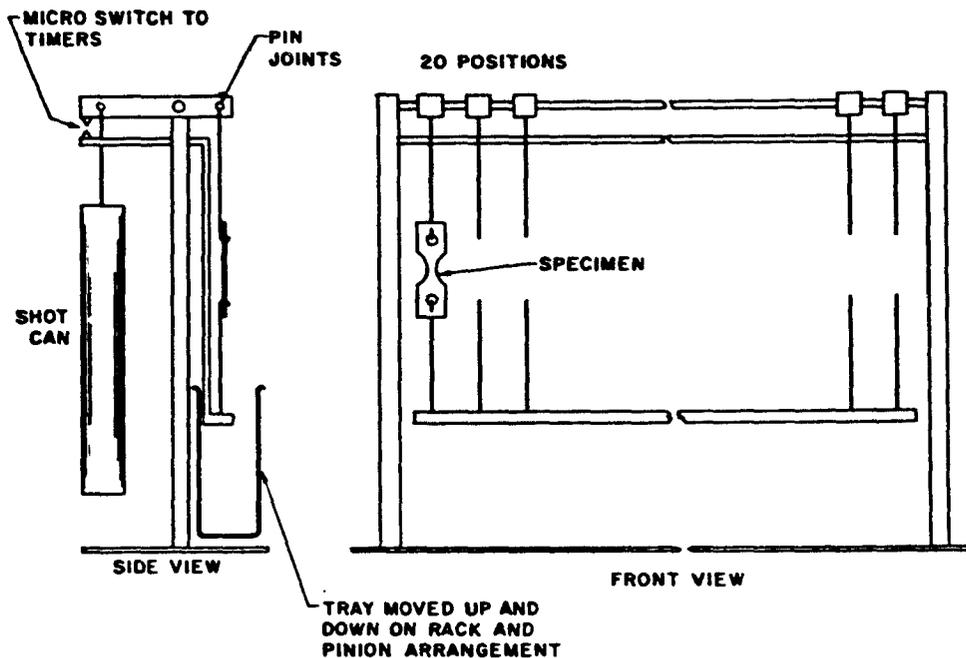


Figure 4-45. Schematic view of constant-load stress rupture test apparatus of ASTM D2552. (Based on ASTM D2552).

Low-Temperature Properties. Liners can encounter low temperatures before installation, during installation, and in some cases during service depending on the climate in which they are installed.

Some FMLs are quite sensitive to low temperature, becoming stiff and even brittle on exposure to moderately low temperatures. The rate varies at which these changes take place as does the time it takes for a material to soften when the temperature is raised. Some changes can take an extended time; consequently, short-term tests can be quite misleading. A variety of tests exist for measuring the effects of low temperatures on materials. Brittleness test methods are some of the most available. However, they vary greatly in low temperature soak time, rate of test, configuration of specimen, etc.; consequently, even for a given polymer type, results can vary greatly, depending on thickness of specimen, time of soak and the specific test used. Some of the commonly used low temperature tests are:

- ASTM D746 - Brittleness Temperature of Plastics and Elastomers by Impact.
- ASTM D1034 - Stiffness Properties of Plastics as a Function of Temperature by Means of a Torsion Test (also used on rubber compositions).
- ASTM D1790 - Brittleness Temperature of Plastic Film by Impact.

ASTM D2136 - Low Temperature Bend Test of Coated Fabrics.

ASTM D2137 - Brittleness Point of Flexible Polymers and Coated Fabrics.

High-Temperature Properties. An FML may encounter higher than normal temperatures prior to installation, during installation, and during service. Thermoplastic FMLs, if allowed to be exposed to heat as rolled or folded panels prior to installation, such as being left in the sun, can block or stick together; when unfolded, a coated FML may split or an unreinforced FML may tear and become unserviceable. During installation, a black FML can reach temperatures of more than 160°F (71°C). At such temperatures, tensile and tear strengths can be significantly lower than at normal test temperatures. Appropriate tensile, modulus, and tear tests can be run at temperatures of 60°C or higher to indicate the effects of elevated temperature. At such temperatures the percent crystallinity in semicrystalline polymers, such as PE, drops (Miller, 1966). The results of some high temperature testing are presented in the paragraph "Effect of Temperature on Properties" in Section 4.2.2.4.2 above.

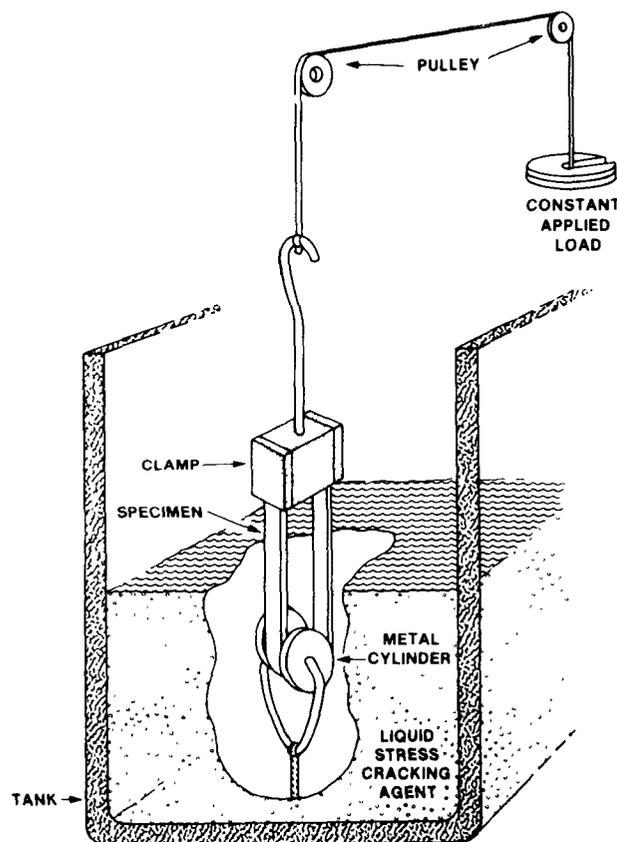


Figure 4-46. Schematic of a proposed test method for determining environmental stress-cracking resistance. (Source: Crissman, 1983).

Dimensional Stability. In addition to causing changes in the mechanical properties of an FML, higher temperatures can also cause shrinkage and distortion due to relaxation of stresses in an FML compound, particularly in unreinforced thermoplastic FMLs. ASTM D1204 measures changes in the linear dimensions of 10 by 10-in. specimens resulting from exposure at 100°C for "the length of time applicable to the material being tested."

Water Absorption. The absorption of water can adversely affect many polymeric compositions. Since most waste liquids contain water, the effects of immersion in water on FMLs should be determined as part of the selection process. The effects of immersion are evaluated by changes in weight, dimensions, or properties. A water absorption test, such as ASTM D471 and D570, can be included in a test program to provide a relatively precise comparative index. (Note: ASTM D471 covers the testing of crosslinked materials and ASTM D570 covers plastics.) In performing these tests, extended immersion of specimens until the weight is constant is recommended.

To assess the effects of water absorption on tensile properties, sufficiently large strips can be immersed so that tensile specimens can be died out of them and tested. Precut tensile specimens can also be used. Water absorption tests at elevated temperatures accelerate the effects of immersion. However, test results have indicated that tests at 70°C and above are too severe to serve as accelerated aging tests for most FMLs (Haxo et al, 1982, p 87).

Liner/Waste Compatibility Testing. The compatibility of a candidate FML with the leachate or waste liquid to be contained is an essential consideration in making the final choice of an FML for use as a liner in a waste storage or disposal facility.

The EPA has developed Method 9090 to determine the compatibility of FMLs and waste liquids. In this test, samples in slab form are immersed for up to four months at 23°C and 50°C in a representative sample of the waste liquid or leachate to be contained. Physical and analytical testing are performed on the unexposed FML for baseline data and on samples after exposure to the waste liquid for 30, 60, 90, and 120 days. Thus, the entire test involves many steps including:

- Selecting representative or appropriate samples of the waste liquid or leachate and the FML.
- Exposing the FML samples to the waste liquid or leachate under highly controlled conditions.
- Testing the physical and analytical properties of the unexposed and exposed FML samples.
- Interpreting the final results.

This test is discussed in detail in Chapter 5.

In cases which do not require testing in accordance with Method 9090, such as in the selection of an FML for secondary containment of an underground storage tank, the candidate FMLs should still be tested in immersion tests. Recommended immersion tests include ASTM D471 and D543. Sufficiently large strips can be immersed in these tests so that tensile specimens can be died out of the strips and tested in order to indicate the effects of immersion on tensile properties.

Pouch Test. The pouch test, described in Appendix D, can be used to measure the permeability of polymeric FMLs to water, organics, test liquids, or ions, and dissolved organics and is, at the same time, a one-sided exposure test. In this test, a waste liquid or test liquid is sealed in a pouch made of the FML under study. The pouch is then placed inside a container filled with deionized water or a liquid of known composition. At regular intervals, the pouch is removed and weighed to monitor the movement of water or the test liquid through the pouch walls. The electrical conductivity of the liquid outside the pouch is measured regularly to evaluate the permeation of ions through the pouch walls. At the end of the exposure the pouch is dismantled, and the pouch walls are tested for physical and analytical properties. Because of the difficulty of making narrow width seams with crosslinked FMLs, this procedure can only be used to test thermoplastic FMLs. Selected data from pouch tests are presented in the paragraphs in Section 4.2.2.4.1 on the permeability of FMLs to ions and the permeability of FMLs to organics. Results of pouch tests are also discussed in Chapter 5.

Outdoor Exposure Tests. As most FMLs are exposed to the weather at some time during installation and/or service, outdoor exposure tests should be performed. Four tests in which FMLs can be exposed to weathering are:

- Outdoor exposure of test slabs on a rack.
- Exposure as bent loops.
- Exposure as liners in tubs filled with a waste liquid.
- Accelerated weathering test (EMMAQUA).

Outdoor Exposure of Test Slabs--Exposing small slabs of FMLs to ambient weather conditions on panels that face due south at a 45° angle gives an indication of the weatherability of an FML. In this exposure, samples are exposed to UV light, oxygen, ozone, heat, and wind. Changes in physical and analytical properties as well as surface appearance after exposure can indicate relative differences between compounds of different polymer types and among compounds of one polymer type. ASTM D1435 details a procedure for outdoor exposure on test racks.

Bent Loops--In the bent loop test (ASTM D518, modified), small specimens of FMLs are bent into loops, which are exposed to the weather. This test combines exposure to weather (as in roof exposure of test slabs) with exposure to stress provided by the

bent loop. The specimens are inspected regularly for signs of cracking or crazing on the FML surface. This test can be used only qualitatively in the FML selection process.

Tub Test--The tub test, described in Appendix H, can evaluate liner/waste compatibility in a configuration that simulates some actual field conditions. A small tub is placed where it is exposed to the weather. The tub is lined with a seamed sheet of the FML which is carefully folded into place. The tub is then filled approximately 3/4 to 7/8 full with the waste. The waste level is allowed to drop 4 inches by evaporation before the tub is refilled with tap water. Overflow is avoided by covering the tub during periods of precipitation. This test provides exposure to sunlight, a range of temperatures, and ozone, as well as to the test waste. A horizontal area around the tub at the water-line is intermittently exposed to weather and to waste as the waste level fluctuates. Extended exposures of several years duration are recommended. After exposure the various exposed areas of the FML are subjected to physical and analytical tests. This test is semiquantitative and can identify some of the exposure conditions that are detrimental to the FML being tested. Results of tub tests are presented in Chapter 5.

Accelerated Outdoor Weathering Using Concentrated Natural Sunlight--A procedure has been developed for accelerating the effects of outdoor exposure on coatings and polymeric products, including FMLs (ASTM D4364 and G-90). Specimens are exposed in a test machine that concentrates the sun's rays on a test specimen. The test machine follows the sun and has ten flat mirrors, positioned in such a way that the sun's rays strike them at near-normal incident angles while in operation. These mirrors reflect concentrated sunlight onto an air-cooled target board on which specimens are mounted. Maximum sample size, which is 5 x 55 in. in the ASTM D4364 and G-90 design, is limited by the size of the mirrors. Exposure can be either with or without water. Exposure with water involves spraying water on the exposure samples in a regular, cyclic fashion. This exposure is also known as the EMMAQUA (Equatorial Mount with Mirrors for Acceleration plus water spray) test. Samples are exposed either for a specified time period or until a specified quantity of solar irradiation has been reached. Samples can be visually inspected for changes in general appearance, checking/crazing, cracking, blistering, warping. After exposure, the physical and analytical properties can also be measured.

The test machine can be used to determine the effects of weathering in test times considerably shorter than conventional south-facing racks under natural weathering conditions. It is estimated that one year exposure in the test machine equals 8 years of exposure to natural weathering. The effectiveness of the test machine depends primarily on the amount and character of the

ultraviolet in the direct beam component of the sunlight. Thus, this test requires climatic conditions with sufficient short wavelength ultraviolet in the direct beam, i.e. desert or high altitude environments which are also not regions of diffuse irradiance.

Some specifications are now requiring that FMLs to be used as exposed (as opposed to buried) liners shall pass the EMMAQUA test for a minimum of 1,000,000 langleys with a rating of 7 or better, i.e. have no checks greater than 0.006-in. wide.

Morrison and Parkhill (1987) have indicated that a 1-yr EMMAQUA exposure, which exposed FML samples to 1.45×10^6 langleys, was too long resulting in weathering conditions that were too severe for some materials, particularly the PEs, causing thermal degradation that may not occur in long-term exposure to natural weathering. Further studies are recommended to determine if the EMMAQUA exposure of FMLs correlates with field exposure.

4.2.2.5.5 Performance tests--Performance tests attempt to simulate in the laboratory the mechanical behavior of an FML in the field in order to determine the actual engineering properties needed for designing a liner system. At present, all performance tests of FMLs are developmental rather than standard.

Stress-Strain Behavior of FMLs. The usual tension test used to determine the stress-strain characteristics of unreinforced FMLs uses a small "dogbone"-shaped test specimen. Such specimens are convenient since failure always occurs within the central, narrowed test zone and since they require little material, are easy to form, and can be held in the grips of a test machine without slipping. The shape and size, however, are inadequate to predict full-scale stress-strain behavior of an in-service FML. The behavior of a large, i.e. wide, FML can better be reflected by a wide-width tensile specimen and a corresponding test method; just how wide is left up to the user's discretion. ASTM Committee D35 on geotextiles and related products has decided on an 8-in. wide specimen and a 4-in. initial jaw separation (ASTM D4595). While this method is primarily intended for the testing of geotextiles, it can be used for FMLs. One problem with this test method is that the test specimens often fail at the face of the clamps where stress concentrations exist. This, in turn, might be avoided by using roller grips, which are typically used in testing high strength geotextiles, but using roller grips necessitates monitoring deformations with an external device such as a laser or infrared tracking device.

Even the wide-width tensile specimen test, however, does not truly simulate in situ behavior since there are no stresses acting on the surfaces of the FML. FMLs in the field invariably have soil above and below them, and this undoubtedly influences their tensile behavior. Confinement between these two layers must be simulated in order to have an accurate performance test. McGown et al (1982) have developed a test apparatus to simulate in-soil stress-strain, creep, and stress relaxation behavior.

The confinement is mobilized by pressurizing an 8-in. wide and 4-in. long FML specimen with an air-inflated bellows via a thin soil layer placed on both sides of the FML. The resulting influence of this type of confined test on the stress-strain behavior of geotextiles (particularly the nonwoven variety) is seen to be very large. Figure 4-47 presents the results of confined and unconfined stress-strain testing of two geotextiles. Confined testing was performed with a confining pressure of 100 kN m^{-2} (14.5 psi). In general, the stress at failure and the apparent modulus increase, whereas the strain at failure decreases. The amount depends upon the material type and the level of confining stress. Work is ongoing as to the behavior of FMLs under varying confining pressures.

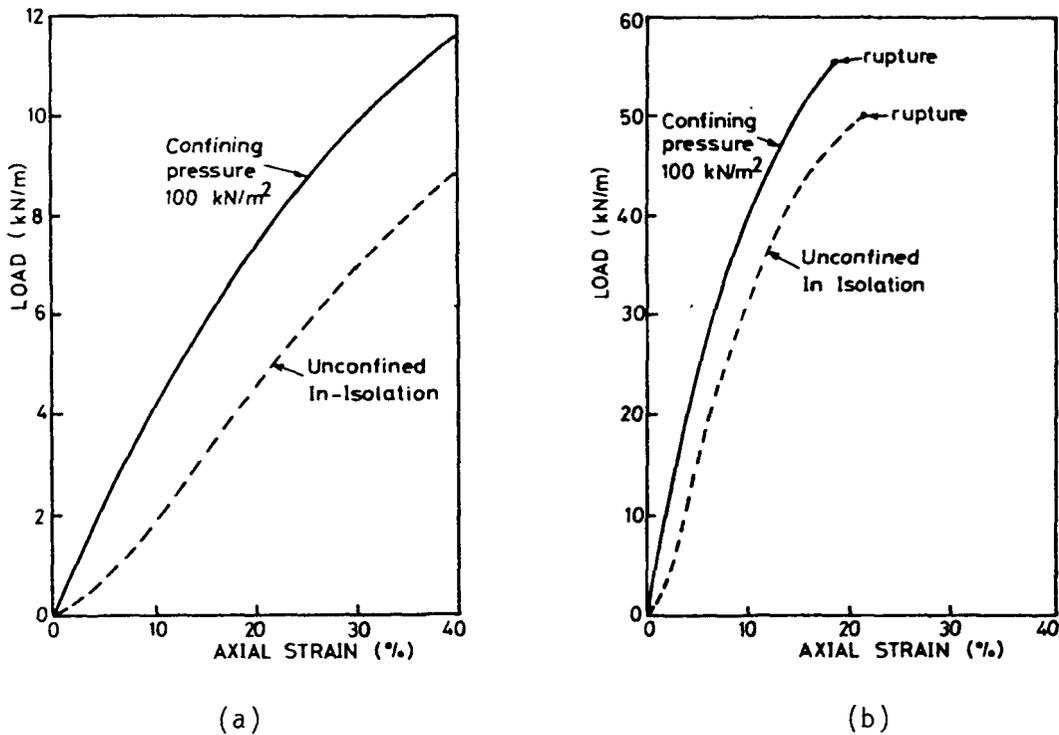


Figure 4-47. Confined and unconfined stress-strain testing of two geotextiles. (Source: McGown et al, 1982, p 797).

Sustained Load (Creep) Behavior of FMLs. Compared with more traditional materials of construction, polymeric materials have a relatively high tendency to creep under constant load, as indicated in Section 4.2.

Creep testing generally results in one of three different deformation vs. time response curves. These response curves are shown in Figure 4-48.

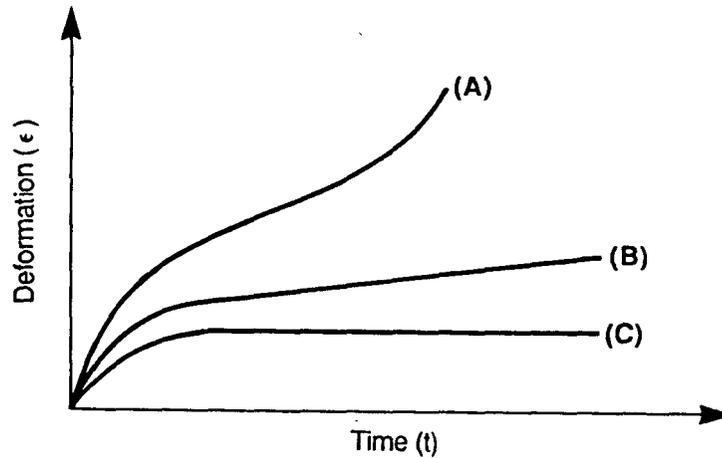


Figure 4-48. Types of creep behavior. Curve A describes creep failure. Curve B shows constant creep after initial deformation by load. Curve C shows no creep after initial deformation by load.

Since Curve A is in, or leading to, a failure state it is beyond consideration and only curves like B or C are to be considered. The empirical relationship defined by these two curves is represented by the following equation:

$$\epsilon_t = \epsilon_0 + b \log t, \quad (4-9)$$

where

ϵ_t = strain at a future time "t",

ϵ_0 = initial, or elastic, strain,

b = experimentally obtained constant, and

t = service time under consideration.

To simulate the creep behavior of an in-service FML, test specimens need to be evaluated under some type of confinement. This confinement can be accomplished using the same equipment that is described in the previous paragraph except that a dead load is applied to the specimen. An example of the unconfined and confined stress-strain testing followed by creep of two geotextiles is presented in Figure 4-49.

Little work has been done on the creep testing of confined FMLs, but work has progressed in assessing polymer behavior under constant stress or constant strain in both the geotextile and geogrid areas (McGown et al, 1982; Shrestha and Bell, 1982; and Tensar, n.d.).

Shear Strength of FMLs Against Soil. Adequate friction between a soil and an FML is important in the performance of FML-lined slopes in land

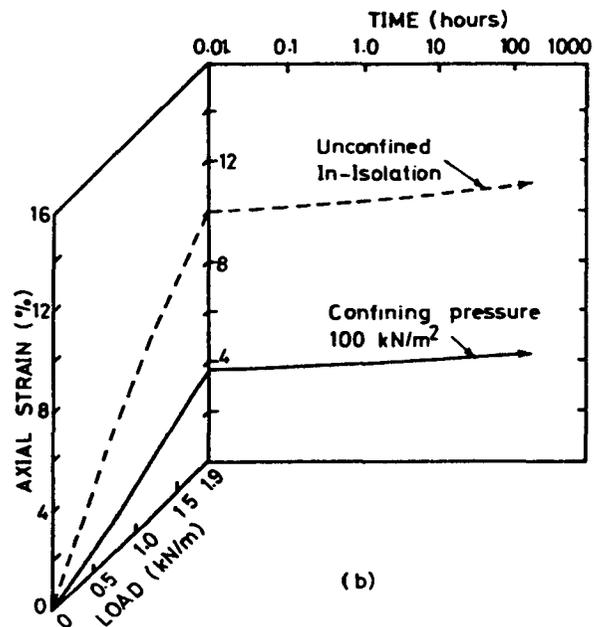
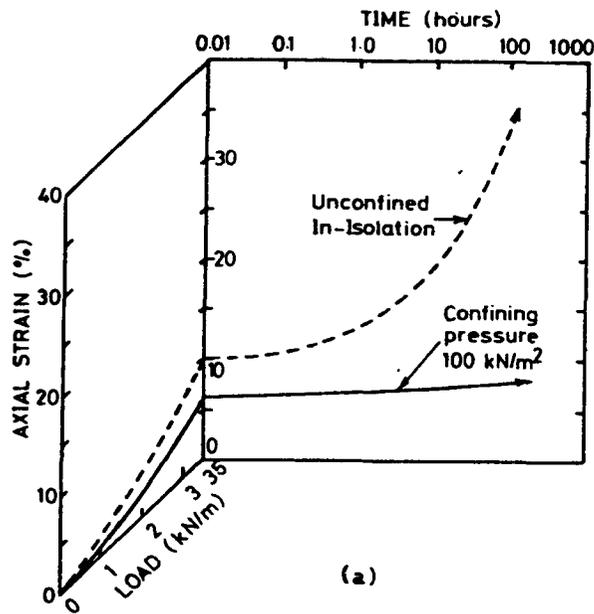


Figure 4-49. Confined and unconfined stress-strain testing followed by creep of two geosynthetics. (Source: McGown et al, 1982, p 795).

storage and disposal facilities. Without adequate friction, there may be slippage between components of the liner system. A laboratory test for determining the shear strength of FMLs against different soil types has been developed (Martin et al, 1984; Koerner et al, 1986). This test is a direct

adaptation of a direct shear test commonly used in geotechnical engineering. Figure 4-50 presents this test schematically. The FML test sample is placed on a rigid block in the upper or lower half of the shear box. The other half has soil at the prescribed density and water content. A normal stress is applied to the system and held constant, after which shear stress is applied at a uniform deformation rate. Although the test method is still in an ASTM D35 Subcommittee, the shear deformation rate commonly used is 0.2 ipm. Figure 4-51a schematically shows the results of testing an FML against a soil three times with the same deformation rate but with three different normal stresses. The peak shear stresses resulting from these tests are used to plot the Mohr Coulomb failure curve of Figure 4-51b. From this curve the shear strength parameters of adhesion (c_a) and FML-to-soil friction angle (δ) can be graphically determined. These values can then be compared to the shear strength parameters of the soil itself to obtain efficiencies in the following manner:

$$E_c = (c_a/c) \times 100, \quad (4-10)$$

$$E_\phi = (\tan \delta / \tan \phi) \times 100, \quad (4-11)$$

where

E_c = cohesion efficiency,

E_ϕ = friction angle efficiency,

c = soil cohesion, and

ϕ = soil friction angle.

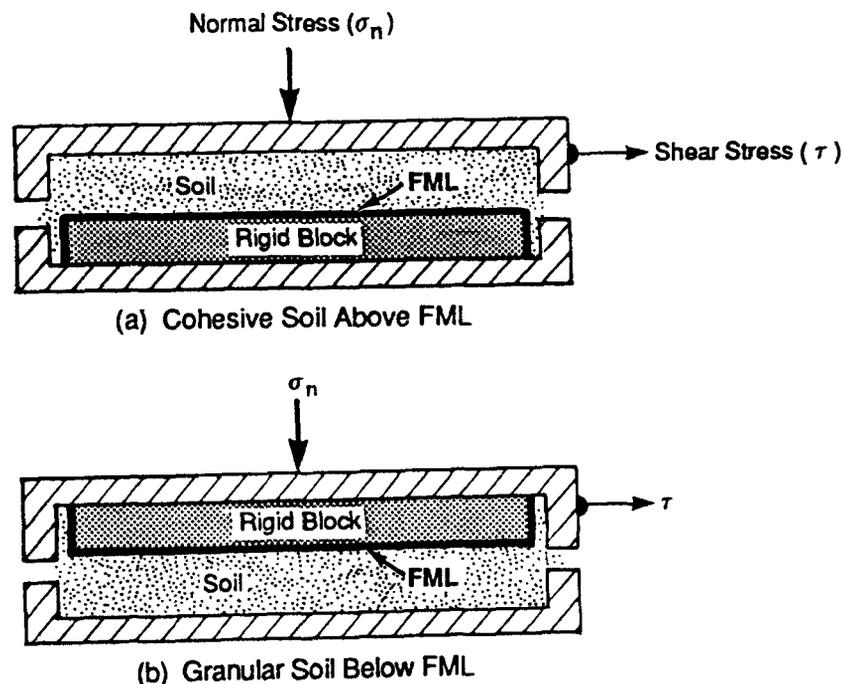
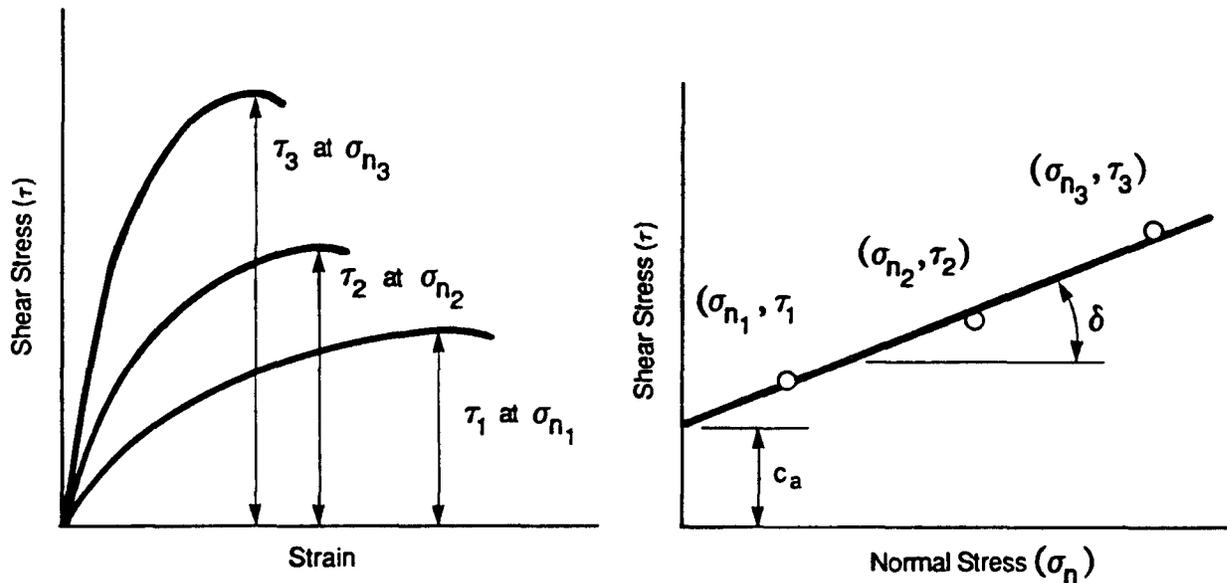


Figure 4-50. Direct shear test to evaluate FML-against-soil shear strength.



(a) Shear stress vs. strain curves of an FML tested three times with a single deformation rate and three different normal stresses, σ_{n1} , σ_{n2} , and σ_{n3} .

(b) Mohr-Coulomb failure curve

Figure 4-51. Typical direct shear curves and determination of FML-to-soil friction angle (δ) and adhesion (c_a).

Tables 4-28 and 4-29 present some relative values of FMLs versus different soils. It should be noted, however, that the tests must be conducted for each situation independently with as close of a simulation as possible to the in situ condition. It should be noted that water content in fine-grained soils is critically important. For example, an FML which is a secondary composite liner in a landfill will be in intimate contact with the clay soil beneath it. The water content of this clay influences the shear strength parameters greatly. When the clay is placed wet of optimum, very low values usually result. The long-term situation as the clay changes in water content is also of interest.

TABLE 4-28. FRICTION ANGLE VALUES AND EFFICIENCIES FOR FMLS TO GRANULAR SOILS

FML	Soil types ^a					
	Concrete sand		Ottawa sand		Mica schist sand	
	δ	E_{ϕ} , %	δ	E_{ϕ} , %	δ	E_{ϕ} , %
CSPE	25°	81	21°	72	23°	87
EPDM	24°	77	29°	68	24°	91
HDPE	18°	56	18°	61	17°	63
PVC:						
Rough	27°	88	...	...	25°	96
Smooth	25°	81	...	...	21°	79

^aSoil friction angle of concrete sand = 30°; soil friction angle of Ottawa sand = 28°; soil friction angle of mica schist sand = 26°.

Source: Martin et al, 1982, p 193.

Anchorage, or Embedment, Depth of FMLs. A test method is being developed to determine the anchorage, or embedment, depth required to mobilize a given stress level in an FML specimen, one end of which is confined in a testing device that simulates vertical burial in soil (GRI, 1987a). This test attempts to determine the minimum depth of burial which will achieve enough friction on an FML in order for the FML to be held in place up to a targeted stress. Various targeted stress levels include:

- Yield stress, for semicrystalline FMLs.
- Scrim break, stress for reinforced FMLs.
- An allowable stress at a given strain level, for unreinforced cross-linked or thermoplastic FMLs, e.g. stress at 50% strain.

This test method uses an 8-in.-wide FML specimen which is firmly clamped at its upper end and sandwiched between back-to-back channels at its lower end, as is shown schematically in Figure 4-52. These channels are pressurized by a hydraulic system. The depth of the specimens in the channels is varied in order to determine the desired embedment depth at a specific normal pressure. Figure 4-53 shows applied normal pressure vs. depth within the channel's curve. The depth in the channels necessary for the specimen to be held in place up to yield, failure, or a predetermined stress or strain is strongly dependent on the applied normal pressure and the type of FML (Lawrence, 1987).

TABLE 4-29. SHEAR STRENGTH PARAMETERS OF FMLS TO COHESIVE SOILS AT OPTIMUM WATER CONTENT

Description	Soil No. 1 ML-CL				Soil No. 2 CL-ML				Soil No. 3 CL				Soil No. 4 SP-CH				Soil No. 5 CH-SP			
	c	E _c , %	φ	E _φ , %	c	E _c , %	φ	E _φ , %	c	E _c , %	φ	E _φ , %	c	E _c , %	φ	E _φ , %	c	E _c , %	φ	E _φ , %
Soil to soil	9.0	100	38	100	12.0	100	34	100	20	100	30	100	25	100	24	100	28	100	22	100
	c _a	E _c , %	δ	E _φ , %	c _a	E _c , %	δ	E _φ , %	c _a	E _c , %	δ	E _φ , %	c _a	E _c , %	δ	E _φ , %	c _a	E _c , %	δ	E _φ , %
FML to soil:																				
CPE	8.0	89	40	100	3.2	27	24	66	13.0	65	17	53	8.0	32	23	95	10.0	36	19	85
EPDM	5.0	55	33	83	5.0	42	23	63	8.0	40	23	74	7.5	30	20	82	9.0	32	18	80
HDPE	5.0	88	26	62	2.0	17	23	63	14.0	70	15	46	3.0	12	21	86	14.0	50	15	66
PVC	8.5	94	39	100	3.7	31	23	63	14.0	70	16	50	7.0	28	24	100	12.0	43	17	76

Note: c and c_a are in units of kN/m², φ and δ are in degrees.

Source: Koerner et al, 1986, p 28.

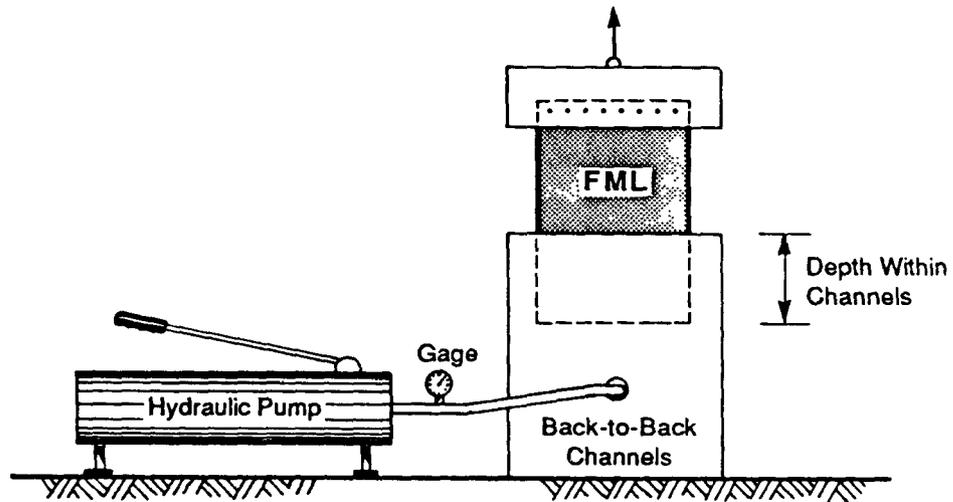


Figure 4-52. Schematic view of embedment depth test apparatus.

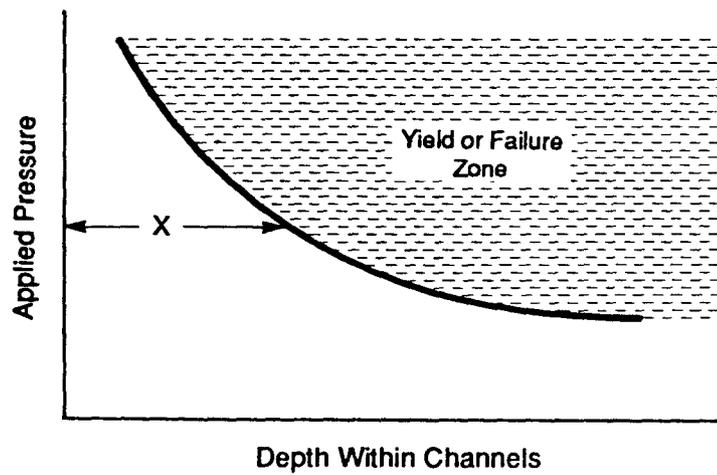


Figure 4-53. Curve representing the relationship between applied normal pressure and depth within the channels in embedment depth test.

Puncture (Hydrostatic) Resistance of In-Service FMLs. The integrity of an FML is essential for its functioning properly during service. The FML may be penetrated or punctured by gradual piercing caused by a protrusion from the subgrade. The load placed on the FML may cause a hole to form gradually as the FML bridges a small cavity and hydraulic pressure forces the liner down into the cavity. The standard tests, including FTMS 101C Methods 2031 and 2065 for puncture resistance and the Mullen hydrostatic test (ASTM D751) which are discussed in Section 4.2.2.5.2, test only a limited-size sample. These test conditions do not simulate the differential stresses of a larger area FML over an irregular subgrade. Various tests have been developed which attempt to simulate the performance on an FML which is under a hydrostatic pressure and which has been placed on an irregular substrate. The conditions that have been simulated include:

- Bursting over interstitial spaces in a subgrade (Frobel, 1983; Morrison and Starbuck, 1984; Fayoux and Loudiere, 1984; Mitchell and Cuello, 1986; Frobel et al, 1987).
- Puncture over protrusions (Frobel et al, 1987; Rigo, 1977; Morrison and Starbuck, 1984; Frobel, 1983).
- Bursting related to settlement of the subgrade (Steffen, 1984).
- Bursting related to damage caused by a load placed on a cover material over the FML (Fayoux and Loudiere, 1984).

All of these tests use similar testing devices. With the exception of Steffen (1984) who used only compressed air, a compressed air-on-water pressurizing system was used to simulate hydrostatic head. Effective diameter of the test specimens ranged from 8 in. up to 39 inches. Hydrostatic testing has also been used to study the effect of using geotextiles to protect FMLs (Frobel et al, 1987; Fayoux and Loudiere, 1984). An example of a hydrostatic testing device is presented in Figure 4-54.

4.2.2.6 Fingerprinting of FMLs--

The fingerprint of an FML is the sum total of its analytical properties as determined by the tests discussed in Section 4.2.2.5. The data generated by these tests establish a body of data that can identify the FML. Fingerprinting a polymeric FML at the time of installation can be used:

- To assess the quality of the specific FML being placed at a site.
- To assure the designer/owner/operator that the FML being placed in the field is equivalent to the FML that was tested in the compatibility studies, such as EPA Method 9090 liner compatibility test.
- To establish a baseline for assessing the effects of service exposure on the FML.

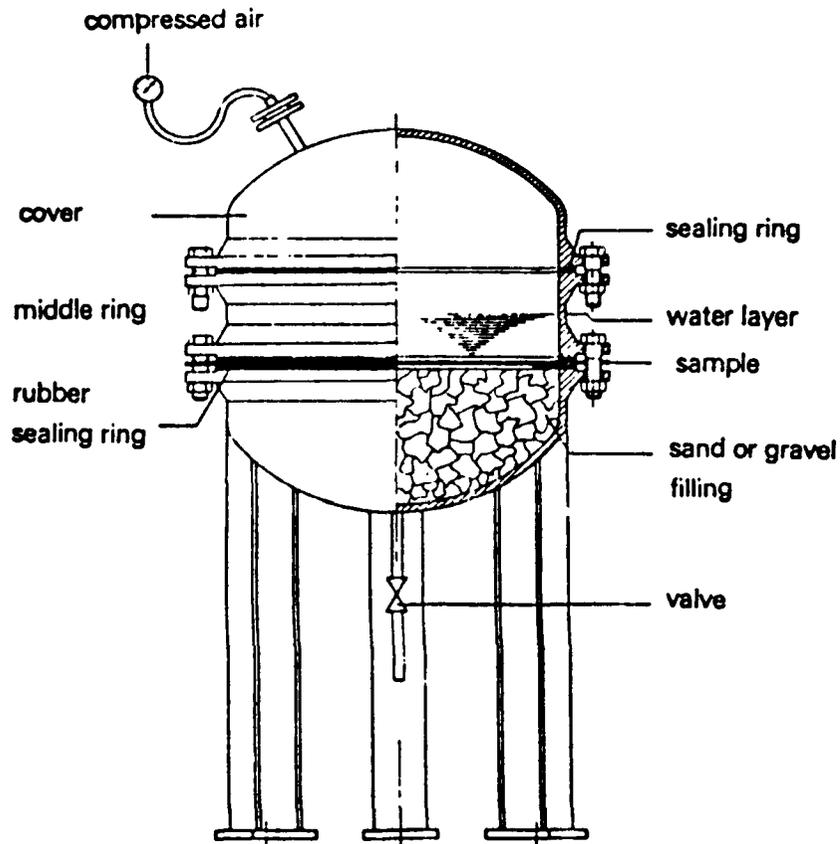


Figure 4-54. Schematic of hydrostatic test facility. (Source: Geosynthetic Research Institute, 1987b).

The analyses used in fingerprinting an unexposed FML can be used to analyze exposed FMLs:

- To identify the FML that was originally installed as a liner, with respect to the type of FML, its composition, and possibly its actual source (in cases where there is some question due to lack of adequate records, etc).
- To determine the effects of exposure on the FML, and thus be able to estimate the probable service life of the liner under service conditions.

In selecting specific analyses for fingerprinting an exposed FML to determine the effects of exposure, it is important to measure critical properties that may have been affected by exposure, e.g. extractables. However, in selecting specific test methods for identifying an exposed FML, it is desirable to select tests that measure characteristics that do not change with exposure. Examples of such tests include analyses for the inorganic constituents of the

compound (e.g. the trace metals residues of the polymerization catalysts) and the percentage of carbon black; these compositional characteristics probably do not change with time since these constituents are insoluble. Most of the other parameters of the analyses will change to a certain degree with aging and exposure; consequently, care must be taken in interpreting the results of these analyses when used for identification purposes, though they can be used as measures of change in the FML.

Haxo (1983) described a general protocol for fingerprinting FMLs. This protocol is presented schematically in Figure 4-55, with particular reference to exposed FMLs. Different polymeric FMLs require different fingerprinting procedures. All tests in the protocol are not used on all materials. For example, the following is a list of potentially useful tests for fingerprinting PE FMLs:

- Density and specific gravity of compound and resin*.
- Carbon black content by TGA*.
- Percentage crystallinity by DSC*.
- Oxidative induction time (OIT) by high-pressure DSC*.
- Determination of extractables for amount and composition of the extract which will include stabilizers and soluble additives that are in the compound.
- GC analysis of the extract to identify stabilizers.
- Ash content and spectographic determination of the ash for trace metals residues of polymerization catalysts.
- Melt index*.
- Molecular weight distribution by gel permeation chromatography (GPC).
- Infrared analysis of the polymer to determine the type of PE and of the extract to identify the stabilizers.

It is not necessary to perform all of these analyses to fingerprint and identify a specific PE FML. Table 4-30 presents the results of fingerprinting two HDPE FMLs using selected analytical tests. These FMLs had been received at different times, and fingerprinting was performed to demonstrate that the two FMLs were probably of the same composition. Similar analyses can be used for fingerprinting various geosynthetics and pipe, particularly those based on PE and PB.

*Suggested minimum tests to be performed for fingerprinting purposes, some of which are incorporated in specifications.

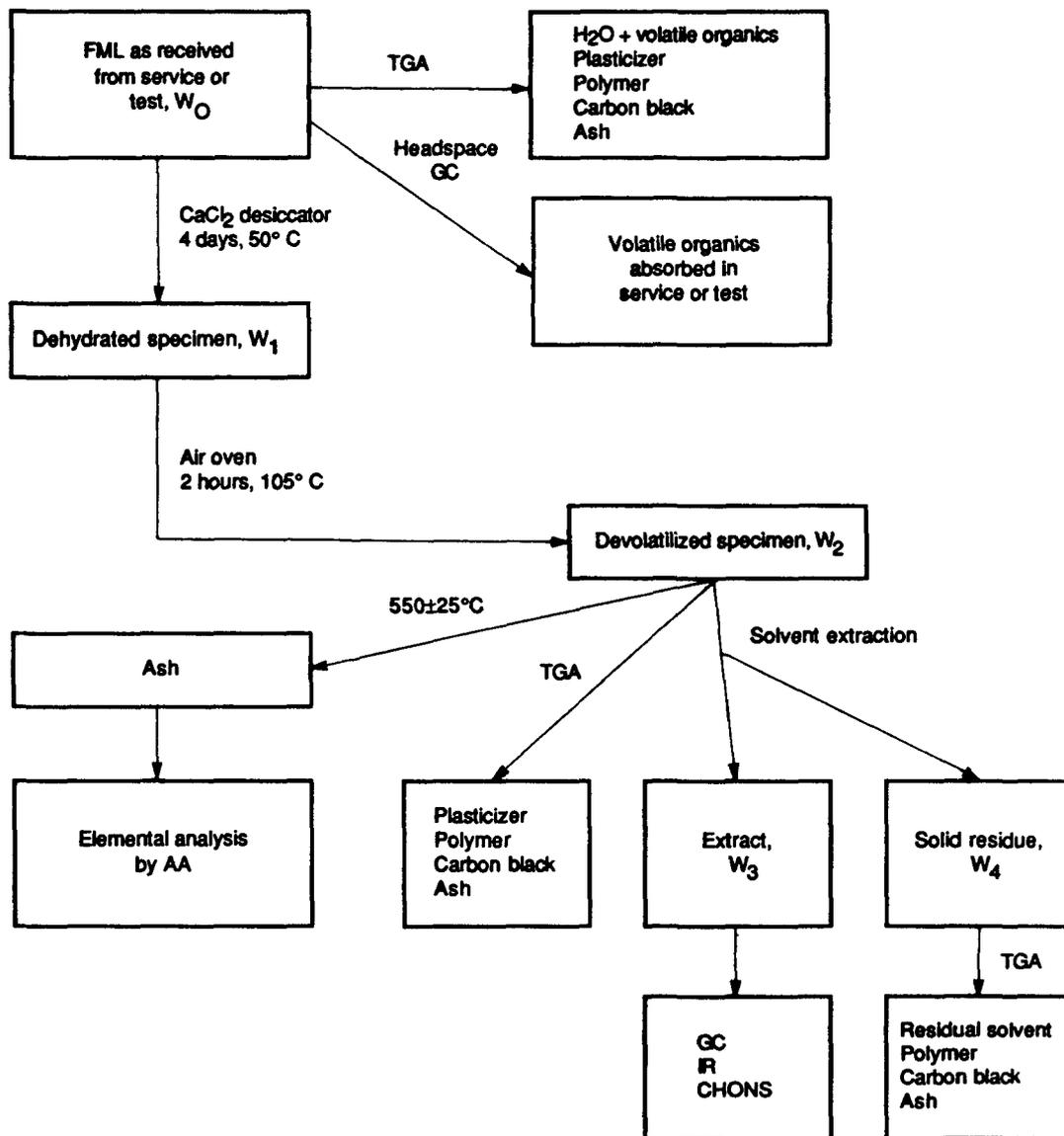


Figure 4-55. Plan for the analysis of exposed polymeric FMLs. AA is atomic absorption analysis for metals; GC is gas chromatograph; IR is infrared; CHONS is the elemental analysis for carbon, hydrogen, oxygen, nitrogen, and sulfur.

TABLE 4-30. COMPARISON OF THE FINGERPRINTS OF SAMPLES OF TWO POLYETHYLENE FMLS

Property	Test method	FML sample	
		503-1	503-2
Thickness, mil	ASTM D1593	75	84
Density of FML, g cm ⁻³	ASTM D792	0.948	0.951
Density of the polyethylene corrected for carbon black content, g cm ⁻³	ASTM D792	0.933	0.935
Volatiles, %	ASTM D3030-84	0.40	0.05
Extractables, %			
By methyl ethyl ketone	ASTM D3421-75	1.91	2.01
By n-hexane	ASTM D3421-75	3.19	3.03
Infrared spectra of extracts			
By methyl ethyl ketone	...	Spectra match ^a	
By n-hexane	...	Spectra match ^a	
GC analysis of extracts to determine antioxidants	ASTM D4275	b	c
Thermal gravimetric analysis (TGA)	d		
Carbon black, %		3.4	3.5
Ash, %		0.22	0.17
Tonset of weight loss, °C		460	465
T _{max} rate of loss, °C		490	495
Differential scanning calorimetry (DSC)	ASTM D3417		
Sample as received:			
Polyethylene crystallinity in sheeting, %		51	49
Crystallinity in polymer, %		52	50
ΔH _{fusion} :			
In cal/g		33.3	31.8
In Joules/g		141.0	134.7
Melting point (nominal), °C		121	120
After quenching from the melt at 160°C/min:			
Crystallinity, %		47.5	39.0
ΔH _{fusion} :			
In cal/g		31.0	25.5
In Joules/g		131.6	108.3
Melting point, °C		120	120

^aIR spectra of the methyl ethyl ketone and n-hexane extracts were slightly different.

^bIdentified antioxidants were dilauryl thiodipropionate and 4,4'-thiobis (6-tert-butyl o-cresol).

^cIdentified antioxidants were 2,6-ditert butyl 4-methyl phenol (BHT), and 4,4'-thiobis (6-tert-butyl cresol).

^dThe ca 5 mg samples were heated in a flow of 40 mL/min. nitrogen from 40° to 110°C at 40°C/minute. The temperature was held at 110°C for 5 min. and then increased at a rate of 10°C/min to 600°C and held until no further weight loss was observed. At that time, oxygen was introduced to burn carbon black and the weight remaining was ash. The weight loss is followed by a first derivative computer (FDC) which indicates the temperature during maximum weight loss. The extrapolated onset temperature (Tonset) is determined by constructing a tangent to the post volatilization weight line and intersecting with the initial constant weight loss line (Earnest, 1984).

Other types of FMLs can be fingerprinted by some of the same methods. However, due to their differences in composition, both in the polymer and in their compounds, they require different analytical tests. Suggested analyses for fingerprinting CSPE FMLs include:

- Density and specific gravity.
- TGA to measure the overall composition with respect to plasticizers and the type of fillers.
- Elemental analyses to measure chlorine and sulfur contents.
- Extraction and analyses of the extract by IR and GC.
- Ash determination followed by spectographic analysis or atomic absorption (AA) analysis for the metals that are used in the slow crosslinking of the CSPE during exposure, e.g. magnesium, zinc, and lead.

Suggested analyses for fingerprinting PVC and CPE FMLs include:

- Density and specific gravity.
- TGA to measure the overall composition with respect to plasticizers and the type of fillers.
- Extraction and analysis of the extract by IR, GC, or gas chromatography/mass spectrography (GC/MS) for identification of the various plasticizers incorporated in the FML. Many of the plasticizers are themselves mixtures of a variety of oily liquids.
- Ash and analysis of the ash for trace metals and fillers.

In addition to being based on a single polymer, FML compositions can also be based on blends of two or more polymers of different compositions. The fact that the polymer component of an FML is a blend will be apparent in several of the analyses, e.g. TGA, IR, etc.

4.2.3 Geotextiles

Geotextiles can perform a number of functions and have grown into a viable industry in their own right. In waste containment practice, however, their use is primarily in providing a filtration function. This function is emphasized in this section. This is not to say that strength or modulus is not important. A weak geotextile can easily intrude into the pore space of a drainage net or composite rendering its flow significantly less than its as-manufactured capability. This is discussed later in Section 4.2.6.4. In addition, geotextiles have also been used to protect FMLs placed in the field. Various types of geotextiles are illustrated in Figure 4-56.

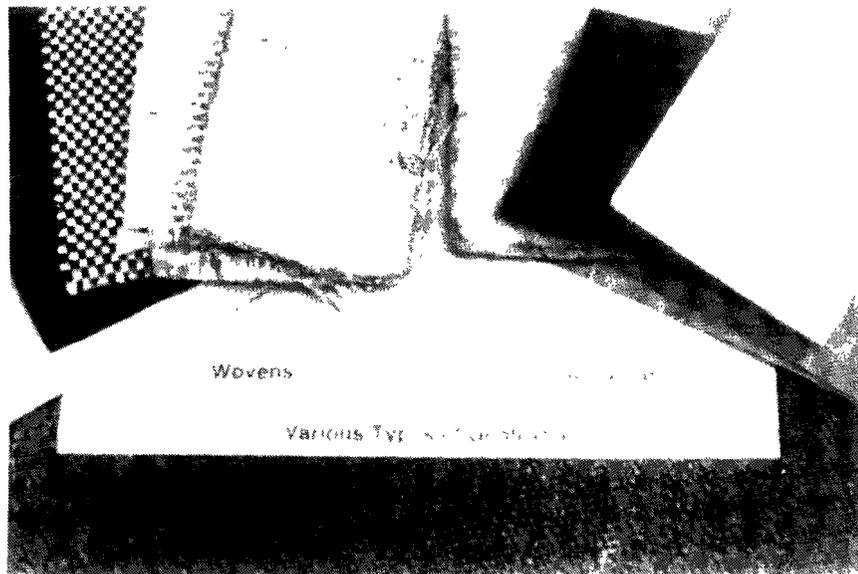


Figure 4-56. Various types of geotextiles.

4.2.3.1 Polymer Types Used in Manufacture--

Geotextiles have been made from many polymer types used for fibers but currently polypropylene and polyester types prevail. Table 4-31 lists some advantages and disadvantages of each polymer. It should be noted that polyester geotextiles are sensitive to alkaline solutions and wastes. There have been concerted efforts recently to produce high and medium density polyethylene geotextiles, which are being aimed directly at the waste containment applications. These materials are now made in Germany.

4.2.3.2 Geotextile Fibers and Fabrics--

A number of fiber types (monofilament, multifilament, slit film) can be used to make a variety of fabric types. As can be seen in Figure 4-56, the fabrics are woven or nonwoven. Furthermore, there is a large variety of weaving patterns (plain, modified, etc.) and nonwoven manufacturing techniques (heat set, needle punched, resin bonded, etc.) which gives rise to a wide variety of products. There are probably 1000 different commercially available geotextiles at the present time (June, 1988). The number of geotextiles available alone demands that rational design toward selection of a geotextile must be used. Such a methodology is at the heart of the "design-by-function" concept.

4.2.3.3 Filtration Principles--

When filtration is the primary function to be achieved, rational design requires two competing mechanisms to be achieved:

- Adequate flow capability.

- Upstream soil particle retention.

Note that these are competing mechanisms where adequate flow requires large fabric pores and soil particle retention requires small fabric pores. Thus, knowledge of both the flow regime and soil characteristics are essential for proper design.

TABLE 4-31. GENERAL COMMENTS ON POLYMERS USED IN MANUFACTURE OF GEOTEXTILES

Type	Advantages	Disadvantages
Polypropylene (PP)	Not sensitive to varying pH	Somewhat creep sensitive
	Widely used	Poor ultraviolet stability without carbon black
	Relatively low cost	Some uncertainty in organic solvents
	Good temperature stability	
Polyester (PET) ^a	Good creep resistance	High alkalinity degradation (pH > 11) for some polyesters
	Good ultraviolet stability	Slightly higher cost than PP
	Widely used	
	Good temperature stability	Some uncertainty in organic solvents

^aPolyethylene terephthalate.

4.2.3.3.1 Adequate permittivity--Flow through geotextiles is governed by its permittivity which is obtained directly from modification of Darcy's law as follows:

$$q = k_n i A , \quad (4-12)$$

$$q = k_n \frac{\Delta h}{t} A , \quad (4-13)$$

$$\frac{k_n}{t} = \psi = \frac{q}{\Delta h A} , \quad (4-14)$$

where

- q = flow rate (ft³ min.),
 i = hydraulic gradient (ft ft⁻¹),
 Δh = hydraulic head difference (ft),
 A = area of flow (ft²),
 k_n = permeability normal to the plane of the fabric (ft min.⁻¹),
 t = thickness of the fabric (ft), and
 ψ = permittivity (min.⁻¹).

This value of permittivity is calculated using known or estimated flow rates and then compared to the actual, or test, value of permittivity to obtain a flow rate factor of safety (FS) as follows:

$$FS = \psi_{act}/\psi_{req'd} \quad (4-15)$$

where

- ψ_{act} = actual, or test, value and
 $\psi_{req'd}$ = required, or design, value.

Some actual, or test, values of permittivity of typical commercially available geotextiles are shown in Table 4-32. Values were obtained in accordance with ASTM D4491.

TABLE 4-32 TYPICAL PERMITTIVITY AND PERMEABILITY
VALUES OF GEOTEXTILES

Fabric type	Permittivity, sec ⁻¹	Permeability, cm sec ⁻¹
Woven monofilament	1000 - 0.1	10 - 0.001
Nonwoven needled	50 - 0.1	1 - 0.01
Nonwoven heat set	10 - 0.1	0.1 - 0.005
Nonwoven resin bonded	1 - 0.005	0.05 - 0.001
Woven silt film	1 - 0.01	0.01 - 0.001

The value of the resulting FS should be above 10, and even 100 is not uncommon when considering the potential of long-term clogging.

4.2.3.3.2 Soil retention--The voids in a geotextile should not be too large since this results in a loss of upstream soil and eventual clogging of the downstream drainage system. Most soil retention criteria are formed around the following concept:

$$O_{\text{fabric}} \leq \lambda d_{\text{soil}} \quad (4-16)$$

where

O_{fabric} = an opening size of the fabric (often O_{95}),

d_{soil} = a particle size of the soil (often d_{85}), and

λ = a value depending on soil density, gradation, fabric-type, etc.

Betacchi and Cazzuffi (1985) compare a number of criteria; of these, the criteria described by Carroll (1983) is widely used. This criteria is as follows:

$$O_{95} < (2 \text{ or } 3) d_{85} \quad (4-17)$$

where

O_{95} = 95% opening size of the fabric, and

d_{85} = particle size, at which 85% of the soil is finer.

4.2.3.4 Long-Term Compatibility--

A significant consideration in designing geotextile filters is their long-term compatibility with the environment that surrounds them (Koerner et al, in press). For geotextiles in waste containment facilities having design lifetimes of 30+ years, several potential problems need to be considered:

- Soil particle clogging.
- Mineral clogging, e.g. ocher and carbonates.
- Biological clogging.
- Chemical degradation.
- Burial degradation.
- Long-term creep and possible puncturing.

4.2.3.4.1 Soil clogging--Soil clogging of geotextile filters has been a topic of considerable past research (Koerner and Ko, 1982). While a precise formulation of the soil/geotextile combinations that lead to clogging is not yet available, several guidelines have emerged (Halse et al, 1987). Problem areas that are known to exist are the following: gap-graded cohesionless soils under high hydraulic gradients and highly alkaline conditions. Both of these situations can lead to complete clogging of the geotextile. For a precise evaluation, however, laboratory testing of the proposed soil and candidate geotextile is necessary. Two options are available:

- The gradient ratio test (Haliburton and Wood, 1982).
- The long-term flow test (Koerner and Ko, 1982).

For granular soils and woven monofilament geotextiles the short-term gradient ratio test can be used. For other conditions long-term tests must be performed; these tests can take up to four months to complete, but they are necessary to determine if a potential clogging problem exists.

4.2.3.4.2 Biological clogging--Only recently has biological clogging of geotextile filters (and other drainage-related components) been considered. The concern is that in the aerobic atmosphere that can exist in drain media, waste-generated bacteria and fungi can grow in the voids of the geotextile, thus reducing, or even completely blocking, the flow. Biological clogging is not considered to be a major problem at hazardous or industrial waste sites, but could be a problem at municipal waste sites where biological stability is not ensured. Research is just now beginning that focuses on both the type of microorganisms that might be present and the type of biocide that might be used to remedy a situation resulting from the growth if it should occur.

4.2.3.4.3 Chemical degradation--As with all synthetic materials used in a waste containment system, the geotextiles should also be assessed for chemical compatibility by immersion in a representative sample of the proposed leachate or waste liquid to be contained or in a simulated leachate. The exposure procedure can be similar to the one described in EPA Method 9090 for exposing FMLs (EPA, 1986). Tests to determine the effects of exposure should relate to the specific material being tested for compatibility and its proposed use in the lining system. Assessment of any adverse performance must be made, but limits are not available. It should be noted, however, that the inherent variability of nonwoven geotextiles is considerably greater than that of FMLs. Test tolerances should be viewed in this light.

4.2.3.4.4 Burial degradation--The effects of soil burial on synthetic polymeric materials has been documented over periods up to about 50 years. Even though the general types of polymers used in the components used in the construction of waste storage and disposal facilities have shown little if any deterioration in soil burial, concern exists about general burial degradation of geotextiles on extended time periods. If deterioration would occur, it would probably be from a number of causes, e.g. oxidation/reduction, hydrolysis, etc. Tests to simulate the effects of long-term burial in a short period of time are not available. What is available, however, are

performance records of geotextiles exhumed over periods of 20 or more years. In general, the performance of geotextiles when buried in soil has been very good. Burial in a waste environment is unknown. Sampling and testing of geotextiles recovered after many years of service in various environments are needed.

4.2.3.5 Other Considerations--

The secondary property that a geotextile filter must have is adequate strength. This requires one also to consider adequate resistance to long-term creep. If the geotextile filter is being used over soil the problem is not too significant because the span from soil particle to soil particle is often small, and intrusion into the upper pore space is not meaningful. When the geotextile is used to cover a geonet or geocomposite, however, resistance to long-term creep must be addressed. While it is possible to provide an analytic formulation based on the modulus of elasticity and Poisson's ratio of the particular geotextile, results are best obtained by testing of the drainage core both with and without the geotextile filter. This type of testing will be described in the geonet and geocomposite sections.

4.2.4 Geogrids

Geogrids are used to reinforce soils, e.g. on the slopes. Examples of this type of product are shown in Figure 4-57. They are sometimes used within landfills to steepen earth slopes or to create embankments used in subdividing individual cells of a disposal facility. There may be other uses as well. Geogrids should not be confused with geonets which are used exclusively as drainage cores. Geogrids are described in this section in terms of the polymers used in their manufacture, the various designs and styles presently available, selected aspects of soil reinforcement design, and some long-term considerations.

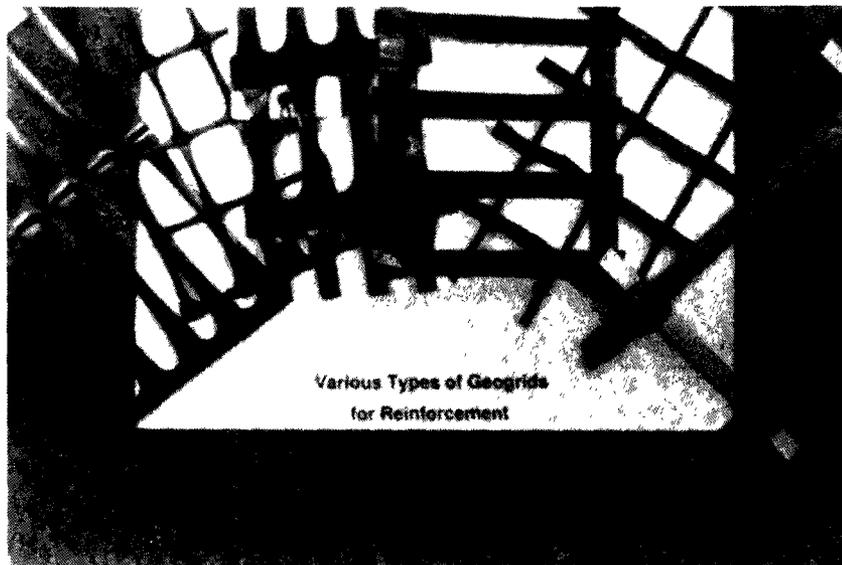


Figure 4-57. Various types of reinforcement geogrids.

4.2.4.1 Polymer Types--

Polyethylene, polypropylene and polyester, all of which have good chemical resistance, have all been used to manufacture geogrids; some polyesters, as noted in the sections on geotextiles, are sensitive to alkalis. When used in landfills, the required service life of geogrids is generally not the usual landfill completion time plus 30 years after closure, but only the landfill completion time itself, i.e. time to complete the construction and filling operations only, which involves time frames of approximately 5 years. Thus, all of the above polymers should be adequate.

4.2.4.2 Various Available Styles--

The geogrids that are available differ in the directionality of their strength, the size and shape of their apertures, and in their node construction. These differences are the results of different manufacturing approaches. Table 4-33 lists various types of geogrids that are currently available.

TABLE 4-33. CURRENTLY AVAILABLE GEOGRIDS

Product	Polymer	Strength directionality	Approximate aperture size, in.	Node construction
Tensar	HDPE	Uniaxial	4 x 1	Unitized
Tensar	PP	Biaxial	1.5 x 1.5	Unitized
ATP	HDPE	Uniaxial	4 x 1	Unitized
Signode	PET	Uniaxial	4 x 2	Ultrasonic
Signode	PET	Biaxial	4 x 4	Ultrasonic
Paragrid	PET/PP coated	Biaxial	6 x 4	Melt-bonded
Miragrid	PET/acrylic coated	Biaxial	1.5 x 1.5	Entangled by knitting

The first geogrids available in the USA were manufactured in England and were subsequently manufactured in the USA. This style of geogrid is manufactured by punching holes in extruded HDPE sheeting and continuously tensioning the sheeting so that the holes become elongated ellipses with an ultimate draw ratio of approximately 8 to 1. The cold-worked longitudinal ribs are then in a post-yield state, with considerably improved modulus,

strength, and stiffness in the direction of elongation. This product is known as a unidirectional strength geogrid. A second product type is also available, wherein the draw is in two perpendicular directions, thus achieving biaxial strength in the resulting product.

Geogrids are also made by overlapping transverse and longitudinal strips of high strength polymers and joining them at their intersections, or nodes. The Signode product is made of high tenacity polyester strips that are ultrasonically bonded at their nodes. Also available is the Paragrid product which consists of high tenacity polyester fibers encased within a polypropylene sheath. These ribs are then melt-bonded at their nodes to form the junction of transverse and longitudinal ribs.

A third approach to geogrid manufacture consists of entangling polyester yarns at the nodes, thereby forming a grid structure. This type of geogrid is manufactured under the name Miragrid. Several other companies are considering variations of this manufacturing approach.

It is important to note in Table 4-33 the type of node construction. Since stress must be transferred from the transverse ribs (where it bears against the adjacent soil) to the longitudinal ribs (where the stress is initially applied), the node strength is critically important. In this regard, the unitized nodes impart essentially 100% of the rib strength, the ultrasonic and entangled nodes somewhat less, and the melt-bonded nodes considerably less.

4.2.4.3 Long-Term Considerations--

Because of the types of applications in which geogrids are used, long-term considerations for geogrids are of less concern than they are for other types of geosynthetics used in constructing waste containment units. Most of the above-mentioned polymers should be sufficiently durable, and creep is not a problem once the facility is filled. For other potential applications, this may not be the case, and the entire range of long-term considerations must be considered (Koerner et al, in press).

4.2.5 Geonets

Geonets are grid-like polymeric products used as in-plane drainage systems. Various types of geonets that are presently available are illustrated in Figure 4-58. Geonets should not be confused with geogrids, since the tensile strength of geonets is quite low. Consequently, they should not be used for soil reinforcement purposes. As geonets are used exclusively for in-plane drainage, they always act with geotextiles, FMLs, or other materials on their upper and lower surfaces. For example, a geonet can be placed between two FMLs, as in a secondary leachate collection system (leak-detection network), or between a geotextile filter and an FML, as in a primary leachate collection system.

This section reviews the various types of polymers used in manufacturing geonets, elements of geonet drainage design, and some long-term considerations.

4.2.5.1 Polymer Types--

Most polymers currently used to manufacture geonets are polyethylene of either medium- or high-density types. Polypropylene has also been used, though quite rarely. The major variation in manufacturing polyethylene geonets is whether or not a foaming agent has been added to the polymer mix during formation. This foaming agent expands into small gas-filled closed cells within the solidified rib material forming a porous structure. The cells are in the order of a micron in size and are closed and connected. This type of geonet, in contrast to a solid rib geonet, is referred to as a foamed geonet. Under long-term load, the latter geonet may lose the gas in the cells by permeation resulting in partial collapse of the net.

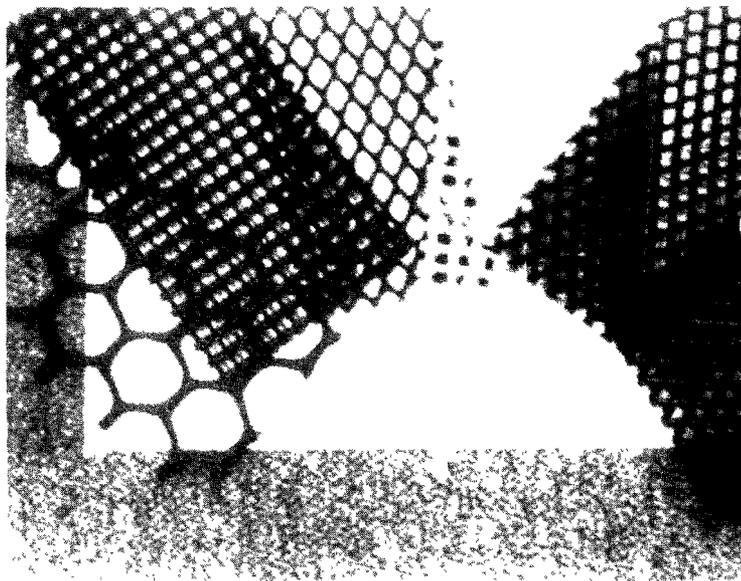


Figure 4-58. Various types of drainage geonets.

4.2.5.2 Manufacturing and Types of Geonets--

Most geonets are made by forcing the molten polymer through counter rotating slots in an extruder. This produces a grid of bonded and adjacent ribs at acute angles to one another. Before and during cooling, the grid is forced over a tapered mandrel which opens up the acute angles between the ribs to form the desired aperture size. Final rib angles are at 60° to 70° to one another. The rib cross sections are either square or rectangular. The deeper the rib size, the thicker the geonet and the greater its drainage capability. The bond between ribs where they cross over is completely polymeric. By virtue of the processing, however, the rib crossovers are usually not vertically aligned, giving rise to a "lay-over" tendency of ribs at high normal stresses.

While the above-described manufacturing process for geonets is the commonly employed one, other variations are also possible. The manufacturing of these systems run the gamut of polymer processing and are beyond the scope of this document. Table 4-34 lists commonly available geonets used in drainage systems and their properties.

4.2.5.3 Drainage Design--

The design of a drainage geonet can follow two paths, both of which are related by Darcy's law of flow. These are flow rate or transmissivity (Koerner, 1986). The following formulation shows this relationship:

$$q = k_p i A , \quad (4-18)$$

$$q = k_p \frac{\Delta h}{L} (W \times t) , \quad (4-19)$$

$$q = (k_p t) \frac{\Delta h \times W}{L} , \quad (4-20)$$

$$\text{let } \theta = k_p t , \quad (4-21)$$

$$\text{so } \theta = \frac{q L}{\Delta h W} , \quad (4-22)$$

where

θ = transmissivity (ft² min.⁻¹),

q = flow rate (ft³ min.⁻¹),

k_p = planar coefficient of permeability (ft min.⁻¹),

i = hydraulic gradient (ft ft⁻¹),

A = Area of flow (ft²),

t = thickness (ft),

L = length (ft),

Δh = hydraulic head difference forcing flow (ft), and

W = width (ft).

TABLE 4-34. AVAILABLE GEONETS FOR DRAINAGE PURPOSES

Manufacturer	Type	Polymer	Specific gravity	Style	Thickness, in.	Aperture size, in.
Tensar	DN1	PE	0.928	Extruded ribs	0.25	0.3 x 0.3
Tensar	DN2	PE	0.928	Extruded ribs	0.20	0.3 x 0.3
Tensar	DN3	PE	0.928	Extruded ribs	0.15	0.3 x 0.3
Poly-Net	PN1000	PE	0.9365	Foamed and extruded ribs	0.25	0.3 x 0.3
Poly-Net	PN2000	PE	0.9365	Extruded ribs	0.16	0.35 x 0.35
Poly-Net	PN3000	PE	0.9365	Extruded ribs	0.20	0.3 x 0.4
Poly-Net	PN4000	PE	0.9365	Foamed and extruded ribs	0.30	0.25 x 0.25
Low Bros	Lotrak 8	PE	...	Extruded mesh	0.12	0.3 x 0.3
Low Bros	Lotrak 30	PE	...	Extruded mesh	0.20	1.2 x 1.2
Low Bros	Lotrak 70	PE	...	Extruded mesh	0.29	2.8 x 2.8
Conwed	XB8110	PE	0.936	Formed and extruded ribs	0.25	0.3 x 0.3
Conwed	XB8210	PE	0.936	Extruded ribs	0.16	0.35 x 0.35
Conwed	XB8310	PE	0.936	Extruded ribs	0.20	0.3 x 0.4
Conwed	XB8315	PE	0.936	Extruded ribs	0.20	0.3 x 0.3
Conwed	XB8410	PE	0.936	Foamed and extruded ribs	0.30	0.25 x 0.25
Tenax	CE	PE	...	Extruded ribs	0.20	0.3 x 0.25
Gundle	Gundnet	PE	0.925	Extruded ribs	0.16	0.3 x 0.3

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Using either transmissivity (θ) or flow rate (q), design proceeds using a factor of safety concept, i.e.:

$$FS = \frac{\theta_{\text{act or test}}}{\theta_{\text{req'd or design}}} , \quad (4-23)$$

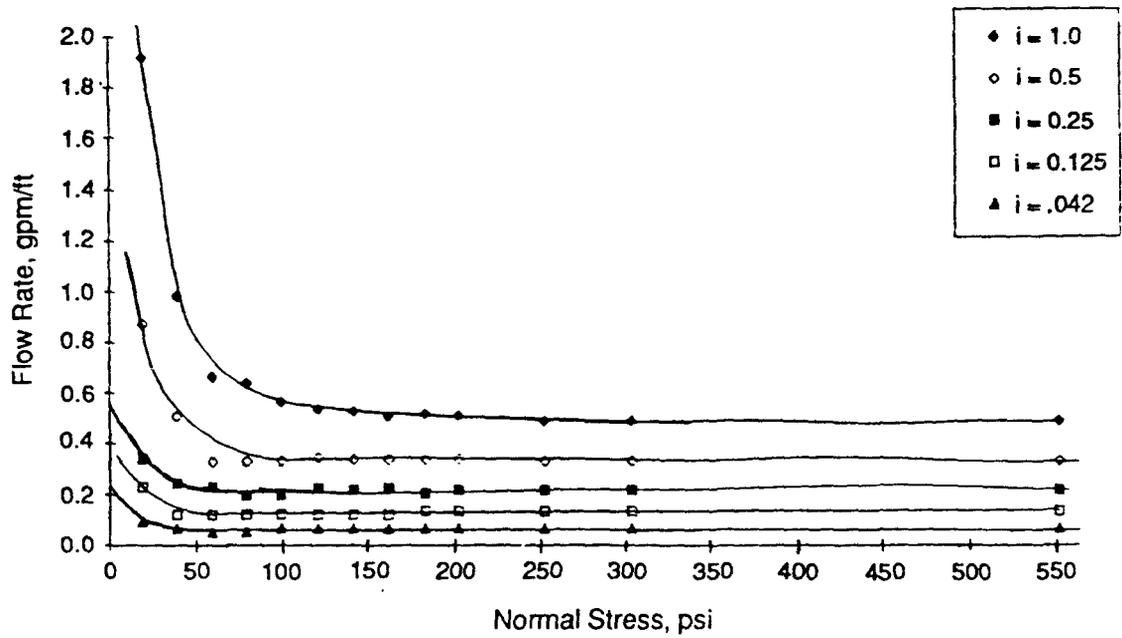
or

$$FS = \frac{q_{\text{act or test}}}{q_{\text{req'd or design}}} . \quad (4-24)$$

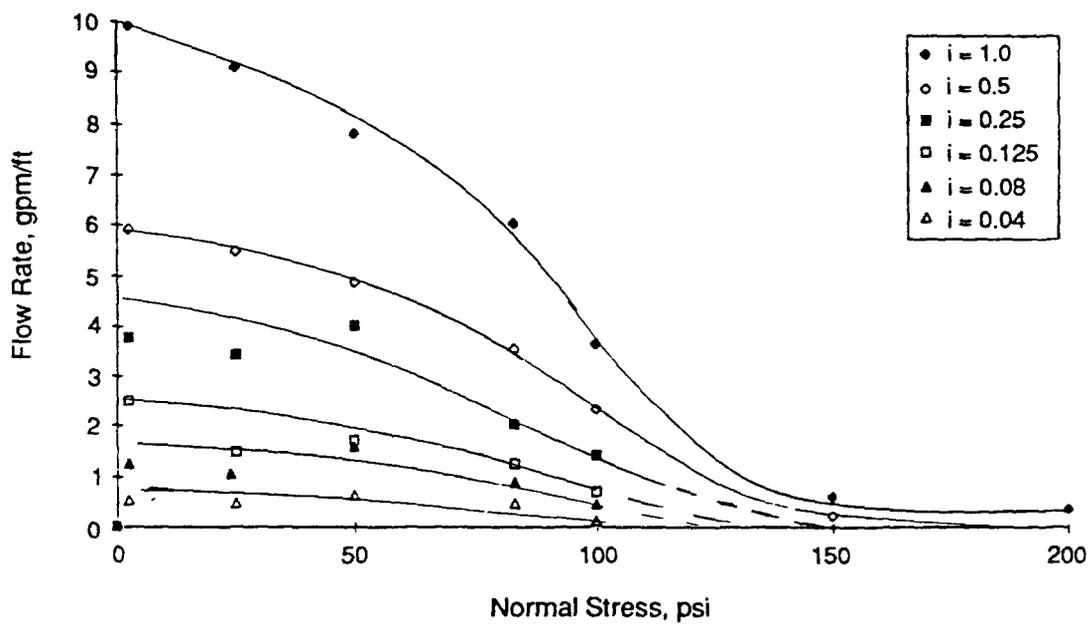
The denominator of these equations is the required or design value which is obtained by calculations, regulations, experience, or judgment. Examples are available (Richardson and Koerner, 1987). The numerator of the equations is the actual or test value of the candidate geonet. It is usually evaluated using ASTM D4716-87 test procedure. This test uses flat plates above and below the net and is for a relatively short duration, i.e. 15 minutes dwell time for the applied normal load and 15 minutes for the flow measurements. Thus, it can be considered to be an index test resulting in "upper bound" flow values vs. the *in situ* (or allowable) values. An example of flow behavior for a solid rib geonet is presented in Figure 4-59a. These results show that there is an initial decrease in flow with applied pressure but, once the system "slack" is eliminated, the flow is stabilized. The next possible event in the flow behavior is where the ribs "lay over" on one another, but for this product "lay over" only occurs at normal pressures over 556 psi. Figure 4-59b shows the behavior of a foamed rib geonet where the flow is generally quite higher than with solid ribs but a flow reduction is also seen indicative of a compression of the pores within the rib structure. Of importance, however, is that flow rates are seen to decrease greatly around 100 psi signifying "lay over" of the ribs with respect to one another.

It was mentioned that these flow values represent the upper limits of the actual performance behavior of the geonet. Field performance flow values will be equal to or less than these test values because of the intrusion of the geotextile or FML into the core space. When pressurizing soil against the geotextile or FML covering the geonet, intrusion occurs which decreases flow. This intrusion is not evaluated in tests when rigid plates are used. The amount of intrusion is site-specific depending upon the following:

- Applied normal pressure.
- Size and type of soil particles causing intrusion.
- Rigidity (stiffness) of adjacent materials.
- Thickness of adjacent materials.
- Spacing of ribs.
- Size of ribs.



(a) SOLID RIB GEONET



(b) FOAMED RIB GEONET

Figure 4-59. Flow rate behavior of geonets at different gradients (i).

This intrusion can be illustrated by infilling a quicksetting elastomer into the core space under simulated operating conditions. Photographs illustrating the intrusion of FMLs into geonets resulting from the application of pressure are presented in Figure 4-60 for both solid rib and foamed rib geonets. The ASTM flow test procedure can be modified to account for these conditions and the reduced value of flow evaluated and quantified. Unless this simulation is performed, quite high factor of safety values should be used when calculations are based on rigid plate test results.

4.2.5.4 Long-Term Considerations--

There are a series of considerations regarding the functioning of geonet drains over the design lifetime of the facility. This time frame includes the 30-year postclosure period as well as the operating lifetime. These considerations are material effects, creep of the geonet, creep of adjacent materials, chemical effects and biological effects. Each will be discussed briefly.

4.2.5.4.1 Material effects--Solid rib constructed geonets appear to be quite stable under load. However, there has been concern expressed over the foamed rib geonets. The foaming agents that are used result in nitrogen being the gas holding the pores open. As is characteristic of closed foam products under external pressure, the nitrogen will diffuse with time through the polymer surrounding it, causing a collapse of the pores, loss of geonet thickness, and proportionate loss of flow capability. The situation should be investigated and evaluated.

4.2.5.4.2 Creep of net-- Under high normal pressures the net itself can deform and cause reduced flow. This is best combated by using high factors of safety on flow and against rib "lay over." Absorption of organics that have permeated the FML will aggravate the tendency toward creep.

4.2.5.4.3 Creep of adjacent materials--Figure 4-60 illustrates the short term, or elastic, intrusion of adjacent geosynthetics into the geonet apertures. Extended time periods will tend to cause creep deformations of the adjacent geotextile or FMLs which will further reduce flow. In the absence of quantitative data, high factors of safety on the strength (or better, the modulus) of the adjacent materials is necessary. Creep of adjacent materials should not be dismissed as a trivial problem; it is very difficult to treat analytically and requires further experimentation and evaluation.

4.2.5.4.4 Chemical effects--Long-term exposure to waste streams could deteriorate the rib strength of the geonets, which must be assessed in immersion tests similar to those used to assess FMLs. The recommended test assessing the possible loss in strength of geonets after immersion is the CBR strength (puncture) test (Murphy and Koerner, for publication in 1988).

4.2.5.4.5 Biological effects--Though the polymers used in the manufacture of geonets are not metabolized by microorganisms, fungi and other growth can attach to the polymer surface. Thus, if microorganisms find their

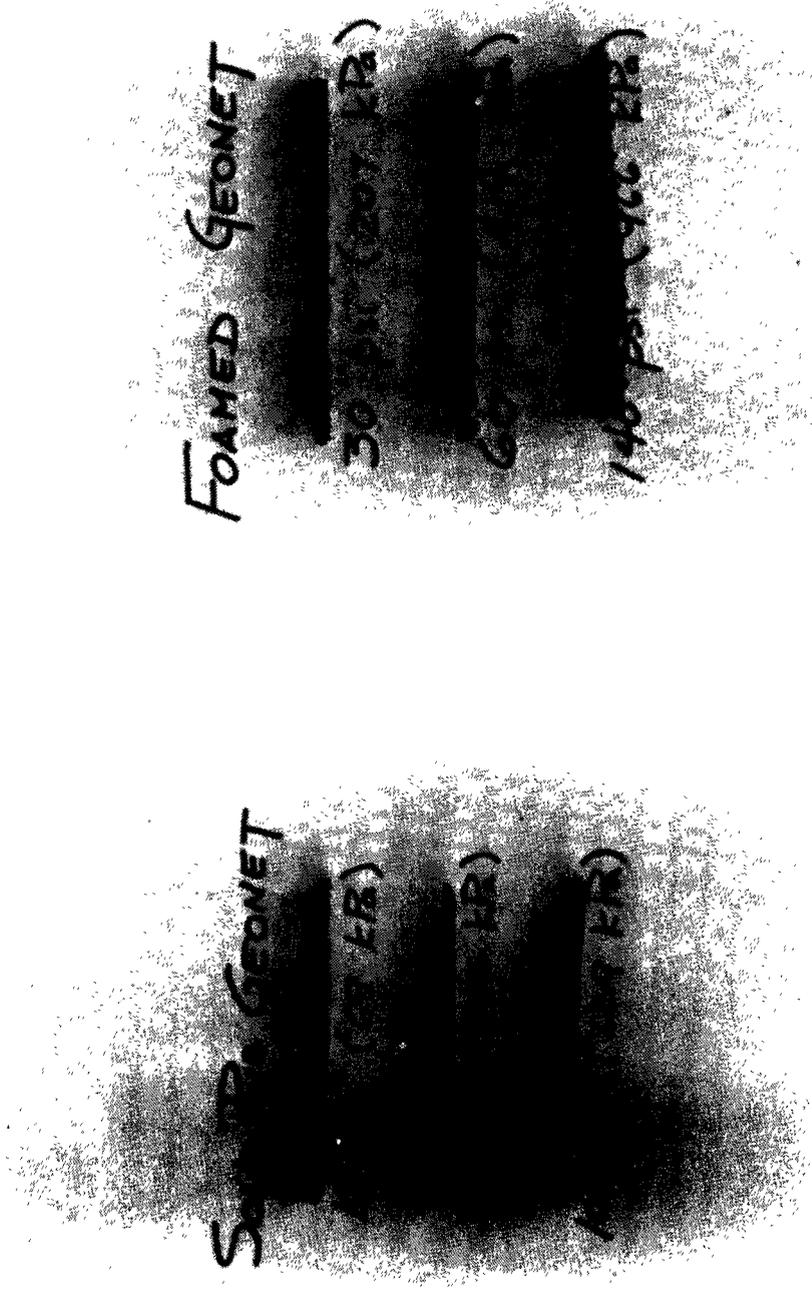


Figure 4-60. The intrusion of FMLs into geonets.

way into geonets, the drainage capability can be reduced. To what degree obviously depends upon the extent and type of bacterial and fungal growth. It is a situation currently being evaluated in hazardous and municipal landfill leachates under both aerobic and anaerobic conditions. This study is also evaluating the types of biocide that might be used to remedy the situation.

4.2.6 Geocomposites

Geocomposites is a term loosely used to identify a wide range of composite materials that consist of two or more geosynthetics. The function of a geocomposite could be any of those listed in Table 4-1 (Koerner, 1986); the function of drainage is emphasized in this section.

Drainage geocomposites are sometimes used as primary leachate collection subsystems with a geotextile filter attached, or as surface water collectors in a landfill closure. An overlap with geonets will be noted, but these drainage geocomposites are quite different in their performance, behavior, and variations. Figure 4-61 shows various types of geocomposites that are currently available. This section discusses the type of polymers used to manufacture geocomposites, the different types of geocomposites currently available, drainage design, and considerations about long-term usage.

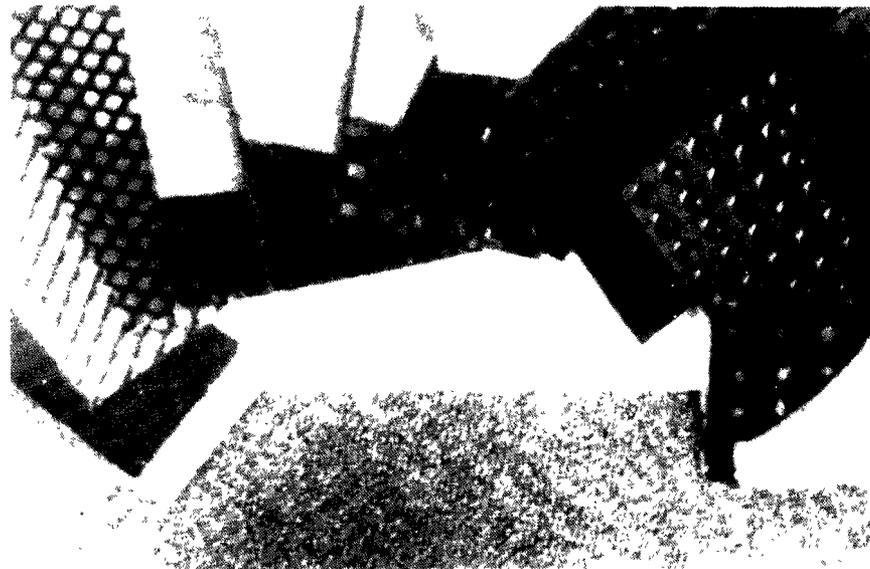


Figure 4-61. Various types of drainage geocomposites.

4.2.6.1 Polymer Types--

A variety of polymers has been used to manufacture geocomposite drainage compositions, including polystyrene, PP, PVC, and PE. Perhaps the most

common is high impact polystyrene since the largest market for these systems seems to be transportation-related projects where the liquid being drained is usually groundwater. Where potential chemical interactions might occur, as in waste containment applications, PE might be the preferred polymeric material.

4.2.6.2 Types of Geocomposites--

A great variety of manufactured products and resulting types of drainage geocomposites is available. The drainage cores themselves take the shape of columns, piers, cuspations, dimples, etc. Manufacturing itself covers many variations of polymer processing. A recent characterization by Kraemer and Smith (1986) is presented in Table 4-35. Review of this table suggests that both mechanical and hydraulic properties will vary widely from product to product. It is simply not possible to have an "or-equal" situation in considering these materials. Their specification will require a specified flow rate or transmissivity, at a given applied normal pressure, at a given hydraulic gradient.

4.2.6.3 Drainage Design--

Drainage design using geocomposites follows that described in the section on geonets. A resulting factor of safety for flow must be formulated using the actual test value as numerator and the required design value as the denominator. When considering the primary leachate collection system, flow rates can be quite high especially during seasons of high precipitation. Thus, drainage capability of primary leachate collection systems is considerably higher than the capacity of secondary leachate collection systems. Richardson and Koerner (1987) offer some guidance as to quantities.

The actual flow capability of the geocomposite can be evaluated using ASTM Test Method D4716. Results from such tests are presented in Figure 4-62. Note that, in comparison to geonets, very high flow rates are available with these systems. However, it should also be noted that the breakdown (collapse) pressure of the geocomposites is much less than with geonets. This latter feature has severe implications when considering long-term creep.

As with geonets, flow values resulting from tests between rigid plates are maximum field service values. Intrusion into the core space by the geotextile filter above the flow columns, and (to a lesser extent) FML intrusion from below, will reduce flow considerably. Figures 4-63 and 4-64 illustrate this feature for both of the products shown in Figure 4-62. Note that the collapse of the cores at the high pressure is clearly evident and must be designed against. Thus, in addition to the flow design, one must be concerned to design against collapse failure as well which requires a high factor of safety.

4.2.6.4 Long-Term Considerations--

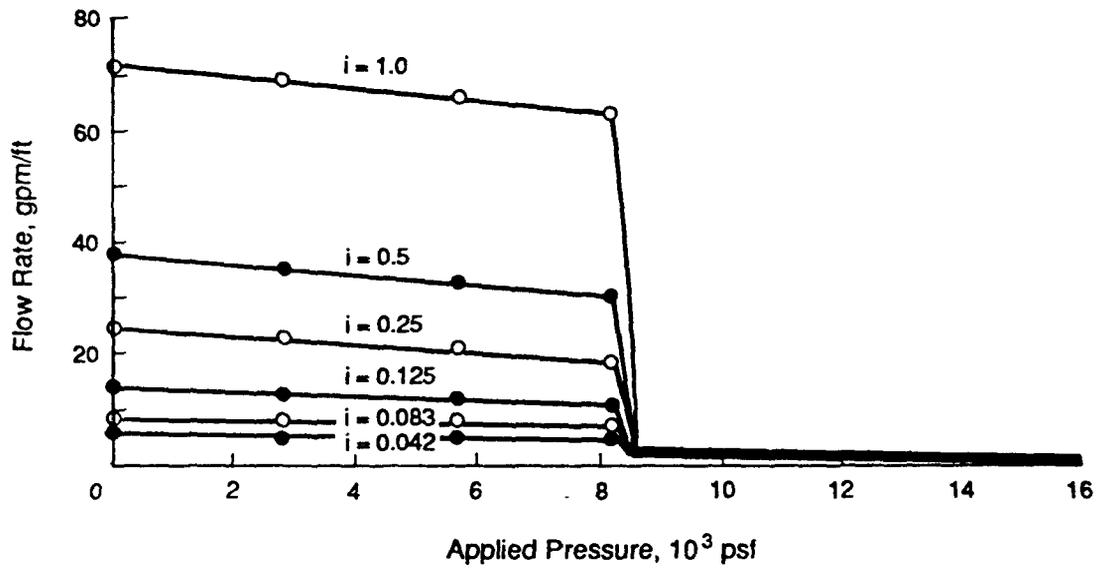
Long-term effects on geocomposites being used as drains in waste applications are similar to those discussed in the section and geonets. Thus material, chemical, and biological concerns must be considered. Again, as with geonets, creep behavior must be assessed. Since many of these systems are built up with hollow cores or cuspatations and have aperture spaces greater than geonets, both axial creep of core and creep intrusion of the adjacent geotextile are of great concern. High factors of safety in both cases are warranted.

TABLE 4-35. VARIOUS TYPES OF DRAINAGE GEOCOMPOSITES

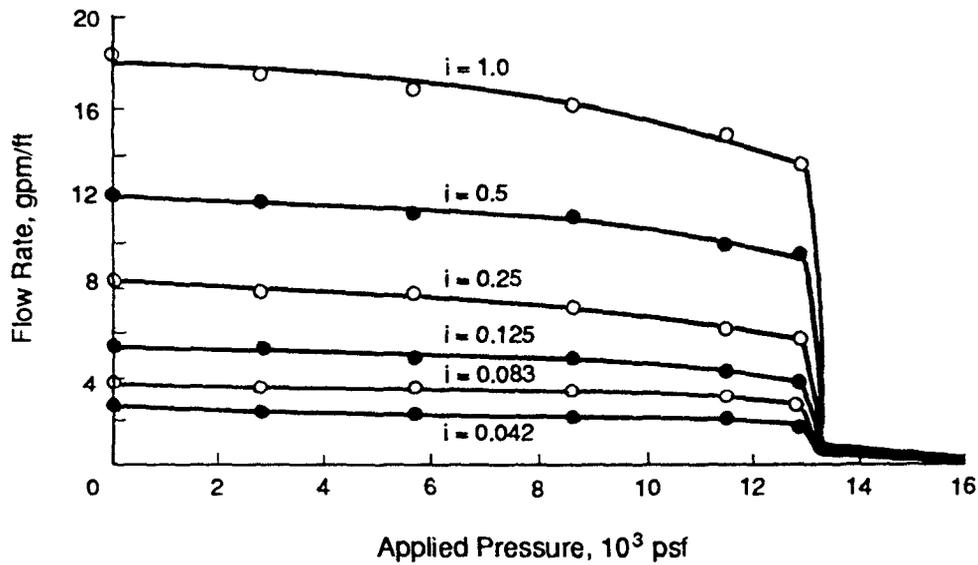
Product	Type	Material ^a	Compression strength, psi
Ameridrain™ 360	Channels	HDPE	28
Eljen Drainage System	Waffle	HIPS	30
Enkadrain 9010	Fibers	Nylon 6	7
Enkadrain 9120	Fibers	Nylon 6	16
GEOTECH™ Drainage Board	Beads	EP	6
HITEK™ 8	Waffle	HDPE	70
HITEK™ Cordrain™	Waffle	HDPE	40
HITEK™ Stripdrain™	Waffle	HDPE	20
Hydraway™	Columns	LDPE	60
Miradrain™ 4000	Waffle	HIPS	30
Miradrain™ 6000	Dimpled sheet	HIPS	75
Nudrain™ A	Waffle	ABS	40
Nudrain™ B	Waffle	PP	15
Permadrain	Waffle	HDPE	28
Stripdrain 75	Waffle	HDPE	35
Stripdrain 150	Waffle	HDPE	20
Tensar DN1	Grid	LDPE	...

^aHDPE = high-density polyethylene; HIPS = high-impact polystyrene;
 EP = expanded polystyrene; LDPE = low-density polyethylene;
 ABS = acrylonitrile-butadiene-styrene; PP = polypropylene.

Source: Kraemer and Smith, 1986.



(a) GEOCOMPOSITE CORE WITH HIGH COLUMNS



(b) GEOCOMPOSITE CORE WITH EXTRUDED CUSPATIONS

Figure 4-62. Flow rate behavior of geocomposite cores between rigid plates in short-term test; "i" is equal to the hydraulic gradient.

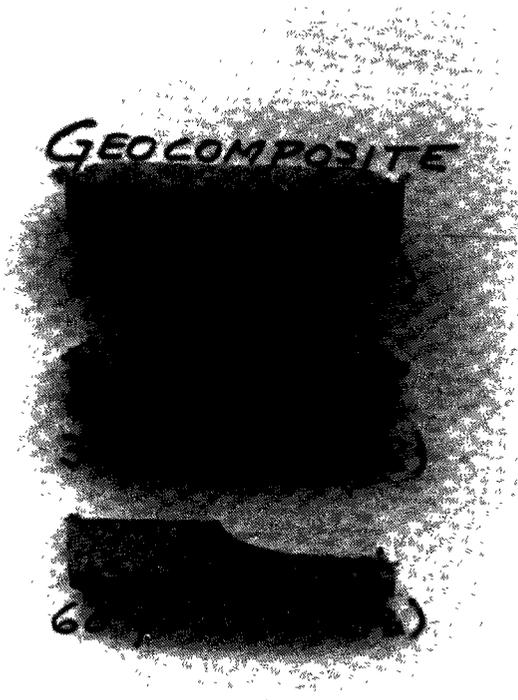


Figure 4-63. Sequence of photographs showing the intrusion of a filter geotextile into drainage core flow space of a drainage composite with high columns when under various loads. The photographs are of a series of test assemblies after the setting of an epoxy resin which had been introduced in assembly after each had been under the indicated load for a few minutes. Note that the columns were beginning to collapse at 30 psi load and had collapsed at 60 psi.

The situation is considerably different when using drainage geocomposites in caps or closure systems, in which case the liquid is usually water from rainfall or snowmelt and the normal stresses are quite low. Thus, high factors of safety can easily be obtained.

4.2.7 Pipes and Fittings

Pipes are used in waste containment in leachate collection and leak-detection systems and in gas venting applications. The pipes used in these applications need to be either perforated or slotted. Pipes will also be used for inlet and outlet structures to convey wastes into and out of the system and in monitoring systems. In all of these applications, penetrations through the liner may be required; current thinking is to avoid, whenever possible, penetration of the liner. For example, waste liquids can be carried into and out of the system over the berm.

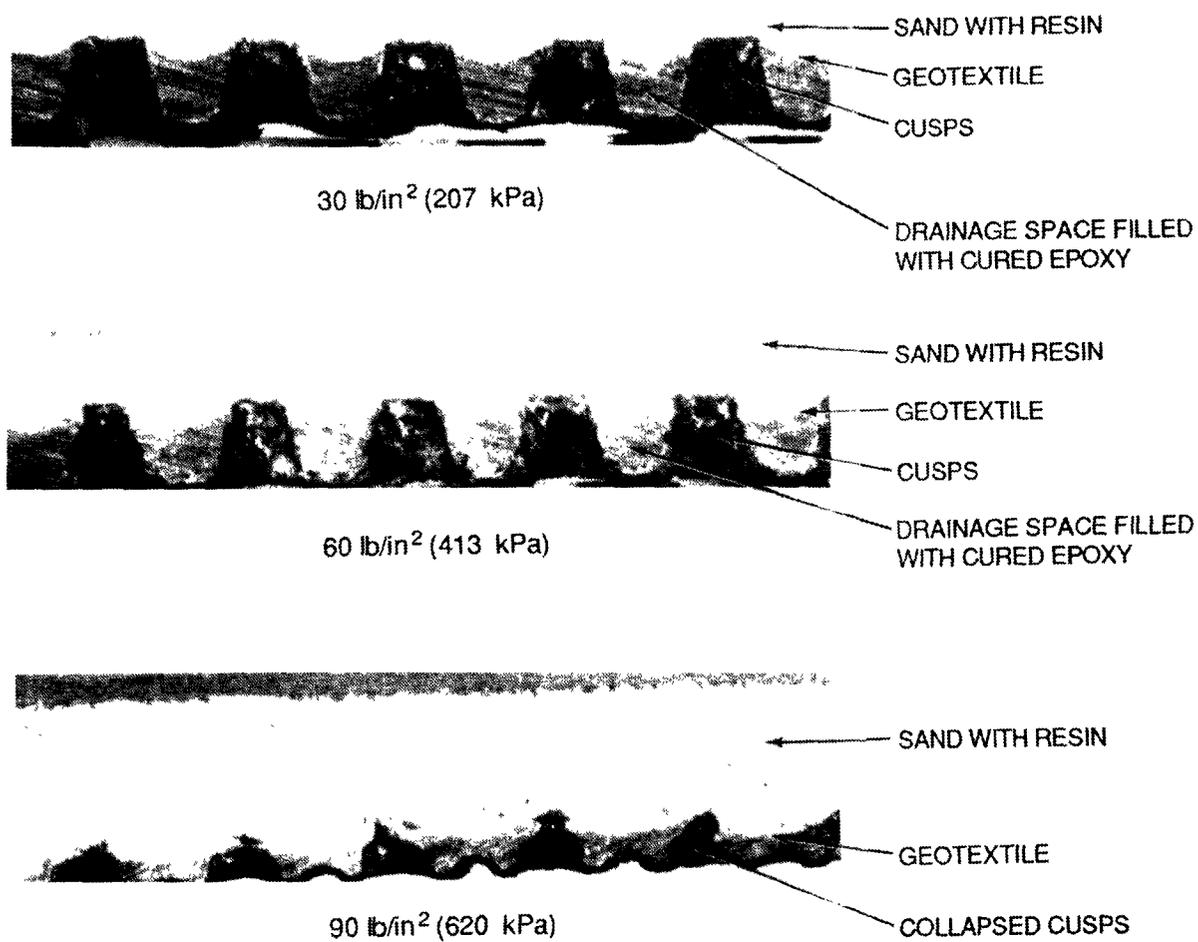


Figure 4-64. Sequence of photographs showing the intrusion of a filter geotextile into drainage core flow space of a drainage composite with extruded cusps when under various loads for short periods of time. Photographs were taken of the cross sections of a series of test assemblies after the setting of an epoxy resin which had been introduced in assembly after it had been under the indicated load for a few minutes. Note that the cusps had collapsed under 90 psi load with almost complete loss of drainage space.

Thermoplastic pipe materials, such as PVC and HDPE, are preferred over nonplastic pipe materials for leachate collection and drainage above a liner because of the wide range of chemical resistance of the thermoplastics, particularly to inorganic chemicals. Typically, for use beneath the liner, design engineers have specified a wider range of materials (E. C. Jordan Co., 1984). Polymeric pipe materials that may be appropriate for use in below liner leachate collection systems and their properties are presented in Table 4-36. The structural properties of pipes range considerably. Flexible and semiflexible pipes derive structural stability from bedding materials, while rigid pipes require less structural support.

TABLE 4-36. PLASTIC PIPE APPROPRIATE FOR USE IN LEACHATE COLLECTION AND LEAK DETECTION SYSTEMS

Type	Characteristics	Factory perforation	Compatibility chemical		Construction considerations	Strength consideration
			Resistant	Susceptible		
Polyvinyl chloride (PVC)	Flexible. Joints: solvent weld, threaded, mechanical flanged, push-on with elastomeric seal.	A ^a	Most inorganic solutions	Organic solvents	Lightweight and easily handled by one person. Pipe bedding crucial to load resistance. Control of trench grade is critical.	Available in many strength classes. Pressure/nonpressure applications.
Polyethylene high-density (HDPE):						
1. Smooth	Flexible. Joints: butt welds.	NAB ^b	Inorganic reactants, aqueous solutions of inorganic salts and bases	Organic solvents, concentrated oxidizing agents	Mechanical handling required. Bedding crucial to load resistance. Control of trench grade not critical.	Available for pressure and non-pressure uses.
2. Corrugated	Flexible. Joints: push-on. Fittings available.	A	Same as above.		Easily handled by one person. Bedding critical to load resistance. Control of trench grade not critical.	Nonpressures uses. Mostly use in shallow cover applications.
Acrylonitrile butadiene styrene (ABS)	Seim-rigid, solid wall. Joints: solvent weld. Fittings available.	A	Resistant to a broad range of chemicals and wastes; see manufacturers recommendations.		Easily handled by one person. Control of trench grade is critical.	Available in two strengths. Pressure and non-pressure uses.
Fiberglass	Rigid, flexible, available as filament wound and contact molded pipe. Joints: solvent weld, flanged, treaded. Fittings available.	A	Highly corrosion resistant. See manufacturers recommendations.		Easily handled by one person; care should be used to avoid damage. Bedding critical to load resistance; control of trench grade crucial.	Pressure, non-pressure uses. Many strength classes available.

^aA - Available.

^bNA - Not Available.

Source: E. C. Jordan Co., 1984, p 17.

Bass et al (1984) summarized the factors affecting pipe stability for above-liner leachate collection systems as:

- Vertical loading of waste and operating equipment.
- Perforations.
- Deflection.
- Buckling.
- Compressive strength.
- Chemical resistance to the waste.
- Natural pipe deterioration.

All are of equal concern in below-liner systems. Pipes in leachate collection systems are generally bedded and backfilled with drain rock. When placed in trenches, the trench containing both the backfill bedding and the pipe is usually wrapped with a geotextile. Design issues relating to determining flow capacity and spacing of the pipe are found in Appendix I.

Pipe durability can be assessed in terms of service life and resistance to deflection and failure under load. The service life of piping materials in waste containment situations cannot be verified based on field data because of the relatively recent usage of these materials in this mode. In order to meet the service life requirements of the total facility, pipe materials should be evaluated for chemical compatibility and should be resistant to excessive deflection and failure, which will ultimately serve to clog the drainage system. Fracture during installation, particularly in the case of rigid wall pipe, should be guarded against, as should the application of live loads during construction. The behavior of pipe under the combined influences of load and waste exposure must be evaluated, when potential incompatibility exists between the pipe materials and the waste.

In above-liner leachate collection systems, piping materials are required to conduct fluid under heavy loads for many years. Since thermoplastic pipes are generally used in above-liner leachate collection systems, potential negative effects resulting from swelling or softening caused by waste materials must be considered. If the waste material to be handled contains organic materials, then chemical resistance of the pipe to the specific waste needs to be evaluated. In general, the chemical compatibility of HDPE pipe can be considered to be equivalent to that of HDPE FMLs. PVC polymers, which are used unplasticized in pipes, may be more susceptible to organics than HDPE.

A wide variety of test methods for characterizing plastic pipe has been published by ASTM, the Plastic Pipe Institute, the Gas Research Institute, and the National Sanitation Foundation. Table 4-37 lists some of the ASTM test methods.

TABLE 4-37. METHODS FOR EVALUATING HDPE PIPE

Property	Test Method
Specific gravity	ASTM D1505
Tensile strength	ASTM D638
Modulus of elasticity	ASTM D638
External loading properties	ASTM D2412
Coefficient of linear expansion	ASTM D696
Thermal conductivity	ASTM C177
Hydrostatic design basis	ASTM D2837
Hydrostatic design stress	ASTM D2837

4.3 ADMIXED LINER MATERIALS

A variety of admixed or formed-in-place liners have been successfully used in the impoundment and conveyance of water. The materials used in these liners include asphalt concrete, soil cement, and bentonite-sand mixtures. All are hard surface, rigid or semirigid materials which are formed in place from raw materials brought to the site. They are composed of a mixture of granular and cementitious materials compacted to form a uniform dense mass, and are porous by nature.

Even though liners constructed from admixed materials have demonstrated durability in the impoundment and conveyance of water, considerably less information is available on the use of some of the admixes for the containment of brines and other waste materials. Materials of this type have undergone pilot- and bench-scale exposure testing in contact with municipal solid waste leachate, and have undergone pilot and bench-scale limited exposure testing with hazardous wastes (Haxo et al, 1982; Haxo et al, 1985). Admix liner materials composed of soil cement and two polymer-modified bentonite-sand mixtures are currently undergoing exposure testing with wastes from coal-fired electric power plants in a research project for the Electric Power Research Institute (Haxo et al, 1987a; Haxo and Nelson, 1986).

This section discusses asphalt concrete and soil cement. Bentonite-sand liners are discussed in the TRD on soil prepared by Research Triangle Institute (Goldman et al, 1987).

4.3.1 Hydraulic Asphalt Concrete

Hydraulic asphalt concrete (HAC) is a hot-mixed and hot-laid controlled mixture of asphalt cement and graded aggregates. The material is hard surfaced and resistant to traffic and impact forces as well as to acids and aging, particularly in the absence of light and air. The use of these materials for water storage has been documented (Hickey, 1971b).

Hydraulic asphalt concrete liners in hydraulic construction and waste containment applications require high quality dense-graded aggregates to create a nearly voidless mix ensuring low permeability. In addition, the aggregate must be compatible with the waste liquid. In comparison to paving asphalt concretes, hydraulic asphalt concretes have a higher content of mineral filler and a higher asphalt cement content (usually 6.5 to 9.5 parts per 100 parts dry aggregate) to reduce voids. The asphalt used in hydraulic asphalt concrete is usually a low penetration grade (40-50 or 60-70) since these harder asphalts are better suited for liners than softer paving grade asphalts (Asphalt Institute, 1981). The final HAC product is harder, denser, and more homogeneous than paving asphalts.

4.3.1.1 Permeability of Hydraulic Asphalt Concrete--

Permeability is the most important property in selecting asphalt liner materials. Initial permeability is influenced by voids ratio, percent asphalt, density at compaction and liner thickness. Hydraulic asphalt concrete can be compacted to have a permeability coefficient less than 1×10^{-7} cm s^{-1} . The liner should be compacted to at least 97% of the density obtained by the Marshall method and have a voids content less than 4% (Asphalt Institute, 1976; Asphalt Institute, 1981). Hinkle (1976) found that a voids content of less than 2.5% produced a permeability of less than 1×10^{-9} cm s^{-1} , as is shown in Table 4-38. Styron and Fry (1979) used an 11% asphalt content compacted to a 2-in. thickness to achieve permeability coefficients in test cells less than 1×10^{-9} cm s^{-1} . Two-inch thick HAC liners with asphalt contents from 7 to 11% have been common field practice for the Bureau of Reclamation in water storage ponds for many years (Asphalt Institute, 1966). Haxo et al (1982) used a 9% asphalt concrete for MSW leachate exposure studies, but after one year of exposure determined that a thickness greater than 4 in. may be necessary to contain wastes, due to potential inhomogeneities in the admixture resulting from inadequate mixing or compaction. This conclusion is borne out by Hinkle (1976) in a study for California Edison, which demonstrated that an optional compacted thickness for a liner containing primary water was 4 in. and that this thickness would be achieved by compacting two layers in separate 2-in. thick lifts.

TABLE 4-38. PERMEABILITY OF ASPHALT CONCRETE TO WATER

Asphalt, %	Compac- tion ^a , %	Voids, %	Specific gravity	Unit weight	Maximum specific gravity	Permeability constant, millidarcys	Coefficient of permeability	
							cm/sec	ft/yr
7.5	99.2	2.8	2.248	140.3	2.313	7.6×10^{-7}	7.9×10^{-7}	0.82
7.5	98.0	3.9	2.223	138.7	2.313	1.6×10^{-7}	1.7×10^{-7}	0.18
7.5	93.8	8.0	2.128	132.8	2.313	1.05×10^{-4}	1.09×10^{-4}	112
7.5	91.4	10.4	2.072	129.1	2.313	1.53×10^{-3}	1.58×10^{-3}	1630
7.75	96.0	6.9	2.147	134.0	2.306	1.97×10^{-6}	2.04×10^{-6}	2.1
7.75	99.0	2.9	2.240	139.8	2.306	9.7×10^{-7}	1.0×10^{-6}	1.0
8.0	93.2	8.0	2.115	132.0	2.299	1.3×10^{-4}	1.31×10^{-4}	136
8.0	93.0	8.4	2.107	131.5	2.299	1.3×10^{-3}	1.3×10^{-3}	1340
8.0	98.7	2.6	2.240	139.8	2.299	$<1.9 \times 10^{-9}$	$<2 \times 10^{-9}$	<0.002
8.5	90.6	9.5	2.067	129.0	2.285	3.0×10^{-7}	3.1×10^{-7}	0.32
8.5	94.4	6.0	2.147	134.0	2.285	5.2×10^{-8}	5.4×10^{-8}	0.056
8.5	94.0	6.2	2.144	133.8	2.285	4.3×10^{-5}	4.4×10^{-5}	46
8.5	96.0	4.2	2.189	136.6	2.285	1.3×10^{-5}	1.4×10^{-5}	14
8.5	96.0	4.2	2.189	136.6	2.285	8.2×10^{-6}	8.48×10^{-6}	8.8
8.5	97.0	3.2	2.313	138.0	2.285	$<4.8 \times 10^{-9}$	$<5 \times 10^{-9}$	<0.005
8.5	98.0	2.1	2.236	139.5	2.285	$<3.8 \times 10^{-9}$	$<4 \times 10^{-9}$	<0.004
8.5	98.0	2.6	2.224	138.8	2.285	$<5.5 \times 10^{-10}$	$<5.7 \times 10^{-10}$	$<0.0005^b$
8.75	99.0	2.3	2.226	138.9	2.279	$<1.6 \times 10^{-9}$	$<1.88 \times 10^{-9}$	$<0.0016^b$
8.75	99.8	1.7	2.240	139.8	2.279	$<9.6 \times 10^{-10}$	$<9.28 \times 10^{-10}$	$<0.0009^b$
8.75	99.5	2.0	2.232	139.3	2.279	$<8.0 \times 10^{-10}$	$<7.79 \times 10^{-10}$	$<0.0007^b$
8.75	98.0	3.6	2.197	137.1	2.279	$<1.2 \times 10^{-9}$	$<1.21 \times 10^{-9}$	$<0.001^b$

^aBased on 35 blows Marshall = 100%.

^bSamples still on permeability apparatus at time of Hinkle's publication.

Source: Hinkle, 1976.

4.3.1.2 Durability of Asphalt Concrete--

Once a material of sufficiently low permeability has been achieved, the second property of concern is durability. Carefully designed and installed facilities for water storage have lasted for more than a quarter of a century in this country. Bureau of Reclamation and Department of Interior experience with this material for water storage and conveyance and for desalinization ponds indicates that it is resistant to light vehicular traffic, freeze/thaw cycles (U.S. Department of Interior, 1971), and the destructive forces of wave action. Its semirigid nature imparts enough flexibility to conform to slight deformations in the subgrade and to resist low-level seismic activity. It maintains integrity well on side slopes and resists creep and slippage.

Asphalt concrete is subject to the following failure mechanisms:

Mechanical: Failure from severe deformation in the subgrade.
Failure at construction joints.

Chemical: Incompatibility of asphalt with wastes.
Incompatibility of aggregate with wastes.
Excessive absorption of water causing swelling and sloughing.

Environmental: Transverse-cracking due to thermal cycling.
Puncture of liner by roots and weeds.
Ultraviolet degradation of the asphalt and certain susceptible aggregates.
Oxidative hardening of air exposed liners.

The durability of asphalt concrete liners in waste containment applications is less well characterized; available information is based on laboratory and pilot-scale field studies as well as limited field experience. The major factor determining durability of asphalt liner materials in these applications is the compatibility of the waste with the asphalt as well as with the mineral aggregate components in the asphalt concrete (Kays, 1977). Of major importance in considering asphaltic materials for lining of waste containment facilities is the sensitivity of asphalt to many organic species.

4.3.1.3 Evaluation of Asphaltic Liner Materials--

Procedures for evaluating the properties of asphalts are listed in Table 4-39. These test procedures can be used to evaluate the material properties of the asphalt mix components before and after exposure to waste materials and for quality control of mix design.

TABLE 4-39. APPLICABLE METHODS FOR TESTING OF HYDRAULIC ASPHALT CONCRETE

Property	Test method
Water permeability	Back-pressure permeameter (Vallerga and Hicks, 1968)
Density and voids	ASTM D1184 and D2041
Water swell	California Division of Highways 305
Compressive strength	ASTM D1074
Asphalt content	ASTM D1856
Penetration of asphalt	ASTM D5
Viscosity of asphalt, sliding plate	California Division of Highways 348
Sieve analysis of the aggregate	ASTM C136 and C117

Source: Haxo et al, 1985.

4.3.1.4 Installation Characteristics--

Hydraulic asphalt concrete is applied as hot-mixed concrete, in-place, using spreaders or slip-form pavers in 10- to 15-ft widths and compacted to the desired density using a vibrator, tamper, roller, or screed. Temperature requirements for the hot-mixes range from 400° to 500°F.

4.3.2 Soil Cement

Soil cement consists of a compacted mixture of selected in-place soils, portland cement, and water. As the portland cement hydrates, the mixture becomes a hard, low-strength portland cement concrete which has greater stability than untreated soil alone can attain. The permeability of soil cement varies with the grain size of the natural soil: the more granular the soil, the higher the permeability. Since the cement component of the soil-cement admix is a minor ingredient by volume, particular attention must be paid to the soil component. Any nonorganic soil with less than 50% silt and clay is suitable for soil cement. A high clay content reduces the efficiency of the soil in producing a low permeability layer, by impairing the formation of homogeneous cemented materials. Best results for water retention are obtained when the cement is mixed with a well-graded sandy soil, with 5 to 35% passing the No. 200 (75 μ m) sieve (PCA, 1978). Cement contents may vary from 7 to 10%, depending upon the porosity of the soil materials used. Generally, the second most important concern in designing soil-cement liners of low permeability is density at compaction, since the higher the density of the soil cement, the lower its permeability. Compactibility in turn depends upon the moisture content of the soil-cement mixture.

Chemical sealants, including epoxy asphalt and epoxy coal tars are often applied over soil cements to decrease permeability, and may be sprayed on or applied in place. The sealing effect of such materials is limited to the upper centimeters of the liner. The compatibility of these materials with the waste to be contained needs to be evaluated separately from evaluation of the soil-cement admixed materials.

Three major concerns in using soil-cement liners are their tendency to develop wet-dry and freeze-thaw cracks leading to seepage, their incompatibility with waste species arising from their cement content, and their brittleness leading to deformation-induced cracking and to leakage.

Soil-cement liners have been recently discussed by Adaska (1985) at a symposium on impermeable barriers for soil and rock. This paper reviews basic information on soil cement as a liner material and describes research on permeability and compatibility testing. The design, construction, and performance of some unique soil-cement-lined projects were presented, as well as information on a new composite soil-cement/FML liner system.

4.3.2.1 Permeability of Soil Cement--

As with all liner materials, permeability is the property of primary significance in selecting liner materials constructed of soil cement. Whenever soil cement is used as a liner in such hydraulic structures as dams, canals, etc., the main emphasis is on reducing the erosivity of the soil, i.e. to increase hydromechanical strength rather than to produce a blanket of low permeability. There have been few studies performed to design soil cements that have low permeabilities (less than 10^{-8} cm s⁻¹) compared with studies of mixes designed for compressive strength.

Literature on the permeability characteristics of soil cement is ambiguous, and does not indicate unequivocally that the addition of cement to soil makes it less permeable. The chemical composition of portland cement does not provide an answer to this question. Indeed, the cement should release to the soil solution calcium ions from the free lime and gypsum present in the cement. The calcium ions should aid soil aggregation and, thus, increase the median pore size which should result in a soil matrix with a greater permeability. Although few studies on design of low permeability soil-cement liners have been conducted, experience indicates that a fine-grained soil can be used to produce a permeability of 1×10^{-6} cm s⁻¹ (Styron and Fry, 1979; Stewart, 1978).

There are five fundamental requirements which are essential to achieving low permeability (less than 10^{-7} cm s⁻¹) in soil-cement liners used in a waste environment. They are:

- The soil material needs to be of sufficiently low porosity to achieve a liner of low permeability.
- The moisture content required to attain maximum density needs to be used.

- The minimum cement content needed to reinforce the soil to specification must be used.
- The soil cement must be compacted to the design density.
- The constituent materials of the soil cement must be compatible with the wastes to be contained.

Examples of water permeability of soil-cement specimens using various soil types and cement and water contents are presented in Table 4-40. The results indicate that permeabilities as low as $4 \times 10^{-8} \text{ cm s}^{-1}$ can be achieved in laboratory and pilot-scale experiments using graywacke fines (Haxo et al, 1985). Thus, it may be possible to achieve soil-cement admixes with lower permeabilities than has been accepted in the field, pending further exploratory research and field experience. Specification of design criteria for acceptable permeability performance and careful selection and preliminary testing of the soil and cement materials to select the optimum design mix are essential to achieve acceptable permeability levels for the design life of the liner.

4.3.2.2 Durability of Soil Cement--

Soil cement has been used for many years for paving applications, for slopes and embankments, and for water storage and conveyance. Applications in the last 25 years have included lining of municipal and industrial wastewater storage and treatment lagoons and ash settlement ponds (PCA, 1981). Soil cement is hard-surfaced, resistant to impact forces, and provides a durable working surface for reclaiming materials from evaporation and settlement ponds. The manufacture of erosion resistant, durable soil-cement materials have been studied for many years, and design factors for selection of these properties are well understood. The aging characteristics of soil-cement are good, especially under conditions where wet-dry and freeze-thaw cycles are minimal.

Soil-cement admixes are subject to the following failure mechanisms:

- | | |
|---------------------|--|
| <u>Mechanical</u> : | Failure from shrinkage and cracking. |
| | Failure at construction joints. |
| | Failure from deformation in the subgrade soil and erosion on slopes and sidewalls. |
| <u>Chemical</u> : | Incompatibility of soil with waste. |
| | Incompatibility of cement with waste. |
| | Incompatibility of sealing or coating material with waste. |

Environmental: Freeze-thaw and wet-dry cycling leading to cracking and failure.

Degradation of surface by wave action, particularly on slopes and embankments.

It should be noted that research by the Portland Cement Association (Wilder, 1976) indicates that soil cement made with fine-grained silty soil is less erosion resistant than soil cement based on coarser materials.

TABLE 4-40. WATER PERMEABILITY OF SOIL-CEMENT SPECIMENS^a

Soil	Type V cement, parts per 100 g dry soil	Water, parts per 100 g dry soil	Coefficient of permeability	
			cm s ⁻¹	in. yr ⁻¹
Tennis court clay	8	10	1.6 x 10 ⁻⁶	20
Tennis court clay	10	10	1.3 x 10 ⁻⁶	16
Tennis court clay	12	10	5.1 x 10 ⁻⁶	63
"Mudjacking" clay	8	12	3.4 x 10 ⁻⁶	42
"Mudjacking" clay	10	12	5.3 x 10 ⁻⁶	66
"Mudjacking" clay	12	12	6.5 x 10 ⁻⁶	81
Graywacke fines	10	13	1.9 x 10 ⁻⁶	24
Graywacke fines	12	12	1.5 x 10 ^{-7^b}	1.9 ^b
Graywacke fines	10 ^c	12	2.9 x 10 ^{-7^d} 4.0 x 10 ^{-7^e}	3.6 5.0
Core from specimen compacted in spacer in cell base	12	13.4	5.7 x 10 ⁻⁸	0.71

^aExcept where otherwise noted, permeabilities determined in a back-pressure permeameter with a confining pressure of 2.0 atm for all specimens except those made with "mudjacking" clay (1.3 atm confining pressure), a back pressure of 1.0 atm, and a gradient of approximately 25.

^bAverage of measurements with back-pressures ranging from 1.0 to 3.0 atm.

^cRice hull ash cement (an acid-resistant pozzolanic cement).

^dAverage of measurement of back-pressures ranging from 2.0 to 4.0 atm.

^eRepeat with back pressure of 1.0 atm.

Source: Haxo et al, 1985, p 46.

It can be expected that a soil-cement mixture will perform differently and show variations in durability at each exposure zone: submerged liner, waste/air interface, and exposed slope. Variations in cement content and soil-grain size may be required to meet the durability requirements of each zone.

4.3.2.3 Evaluation of Soil-Cement Materials--

The composition of soil varies considerably, and these variations affect the manner in which the soil reacts when combined with portland cement and water. The presence of a waste material adds an additional set of variables. The way a given soil reacts with cement is determined by laboratory tests made on mixtures of cement with the soil; cement content directly affects moisture requirements, due to the hydration requirements of the cement.

Table 4-41 presents a list of test methods that may be applied in the design, pre-construction, and construction phases of soil-cement liner evaluation, design and construction.

TABLE 4-41. APPLICABLE TEST METHODS FOR ANALYSIS OF SOIL-CEMENT LINER MATERIALS

Property	Soil cement
Water permeability	Triaxial permeameter ^a with back-pressure saturation
Density and voids	ASTM D558
Water swell	ASTM D559
Expansion/contraction	ASTM D560
Compressive strength	ASTM D1633
Compaction	Percent proctor density
Sieve analysis	ASTM D422
Freeze-thaw	...

^aPermeabilities determined in a back-pressure triaxial permeameter (Vallerga and Hicks, 1968).

Standard laboratory tests should be performed to determine the cement content, optimum moisture content, and maximum density of the soil-cement mixture necessary to meet the performance requirements of the liner. These test must be performed using the specific on-site soils, borrow materials, or

combinations thereof, that are actually being considered for use in the final liner product. This information is required to predict performance as well as to select the most economical combination of materials. Optimum moisture content and maximum density for molding laboratory specimens are determined in accordance with ASTM D558. Test specimens are then molded at several cement contents and subjected to wet-dry ASTM D559 tests and freeze-thaw. For liner applications, samples of the same formulations that are undergoing evaluation using these standardized test methods must be molded into briquets, cured, and subjected to permeability tests such as with the back-pressure triaxial permeameter (Vallerga and Hicks, 1968).

4.4 SPRAYED-ON FMLS

FMLs can be formed in the field by spraying materials (e.g. air-blown and emulsified asphalts) onto a prepared soil surface on which a geotextile may or may not have been placed. The sprayed-on liquid solidifies in place to form a continuous seam-free membrane. Such liners have been used in canals, small reservoirs and ponds for water control and for storage of brine solutions. Water storage applications have used air-blown asphalt; however, FMs from asphalt blends containing additives of elastomeric polymers and fillers are being used in solar ponds for containment of brines, and are being promoted by manufacturers as suitable materials for waste storage applications in the mining industry (Chambers, 1989).

Many sprayed-on liners have a soil cover placed on top of them. Ponds in a recycling system may not be covered because a material would contaminate the liquid being contained. Uncovered sprayed-on FMLs are sometimes painted with white latex paint.

Though sprayed-on FMLs are seam-free, bubbles and pinholes, which are extremely difficult to detect, may form during field installation causing serious difficulties at a late date. The proper preparation of the surface to be sprayed is important. The asphaltic materials are thermoplastic and of low molecular weight, and will react adversely with many wastes. However, in carefully controlled conditions, and when protected from mechanical damage and ultraviolet degradation, they can be used to form a serviceable liner for brines and many inorganic solutions.

Materials discussed in this section will include air-blown asphalt, emulsified asphalt, styrene-butadiene rubber (SBR) asphalt, and urethane-modified asphalt.

4.4.1 Air-Blown Asphalt FMLs

Catalytically-blown asphalt FMLs are the most commonly used spray-on FMLs, and have been used by the Bureau of Reclamation for many years for water conveyance and storage (Bureau of Reclamation, 1963). The asphalts used in making these FMLs have high softening point temperatures and are manufactured by blowing air through the molten asphalt at temperatures in excess of 500°F in the presence of a catalyst such as phosphorous pentoxide or ferric chloride. To fabricate the FML, the asphalt is sprayed on a

prepared soil surface at 400°F at a pressure of 50 psi through a slot-type nozzle and at a rate of 1.5 gal yd⁻² (Bureau of Reclamation, 1963, pp 80-81). The finished liner is usually 0.25 in. thick (Bureau of Reclamation, 1963, p 79) and is formed by two or more passes of the spray device and overlapping sections by one or two feet (Clark and Moyer, 1974). It can be placed during cold or wet weather, in large quantities, by mobile equipment (Bureau of Reclamation, 1963, p 10). Sprayed-on FMLs retain their tough flexible qualities for extended periods of time when properly covered and protected from mechanical damage (Asphalt Institute, 1976). The actual placing of the earth covers on a sprayed-on FML may cause some damage to its integrity.

Studies have shown that the addition of 3-5% rubber improves the properties of the asphalt by inducing greater resistance to flow, increased elasticity and toughness, decreased brittleness at low temperatures, and greater resistance to aging (Chan et al, 1978, p 17). Two types of rubber-modified asphalt are discussed below.

Bituminous seals are used on asphalt concrete, portland cement concrete, or soil-cement liners to close pores, thus improving water-proofing or when there may be a reaction between the stored liquid and the liner. The two types of seals usually applied are:

- An asphalt cement sprayed over the surface about one qt yd⁻² to form an FML about 0.04-in. thick.
- An asphalt mastic containing 25 - 50% asphalt cement, the rest being a mineral filler, squeegeed on at 5 - 10 lb yd⁻².

Sprayed-on asphaltic FMLs are usually installed on a subgrade which has been dragged and rolled to obtain a smooth surface. If there is an excessive number of irregular rocks and angular pieces, a fine sand or soil "padding" is necessary for good FML support (Bureau of Reclamation, 1963, p 81). The asphalt may also be sprayed onto a geotextile placed on the soil surface to give protection against puncture.

A blend consisting of cationic asphalt emulsion, white gasoline, and water was applied as a temporary sealer at a rate of 0.3 gal yd⁻² to a prewetted surface. The rate of application of the asphalt emulsion component was 0.09 gal yd⁻². Assuming a 60% asphalt content, the rate of application was 7.20 oz yd⁻² or 0.8 oz ft⁻². Penetration into the surface varied from 3/16 to 3/8 inch. Based on laboratory tests, the application rate was far less than that required to provide satisfactory penetration and sealing. However, for this installation, only a temporary reduction of water loss during the initial operation period of the lagoon was required because sewage was expected eventually to seal the lagoon (Bureau of Reclamation, 1963, p 115). For this application in the field the asphalt emulsion was considered to have performed satisfactorily.

A proprietary liquid cutback asphalt formulated for deep penetration was applied over natural-on-site soil at a rate of 2 gal yd⁻². Assuming a 50%

concentration of asphalt in the cutback, this rate of application is equivalent to 16.5 oz yd⁻² or 1.8 oz ft⁻². The seepage rate was reduced from 15.9 ft³ ft⁻² yr⁻¹ for the untreated soil to 6.14 ft³ ft⁻² yr⁻¹ for the treated soil (Day, 1970, p 21).

In another example, cationic asphalt emulsion formed a low permeability seal at the soil interface through the attraction of the positively charged asphalt droplets to the negatively charged soil particles as the emulsion penetrates the substrate. In this case, the asphalt emulsion was applied at the rate of 1.05 gal yd⁻², which is equivalent to about 15.6 oz ft⁻² asphalt. This product has been used mainly in reservoirs and ponds (Wren, 1973).

Field data on a hot-applied asphalt FML in a canal lateral was obtained after 11 years of service (Geier, 1968). The seepage rate at this time was 0.08 ft³ ft⁻² d⁻¹. The seepage rate prior to placement of the liner was 9.9 ft³ ft⁻² d⁻¹. Ninety percent of the aging occurred during the first four years of service. A poor correlation was found between the 14-day laboratory aging test at 60°C and actual field aging. Geier (1968, p 3) concluded that, if properly applied and covered, a buried hot-applied asphalt sprayed-on canal liner should last beyond 12 years.

Except for their poor resistance to hydrocarbon solvents, oils, and fats, the chemical resistance of asphaltic FMLs is, in general, good. Asphaltic FMLs are resistant to methyl and ethyl alcohols, glycols, mineral acids other than nitric acid (at moderate temperatures and concentrations), mineral salts, alkalis to about 30% concentration, and corrosive gases such as H₂S and SO₂. Asphaltic FMLs exhibited variable to poor performance when exposed to hydrogen halide vapors, but have very low permeability to water (National Association of Corrosion Eng., 1966).

4.4.2 Emulsified Asphalt FMLs

Emulsions of asphalt in water can be sprayed at ambient temperatures (above freezing) to form continuous FMLs of asphalt after breaking of the emulsion and evaporation of the water. These FMLs are less tough and have lower softening points than FMLs made with hot-applied catalytically-blown asphalt. Toughness and dimensional stability can be achieved by spraying asphalt emulsions onto a supporting fabric. Fabrics of woven jute, woven or nonwoven glass fiber, and nonwoven synthetic fibers have been used with various anionic or cationic asphalt emulsions to form linings for ponds and canals, and as reinforcing patches under asphalt concrete overlays to prevent "reflection" of cracks in the old pavement beneath. Seams in the supporting fabric are often sewn with portable sewing machines after the fabric is placed (Phillips Petroleum, 1973).

4.4.3 Styrene-Butadiene Rubber (SBR)/Asphalt FMLs

Styrene-butadiene rubbers have been used in recent years as additives to catalytically-blown asphalt. Thermoplastic SBR intended for hot-melts has some unique properties that enhance its usefulness for certain liner

applications. At room temperatures it behaves like crosslinked elastomeric rubber; when heated above 212°F (the glass transition temperature of the domains which behaves like crosslinked polystyrene), it behaves like an uncured elastomer. Chambers (1980) reports that, by mixing thermoplastic SBR polymers with prime grade asphalts, it is possible to achieve a thermoplastic material which behaves like an elastomeric polymer. The resultant FML is inert to inorganic acids, bases, and salts and has low permeability to water. The useful temperature range (-40° to 180°F) of the SBR/asphalt is greater than that of common asphalt grades (ca 40° to 120°F). Chambers reports a case history in which an SBR/asphalt FML was used in solar evaporation ponds containing magnesium chloride, applied over a geotextile-covered earthen base (Chambers and Farr, 1984).

4.4.4 Urethane-Modified Asphalt FMLs

A urethane-modified asphalt FML system is being marketed. It is generally spray applied, but may be squeegeed onto a prepared surface. A premix is combined with the activator, and sprayed on at a rate of two gallons per minute, covering about eight square yards per minute. The fabricated membrane is generally recommended to have a thickness of 50 mils, usually obtained by applying one coat at a rate of 0.28 gal yd⁻² on horizontal surfaces or two coats on vertical surfaces. The second coat may be applied about 15 minutes after the first coat. The liner must cure for 24 hours before being put into service. This system has good UV stability and low temperature ductility, eliminating the need for a soil cover in most cases. The liner system is limited to a maximum of 140°F continuous exposure and is not recommended for prolonged exposure to hydrocarbon or organic solvents. It should be applied only to properly prepared surfaces. The surface must be clean and dry. Porous surfaces should be filled. Generally, a primer and a bonding agent are applied before the modified asphalt is applied. The procedures for several base surfaces and the necessary precautions are provided by the manufacturer (Chevron, 1980).

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CHAPTER 5

EXPOSURE OF POLYMERIC FMLS AND RELATED MATERIALS OF CONSTRUCTION IN SIMULATED-SERVICE ENVIRONMENTS

5.1 INTRODUCTION

This chapter focuses on the simulated-service testing of FMLs and other materials of construction used in constructing lining systems for waste containment units, including polymeric materials used in constructing leachate collection and removal systems (LCRSs) and admix lining materials. The results of laboratory, bench-scale, and pilot-scale research performed to evaluate these materials under conditions that simulate service environments in waste containment units are reported. Much of this research was initiated in the early 1970's and was conducted with the materials that were available at that time to assess their usefulness in the construction of environmentally-sound waste storage and disposal facilities. Many of these materials were tested on the basis of their prior use in lining water conveyance and storage facilities.

As background to discussing tests of FMLs and ancillary materials under simulated-service conditions, the environments that FMLs and other materials may encounter in actual waste storage or disposal units are described. These environmental conditions either have been observed directly or are considered highly probable. The types of containment units discussed include municipal solid waste (MSW) landfills, surface impoundments, hazardous waste landfills, waste piles, heap leach pads, secondary containment facilities, and tailings ponds.

The types of stresses encountered by materials in these environments include chemical, mechanical, and biological stresses. Since the polymers used in manufacturing polymeric materials of construction for waste containment units are essentially not biodegradable, the effect of chemical, mechanical, and combined chemical and mechanical stresses on FMLs and other materials of construction are of particular interest. Initial research evaluating lining materials in waste environments focused particularly on the effects of chemical stresses.

This chapter presents representative data on the performance of polymeric FMLs and admix and sprayed-on liner materials exposed in simulated-service tests. These materials were exposed to a variety of test liquids and actual waste liquids, including MSW leachate and hazardous, toxic, and

industrial wastes, under a variety of simulated-service conditions, including exposure in one-sided exposure cells (to simulate exposure at the bottom of a containment unit), two-sided immersion tests, and roof tubs (to simulate exposure in a surface impoundment). Data on changes in physical and analytical properties of these liner materials after long-term exposure to the waste liquids and/or after long-term weathering, as well as test data on changes in permeability after exposure, are presented. The potential effects of these environmental conditions on FML durability and long-term performance are discussed. This chapter also presents data on the mechanical interaction of materials (e.g. liners and geonets) within the same system, and the effects of biaxial stresses on liner materials exposed to waste liquids or other aggressive environmental conditions. Available data on ancillary materials in simulated service environments are presented.

One objective of these studies was to develop criteria to establish and predict compatibility and long-term serviceability of a given material in a given service environment. The first step in developing such criteria involves establishing a correlation between the measured properties and the performance of a given material in a given service environment. Given this correlation between properties and performance, the rate of change in the properties of a material in a given environment could then be used to estimate the service life of that material. For example, in the case of many rubber products produced and used over the years, a series of laboratory-measured properties have been found to relate directly to the functioning and service life. It has been found from experience that when certain values are reached or when certain changes have occurred, the product becomes no longer functional for the purpose for which it was designed. For instance, a 50% loss on aging in the values of such properties as tensile strength and elongation have indicated a failure of many products; also, in some applications an increase of 15 hardness points or a doubling of modulus has also been indicative of failure in the performance of that product. Such properties as these may have used directly in the designing and compounding of these products to meet performance needs or they may correlate with other properties that relate directly to a performance requirement. At this point in the technology of waste storage and disposal facilities and the materials that are used in their construction, the correlation between properties and changes in their measured values and performance requirements has not been developed.

It must be recognized that waste containment technology is a comparatively recent development and is still in the process of development. The synthetic polymers, such as those used in the manufacture of FMLs and other geosynthetics, have only been available for about 60 years. Furthermore, these materials have been used in the manufacture of FMLs for only 35 years (and less for other geosynthetics), and FMLs have only been used in waste containment for approximately 20 years. However, even though much proprietary data may exist, the information on performance in the available literature is limited and generally poorly documented. Consequently, the data based on experience which can be used for establishing correlations with

laboratory results are limited. At this time criteria which can be applied to laboratory and small-scale testing to indicate the compatibility and the long-term performance of various materials in waste containment environments still need to be established.

The data reported in this chapter include data on materials that are no longer available or no longer being used for the specific purposes for which they were evaluated. However, these data are included because they describe the approach that was taken in assessing the materials. These data can be used to indicate the pitfalls in materials that may be under development. Also, they indicate the limitations of many of the materials which may be considered for applications that approximate the applications for which these materials were tested. In view of the fact many of the initial containment units were lined with these materials and are still in existence, their performance can be observed. The results may also be useful in developing correlations between laboratory and bench-scale testing and field performance.

5.2 ENVIRONMENTS IN TREATMENT, STORAGE, AND DISPOSAL FACILITIES (TSDFS) ENCOUNTERED BY FMLS AND ANCILLARY MATERIALS DURING CONSTRUCTION AND SERVICE

5.2.1 Introduction

The environment in which an FML liner material is exposed during construction and service will ultimately determine its service life, that is, how long it will perform its designed functions. Table 4-20 enumerates environmental factors that can affect the durability of polymeric FMLs and ancillary materials. Environmental factors during installation and in specific applications are discussed in the following sections. The types of facilities that are discussed include the following:

- MSW landfills.
- Surface impoundments.
- Hazardous waste landfills.
- Waste piles.
- Heap leach pads.
- Secondary containment facilities.
- Tailings ponds.

5.2.2 Environments Encountered During Construction

The conditions that an FML encounters from the time of manufacture and fabrication into panels through installation to the final acceptance by an owner of the lined storage or disposal facility require the FML to have a substantial degree of ruggedness. Most of the FMLs and the ancillary

materials have relatively little structural strength. They must be protected in various ways from mechanical and other environmental damage during fabrication, shipping, field construction, and inspection. Table 5-1 lists some of the significant conditions that an FML and other construction materials may encounter in the construction of waste storage and disposal facilities. In assessing FMLs and the other materials for lining TDSF facilities, these environmental conditions must be recognized in testing and evaluating FMLs and their seam systems.

TABLE 5-1. ENVIRONMENTAL CONDITIONS ENCOUNTERED BY FMLS AND ANCILLARY MATERIALS PRIOR TO AND DURING CONSTRUCTION OF WASTE STORAGE AND DISPOSAL FACILITIES

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- Temperature extremes; low temperatures can cause embrittlement, and high temperatures can cause softening, reduced strength, and shrinkage of some FMLs and expansion of others.
 - Temperature variation during a day and for very short intervals (clear to cloudy skies).
 - Wind and wind variation over short time periods.
 - Humidity variation during the day.
 - Much of the construction must be done on slopes, an important factor in seaming.
 - Workers' traffic during seaming operation and liner inspection.
 - Light equipment traffic which might puncture, tear, or abrade the FML surface. No equipment should be allowed on the FML surface after installation has been completed.
 - Dust and possibly gravel which might affect seam strength.
 - Impact damage from dropped tools.
 - Stretching and tensioning during FML placement.
 - UV light and oxygen which might affect the surface of some FMLs before being covered; both UV light and oxygen can also degrade geotextiles and some geonets and geogrids.
 - Dimensional change, including shrinkage due to heat and relaxation of residual strain from manufacture and thermal expansion.
 - Soil covering operations.
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5.2.3 MSW Landfills

During service in a lined MSW landfill, the components of the liner and leachate collection systems can encounter a variety of conditions in different parts of the landfill ranging from the exposure environment for the cover and venting system above the MSW to the environment in the leachate drainage and liner system below the waste. Of particular importance are the liner drainage and sump systems which are underload and may be in continual contact with the leachate. A schematic of a closed landfill is presented in Figure 5-1.

Exposure conditions for an FML in an MSW landfill are represented schematically in Figure 5-2. Some of the conditions at the base of such a landfill should have no adverse effect on life expectancy of a polymeric FML and other polymeric materials, whereas other conditions could be quite deleterious. Some of the important conditions that exist at the bottom of an MSW landfill in the proximity of the liner system and may influence its service life are presented in Table 5-2.

The environment that a cover liner system is exposed to differs from that at the bottom of a landfill. The principal function of a landfill cover is to prevent the intrusion of water into the landfill and thus minimize the production of leachate. The cover system as described in Chapter 7 includes an FML, layers of geotextiles, geonets, and possibly plastic pipes for venting the gases generated within the landfill. A soil layer of two or more feet in thickness can be placed on the FML and planted with grass and shallow-root plants. The FML would prevent escape of gases which affect plant growth. The load on the FML in the cover system would not be great; however, the coefficient of friction between the soil and the FML would be a significant factor, as a heavy rain could result in slippage of the heavy wet soil on the FML surface. As MSW tends to consolidate unevenly with time, strains in the FML and other components of the cover system could result and cause breaks in the FML.

5.2.4 Surface Impoundments

The environmental conditions encountered by FMLs and other construction materials in surface impoundments contrast greatly with those encountered in an MSW landfill or in a water reservoir. Figure 5-3 schematically presents the environmental conditions encountered by an uncovered FML in a service impoundment. Depending on the waste or liquid being impounded, these conditions can pose a much greater test of the durability of the materials. The principal difficulties arise in the highly aggressive nature of some of the wastes to be contained (e.g. in hazardous waste surface impoundments) and the stringent requirements to prevent transport of waste constituents out of the impoundment.

Environmental conditions that could be encountered by FMLs in service in surface impoundments are listed in Tables 5-3 through 5-5 by type of exposure within an impoundment. These tables describe the effect that particular

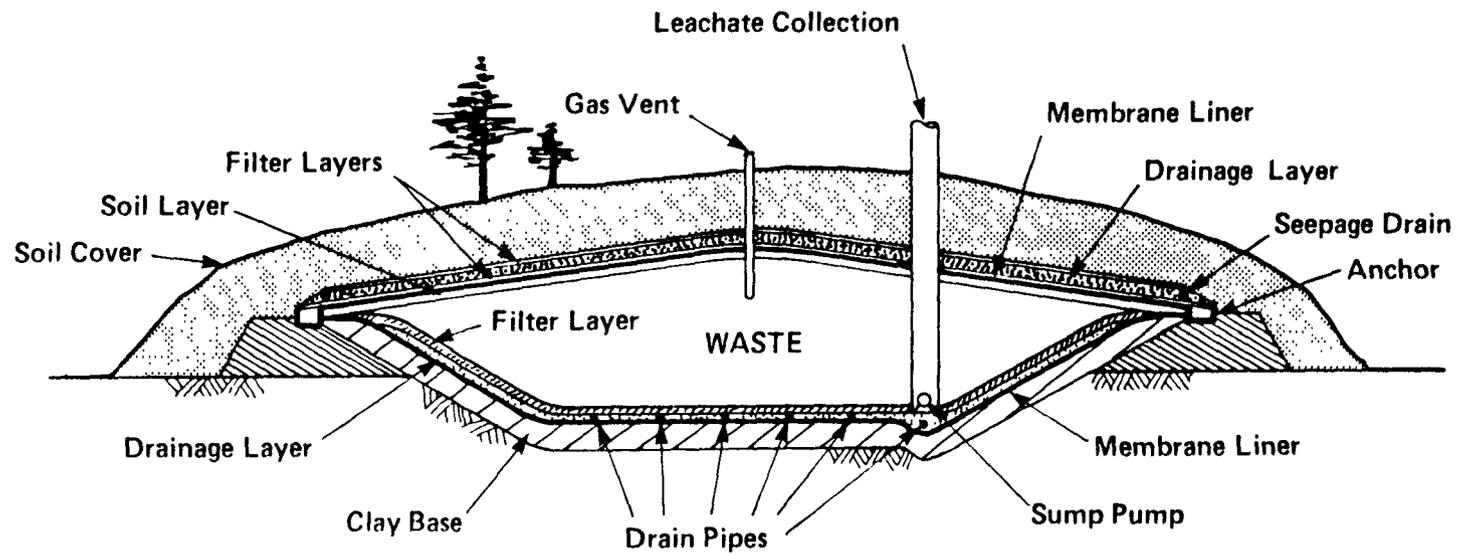


Figure 5-1. Schematic of a closed landfill with bottom and cover liners of polymeric FMLs. Bottom liner consists of a single composite liner.

environmental conditions can have on FMLs and ancillary materials. These three types of exposure are:

- Exposure to weathering only (Table 5-3).
- Exposure at the air-waste liquid interface (Table 5-4).
- Exposure to waste liquid only (Table 5-5).

It should be noted that the design of the surface impoundment will depend on the type of waste to be contained, i.e. whether or not the type of waste to be contained is considered hazardous, etc. Figure 5-4 presents a schematic drawing of an FML/composite double liner system for a surface impoundment for storage of hazardous wastes or hazardous materials. This design shows the leachate drainage or leak detection system that is required by the Hazardous and Solid Waste Amendments of 1984 (EPA, 1984).

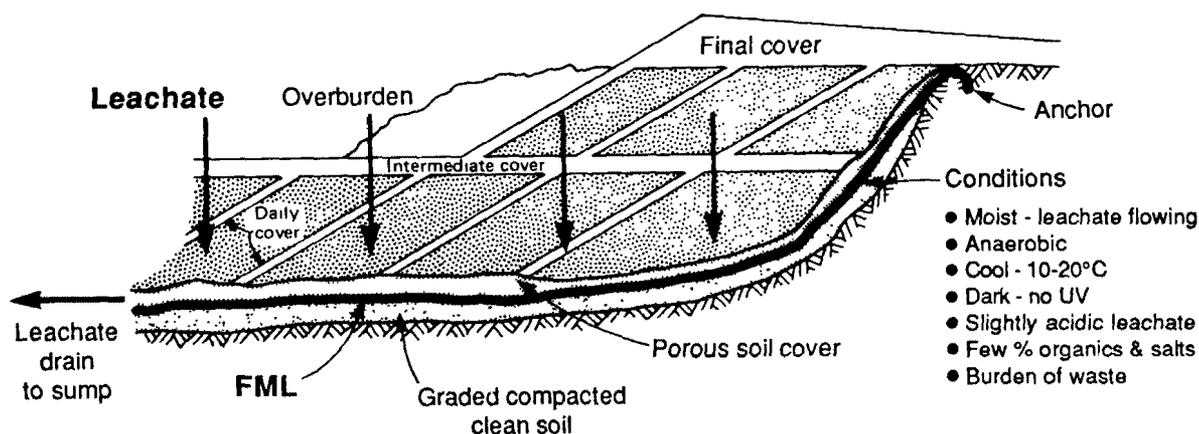


Figure 5-2. Schematic of a lined MSW landfill showing basic components and some of the environmental conditions that exist. (Source: Haxo, 1976).

5.2.5 Hazardous Waste Landfills

The conditions that FMLs and other construction materials may encounter in service in hazardous waste landfills are a combination of many of the conditions that are encountered in MSW landfills and hazardous waste surface impoundments. Figure 5-1 schematically illustrates the principal features of a closed landfill including the FML bottom and cover liners. Figure 5-5 schematically represents a bottom double-liner system for a hazardous waste landfill. This figure presents the basic requirements of a double liner, showing the arrangements for drainage above the liner and the drainage and leak detection system below the liner. Figure 5-6 is a schematic profile of an FML composite double-liner system for a hazardous waste landfill; the dimensions and specifications presently recommended by the EPA for each

TABLE 5-2. ENVIRONMENTAL CONDITIONS ENCOUNTERED BY LINER SYSTEMS DURING SERVICE IN AN MSW LANDFILL

-
-
- Placement on a prepared surface, i.e. either a geotextile or a soil surface which has been graded to allow drainage, has been compacted, and is free of rocks, stumps, etc.
 - Anaerobic conditions. In an anaerobic environment, the lack of oxygen can essentially eliminate oxidative degradation of the materials and greatly reduce biodegradation by microorganisms; however, some designs for drainage and leak-detection systems may allow air into a liner system.
 - No light; the absence of light removes a significant cause of polymer degradation.
 - Generally wet-humid conditions, particularly if leachate is being generated regularly, that could result in the leaching of ingredients, such as plasticizers, from the FML.
 - Temperatures ranging from 40° to 70°F normally, although high temperatures can be generated within the fill if aerobic decomposition takes place.
 - Generally slightly acidic conditions from the leachate due to presence of organic acids formed in the degradation of the MSW.
 - High concentration of ions in the leachate that will probably have little effect on FMLs, but may affect the soil below it if the liner is breached.
 - Considerable dissolved organic constituents in the leachate which may swell and degrade some FMLs.
 - Only modest head pressure, since drainage through porous soil or geosynthetics above the FML is designed to take place continually.
 - Overburden pressure up to more than 100 psi on the FML and the leachate collection and removal system. Overburden pressure can range from 10 to more than 100 psi depending on the depth of the fill and the cover system. High overburden pressure may cause damage to the FML if the soil below it is rough and may pose severe conditions in the leachate collection and leak-detection systems, particularly if the materials used are sensitive to constituents in the leachate. For example, the collapse of drainage pipe above an FML would not only reduce leachate collection, but could also result in puncturing of the FML. If the pipe is below the FML, a collapse could result in localized subsidence that could cause a breach in the FML.
 - The presence of gases (i.e. carbon dioxide and methane) generated in the anaerobic decomposition of the refuse. The carbon dioxide will probably be dissolved in the leachate and contribute to its acidity and may cause mineralization of the soil in the area of the liner and potential clogging of the drainage system.
-
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component are shown (EPA, 1985). These requirements are discussed in more detail in Chapter 7. Some of the major conditions that exist in a hazardous waste landfill and differ from the conditions in a MSW landfill and surface impoundment are discussed in the following sections.

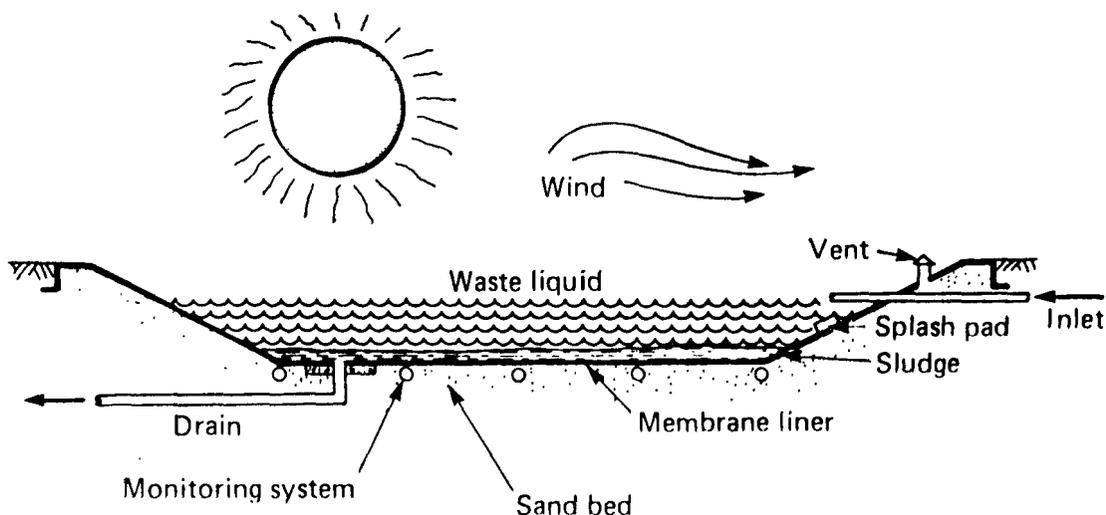


Figure 5-3. Environmental conditions encountered by an uncovered FML in a surface impoundment.

The organic constituents that are present in a hazardous waste landfill may be more likely to partition to polymeric materials, such as an FML, than the organic constituents of the leachate from an MSW. Many of the organics are volatile and can migrate throughout a hazardous waste landfill and be absorbed by polymeric materials that are not in direct contact with the leachate. These organics can permeate the FML and be absorbed by ancillary materials such as geotextiles and geonets. Depending on the organic, this absorption can soften geonets and thus, in conjunction with the overburden placed on a drainage system, can reduce the drainage capacity of a system that depends on geonets as the drainage medium.

In contrast to an MSW landfill, a hazardous waste landfill is probably aerobic, which means that microbial action could proceed if the constituents of the waste do not sterilize the microbes. Microbial action would aid in the biodegradation of the contents of the landfill, but also may cause fungal growth and potential clogging of the drainage system.

The hazardous waste will probably not generate the amount of gases that are generated by MSW. Nevertheless, the volatile organics in the hazardous waste landfill may need to be controlled as they can permeate the cover liner and may affect plant growth on the cover. Also, hazardous wastes, if properly placed with a minimum amount of voids in a landfill, will not consolidate as much as MSW does; consequently, the strains that might develop in a final cover system placed on a hazardous waste landfill could be less than those that develop in a cover for an MSW Landfill.

TABLE 5-3. ENVIRONMENTAL CONDITIONS POTENTIALLY ENCOUNTERED BY POLYMERIC FMLS IN WEATHER EXPOSURE IN SURFACE IMPOUNDMENTS

Condition	Potential effect on FMLs
Presence of air/oxygen	Oxidation Stiffening Reduction of mechanical strength
Ozone	Cracking of some FMLs at points of strain
Sunlight	Degradation of polymer: UV - Stiffening and cracking IR - High membrane temperature Crosslinking of some FMLs
High humidity/rain	Water absorption, leaching of compounding ingredients
Elevated temperatures:	
Short-term	Softening Reduction of mechanical strength
Long-term	Stiffening and loss of plasticizer Acceleration of other forms of degradation
Low temperatures	Possible embrittlement
Wind	Movement of the liner on the slopes Stiffening and loss of plasticizer Flexing and mechanical damage due to wave action on the FML, particularly if the large dimension is oriented with the prevailing winds
Mechanical stress	Cracking or tearing
Fluctuating temperature (diurnal, clear to cloudy)	Variation in strain in the FML being installed Complications in seaming operations
Animals	Punctures, gnawing of holes
Rain	Slipping of soil cover on the FML surface
Ice	Puncture of some FMLs
Soil cover	Protects FML from UV light but may slip on liner and pull liner down

TABLE 5-4. ENVIRONMENTAL CONDITIONS POTENTIALLY ENCOUNTERED BY POLYMERIC FMLS AT THE AIR-WASTE LIQUID INTERFACE IN SURFACE IMPOUNDMENTS

Condition	Potential effect on FMLs
Intermittent exposure to weather and waste liquids	Acceleration of degradation of FML
Presence of oily layer or slicks on the surface of the liquid	Swelling of FML; softening of FML
Wind and waves	Flexing and mechanical damage Evaporation of plasticizers and antidegradents Damage to underlying earthwork
Biological growth on the surface of the FML	Surface damage due to adhesion of the growth and cracking after growth dries out

5.2.6 Waste Piles

Waste piles are noncontainerized accumulations of solid waste which can be used for treatment as well as storage of dry materials. As they are temporary in nature, design constraints on waste piles are generally less rigorous than for liquid storage ponds or for long-term disposal facilities. Even for hazardous waste handling purposes, waste piles may require only a single liner under the facility; however, if a pile is closed as a permanent disposal facility, it must be double-lined. This type of disposal unit is usually constructed in relatively flat areas. Waste piles are used for the short-term storage of high-volume dry wastes such as coal ash, for stacking of abatement gypsum, for stockpiles of bottom ash, and for surge storage of any dry, high-volume waste. A schematic of a typical gypsum stack design is presented in Figure 5-7. The most important environmental condition to which a liner system is exposed to in a waste pile is the overburden pressure.

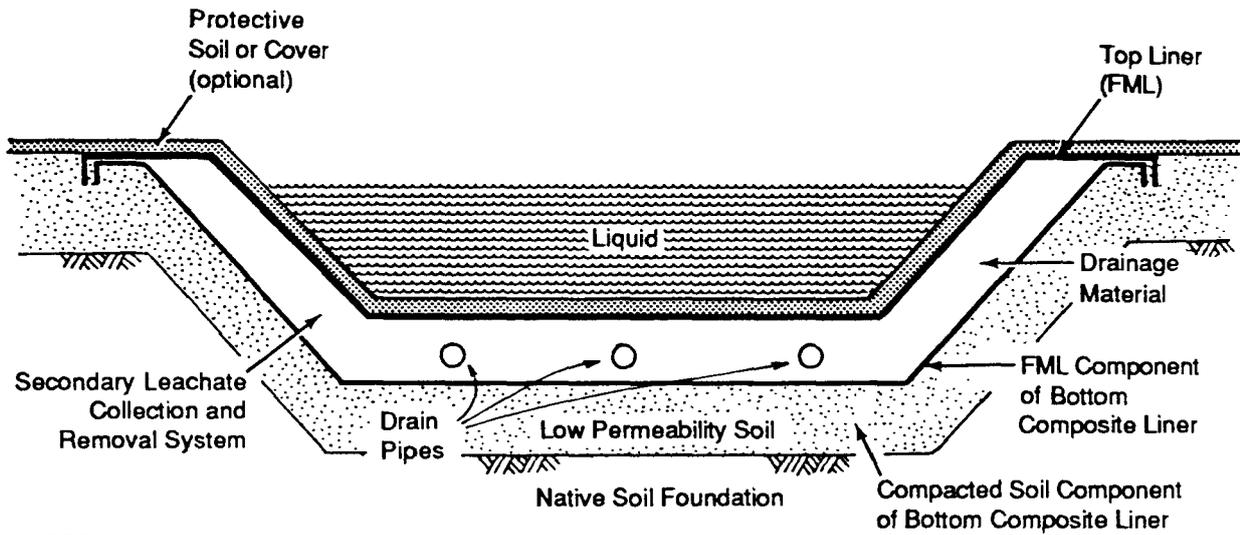
5.2.7 Heap Leach Pads and Ponds

Liner systems based on FMLs are being used as barriers in heap leaching of low-grade ores to recover valuable metals, i.e. gold and silver. In this relatively recently developed technology (Hoye et al, 1987), the liner system acts as a barrier not only to prevent the loss of the dissolved metals but also to prevent the release to the environment of the cyanide or sulfuric acid solutions used to dissolve the metals. Pads from 0.25 to 50 acres in size are constructed of native or modified clays, FMLs (e.g. HDPE, PVC, or

TABLE 5-5. ENVIRONMENTAL CONDITIONS POTENTIALLY ENCOUNTERED BY POLYMERIC FMLS AND OTHER MATERIALS OF CONSTRUCTION IN EXPOSURE TO WASTE LIQUIDS AND LEACHATES IN SURFACE IMPOUNDMENTS

Condition	Potential effect on FMLs
Presence of water and organics	Swelling Softening and loss in strength Increase in permeability Possible stress cracking Reduction of seam strength
Presence of strong acids, bases	Extraction of compound ingredients Stiffening
Presence of vast array of different organic chemicals	Extraction of compound ingredients Stiffening
Presence of liquid with similar solubility parameter	Swelling and potential dissolution of FML
Mechanical stress, both uniaxial and multiaxial	Creep of liner, cracking
Waste temperature	Acceleration of other effects Softening and loss in strength
Presence of air (probable)	Oxidative degradation Biological growth in drainage system, e.g. pipe
High overburden pressure	Settling of the native soil base Shifting of the components in the liner system, particularly the components of the leachate drainage and the leak-detection systems
Hydraulic head on liner system (up to 30 ft)	Hydrostatic pressure on the liner system potentially resulting in distortion of liner and stress due to uneven subgrade surfaces High flow through any hole in the liner that might develop

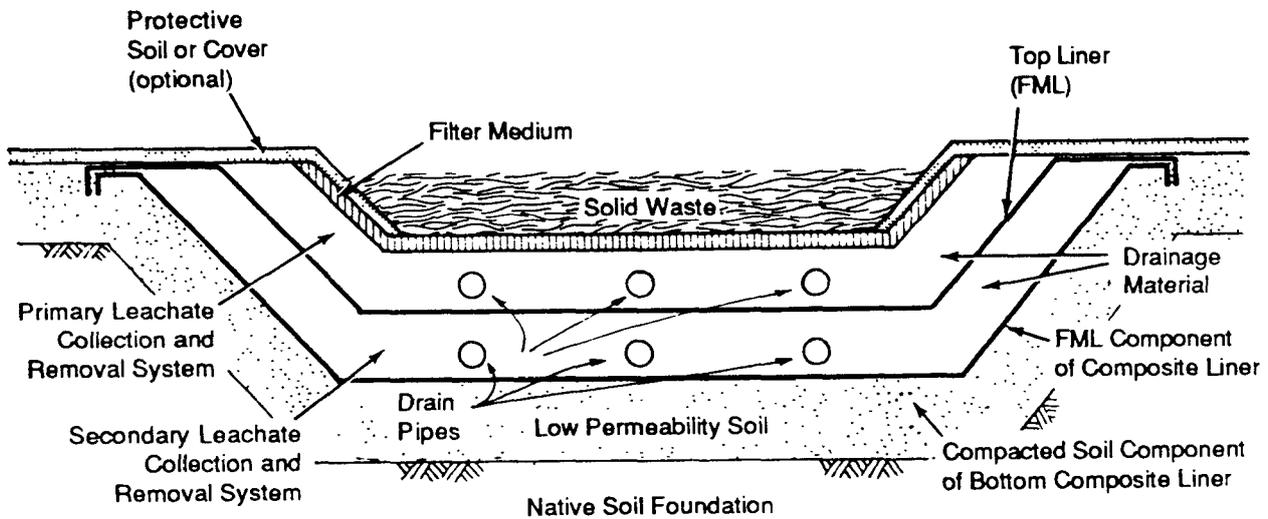
CSPE), or asphalt. Both single- and double-lined pads and ponds with leak detection and solution collection systems have been used.



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

NOT TO SCALE

Figure 5-4. Schematic of an FML/composite double-liner system for a surface impoundment. (Based on EPA, 1985).



NOT TO SCALE

Figure 5-5. Schematic of an FML/composite double-liner system for a landfill. (Based on EPA, 1985).

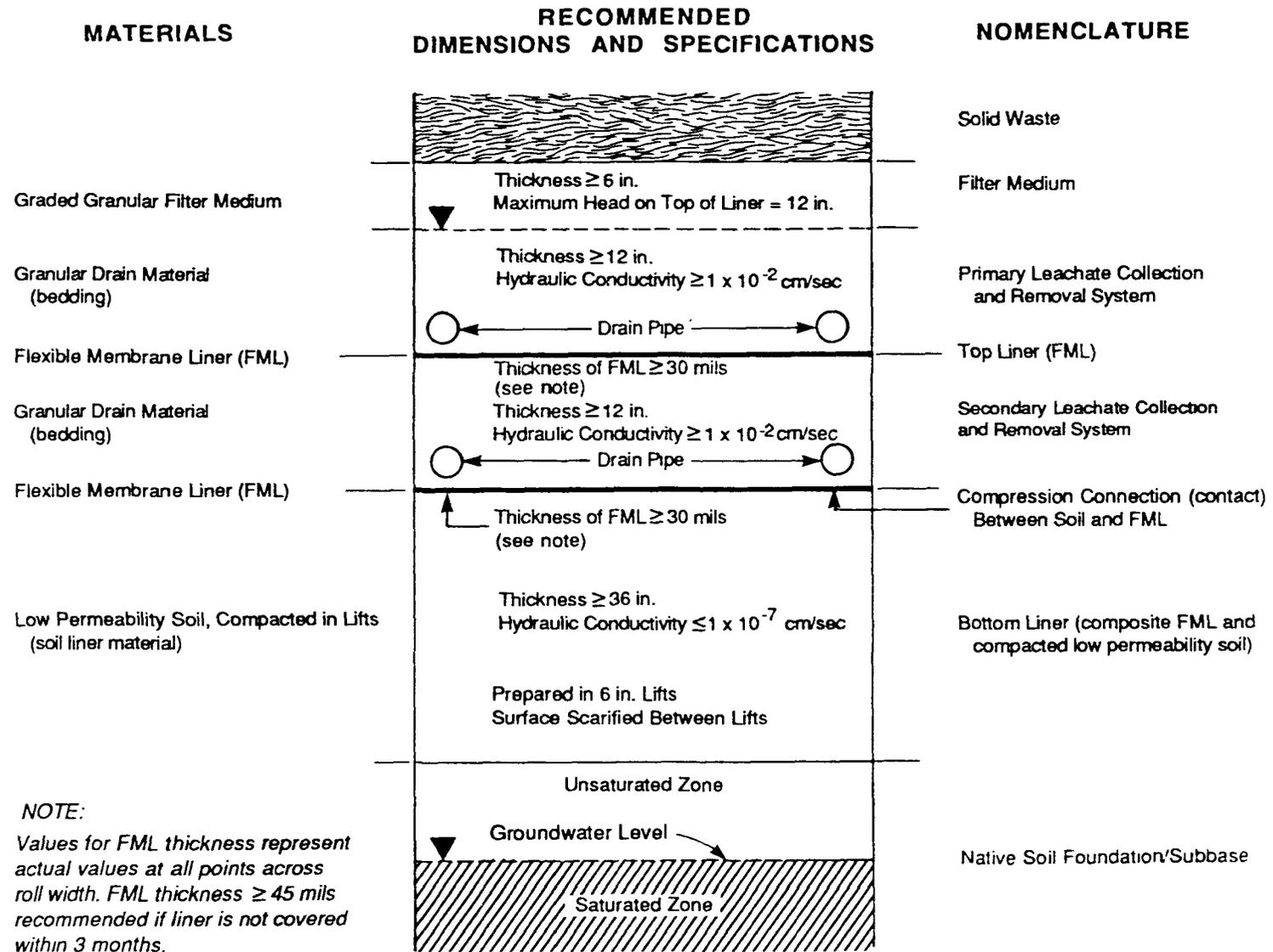
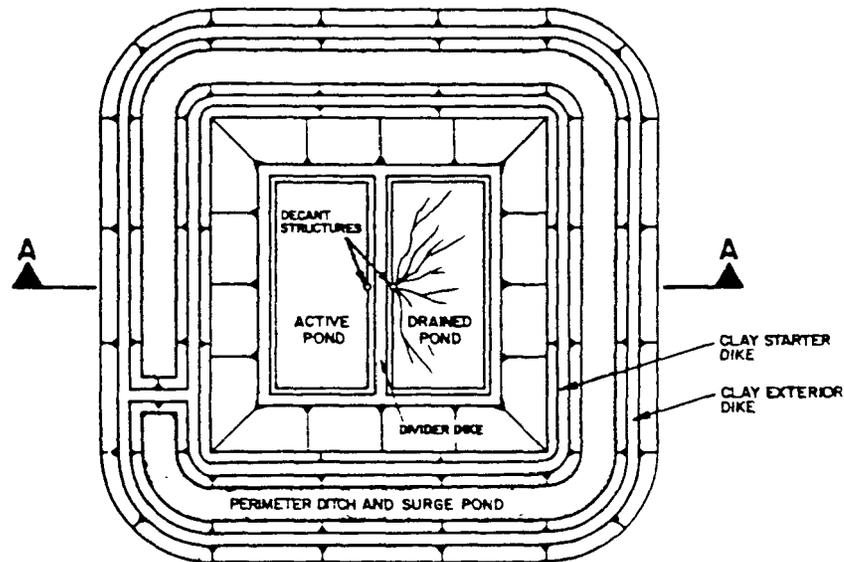
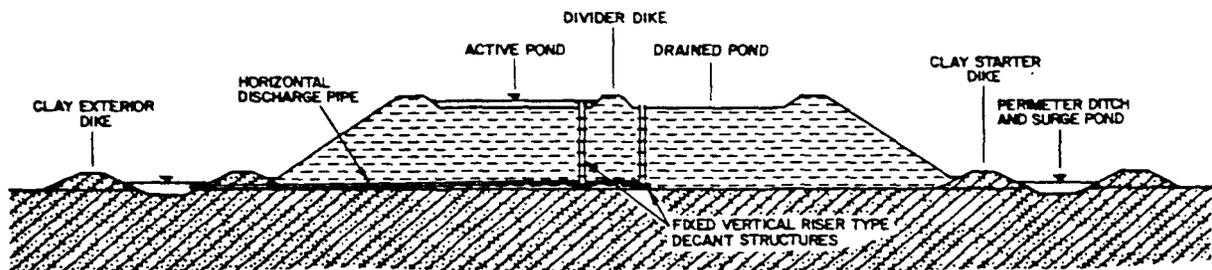


Figure 5-6. Schematic profile of FML/composite double-liner system for a hazardous waste landfill presenting EPA draft guidance. Synthetic drainage media and synthetic filter media can replace granular media if equivalency of performance is demonstrated. (Based on EPA, 1985).



GYPSUM STACK SITE PLAN



SECTION A-A GYPSUM STACK CROSS SECTION

Figure 5-7. Typical gypsum stack design. (Source: EPRI, 1980, p 16-6).

The basic design and operational layout of heap leach projects are similar at all facilities (Hoye et al, 1987). Low-grade ore is stacked from 15 to over 50 ft high in engineered heaps on lined pads sloped 1 to 6% and a weak alkaline cyanide solution for gold and silver extraction and sulfuric acid solution for copper extraction is sprayed over the ore. The optimal pH of the solution for gold dissolution is 10.3, and the cyanide content is maintained at approximately 250 mg L⁻¹. This solution has a pH of 10.3 and a cyanide content of 250 mg L⁻¹. The solution percolates through the heap and dissolves finely disseminated free metal particles. The pregnant solution flows over the pad to a lined collection ditch, which carries the pregnant solution to a lined pond. The product metal is then recovered from solution by precipitation or carbon adsorption (gold). Heap leach operations are typically zero discharge facilities. The leaching cycle is relatively short (20 to 90 days). At the end of the cycle, the ore is rinsed with fresh water to remove residual cyanide solution and dissolved

metals. The leached ore is then usually left in place. A conceptual flow diagram of the heap leach operation is presented in Figure 5-8.

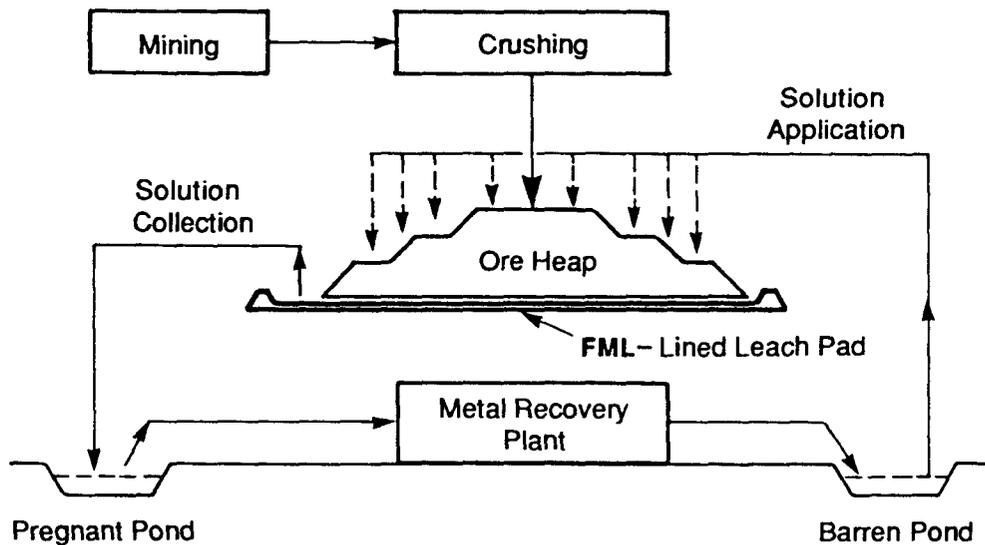


Figure 5-8. Conceptual flow diagram of typical heap leach operation. (Based on Leach et al, 1988).

The liner system in a heap leach system is usually exposed to a relatively light load in comparison with other end uses, though some heap leach projects are known to be 300 ft in depth which would yield a pressure of 350 psi on the liner system. However, an FML can be exposed to irregularities in the surfaces containing it.

5.2.8 Secondary Containment Facilities

A relatively recent application of FMLs is in secondary containment of substances that are potentially hazardous or could cause environmental damage. This application is both for the secondary containment of hazardous substances and liquids that may be stored in tanks above ground and of liquids, such as petroleum and petroleum products, that are stored in underground storage tanks. Waste liquids and in-process liquids may also be stored in tanks that require secondary containment. In all cases, FMLs used for secondary containment will contact the liquids being contained only in case there is an emergency, i.e. in case there is leakage from the primary storage tanks. When used for secondary containment of aboveground tanks, such as for petroleum storage, the FMLs are usually covered with soil or aggregate to protect them from weathering, wind lift, and mechanical damage. Contact with the liquid being stored would be for relatively short time periods until the liquid can be removed or evaporated. An FML used in secondary containment of a liquid stored underground would not be exposed to weather and to the liquid being stored except in the event of leakage from

the tank. Figure 5-9 is a schematic of an underground storage tank with an FML secondary containment.

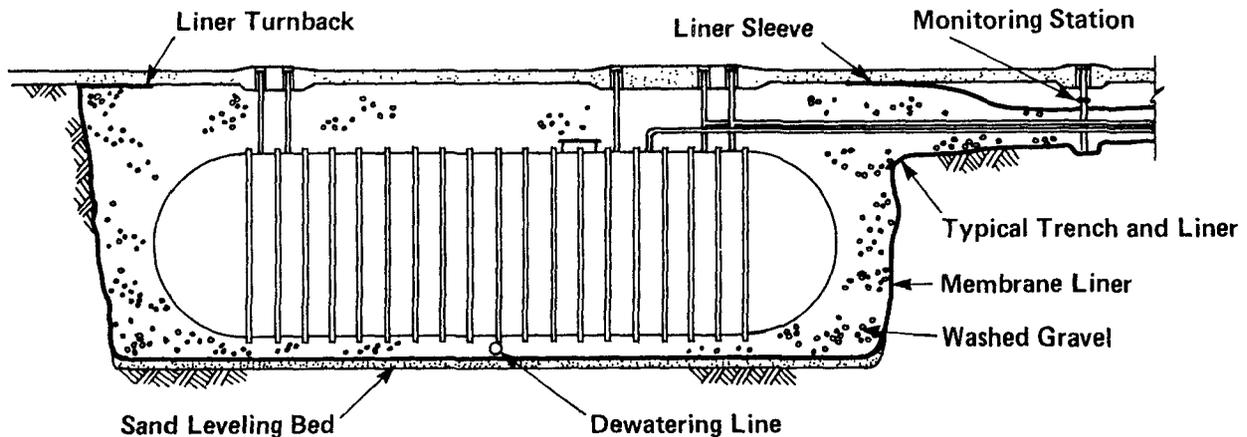


Figure 5-9. FML used for secondary containment. (Based on Haxo, 1984).

5.2.9 Uranium Tailings Ponds

Disposal of uranium tailings in surface impoundments has been the conventional practice to date. Tailings are disposed of in any of several types of surface impoundments near the mill, some of which are lined with FMLs. Such impoundments can be constructed as four-sided structures in relatively flat areas; they can also be formed by constructing a dam or embankment in an existing natural drainage area. In the latter case, diversion ditches are constructed to divert runoff around the impoundment. Embankments for impoundments have, in the past, been constructed of tailings, but newer impoundments have been constructed from local earthen materials. Heights of tailings embankments, which vary from 10 to 30 m (30 to 100 ft) above surrounding terrain, can place a heavy overburden on a liner as well as the drainage systems. The leachate generated in such facilities is essentially inorganic, as is shown in Appendix A, and may be collected at the bottom and recycled for use in the mill.

5.3 PRINCIPAL ENVIRONMENTAL STRESSES ENCOUNTERED BY FMLs AND OTHER MATERIALS OF CONSTRUCTION IN SERVICE IN TSDFS

In the previous section the conditions that FMLs and other materials of construction encounter in service in individual types of waste storage and disposal facilities are described. As the principal function of a lining system is to minimize or prevent the escape of toxic and hazardous constituents of the wastes, it is necessary to prevent any breach in the lining system. The original low permeability of a lining system must be maintained throughout its service life.

In reviewing the environmental stresses that construction materials encounter in lining and drainage systems, it appears that these stresses can be classified into two principal types: chemical and physical. These stresses can affect the performance of an FML and other construction materials and reduce their service lives. Furthermore, these stresses may act individually, but, in most cases, they will act together to determine the service lives of these construction materials. Biological stresses, which affect polymeric materials to a limited degree, have eliminated some materials from subsurface applications. In particular, biological stresses are a factor in the performance of some FMLs, such as those that contain low molecular weight fractions. These stresses may become important factors in very long exposures of materials that, at the present, appear to be resistant to biodegradation.

In the following subsections these environmental stresses will be discussed in terms of the performance and permanence of FMLs.

5.3.1 Chemical Stresses

Due to the immense variety of wastes and combinations of dissolved organic and inorganic chemicals in the wastes and waste liquids that are contained in storage and disposal facilities, the effects of chemical stress on the performance of liner systems is of primary concern, particularly for long-term service. The effects of chemical stresses are manifested by:

- Degradation of the base polymer through oxidation, hydrolysis, photo-oxidation, etc., which results in embrittlement and loss of physical properties of the FML that may be important to its performance.
- Depolymerization, which results in softening and loss of physical properties.
- Absorption of waste constituents, which can result in increased permeability and loss in strength and other physical properties if the amounts become sufficiently large.
- Extraction of components of the original FML compound.

The effects of chemical stress may take extended periods of time to become apparent, particularly when the concentration of aggressive constituents in a waste liquid is low.

Because of the known low permeability of polymeric FMLs to water, gases, and other permeants, FMLs were considered as likely candidates for lining waste storage and disposal facilities constructed on land. However, at the time polymeric membranes were first being considered for such applications, there was great concern about the possible effects various constituents in waste liquids would have on the serviceability of these materials, even though considerable experience had already been accumulated with using polymeric FMLs to contain specific liquids of known composition.

A variety of FMLs had been successfully used in the impoundment and conveyance of water and in the impoundment of brines and some wastewaters. FMLs had also been used to line facilities and equipment for handling very specific chemicals and substances of known composition. Examples of such facilities include lined chemical process equipment and storage tanks. In this type of application, which was generally above ground, the required service life was relatively short and, if a leak occurred in the lining, it was accessible and could be repaired or replaced.

In all of these applications, there was no attempt to achieve a minimum level of escape from the impoundment or conveyance system. In addition, the materials being contained generally were not aggressive to the lining materials. However, as pointed out in Chapter 2, the waste liquids generated by MSW or impounded in hazardous waste facilities contain a vast number of different chemicals in complex mixtures, both organic and inorganic, some of which in concentrated form can affect FMLs. It was not known how the various FMLs would resist dilute aqueous solutions as well as uncontrolled concentrated solutions.

Exposure to some of the chemicals contained in waste liquids can increase the permeability and result in changes in the stress-strain characteristics of FMLs, and possibly even result in their disintegration with time. These effects, which can be the result of absorption of constituents from a waste liquid, are apparent on simple immersion in the liquid. Immersion tests have been used by the polymer industry to determine the compatibility of polymeric compositions with various liquids in the selection and design of compositions for service in contact with these liquids. In this type of test, the weight changes and changes in physical properties are measured to assess compatibility. Immersion-type simulations of field service are performed as an initial assessment of the ability of the FML and the other construction materials to perform in a liner system for a waste storage and disposal facility.

This chapter, which presents data from simulated exposure tests, emphasizes the effect of the chemical environment on the tested FMLs. Data are presented resulting from exposure of FMLs to actual waste streams to determine their chemical compatibility. Exposure conditions include both one-sided exposure in test cells designed to simulate service environments and two-sided in exposure in immersion-type tests. In addition, data are presented from immersion tests run either in neat solutions of various chemicals that may be encountered in service or in dilute aqueous solutions. Predominantly, the samples under exposure were not subject to concurrent physical stressing.

Chemical stresses are also encountered in surface impoundments in the area where the FML is exposed to the weather. The effects of the chemical stresses are the result of:

- UV radiation.
- Infrared radiation.

- Rain water.
- Oxygen.
- Ozone.

All these factors can contribute to the general aging of an FML exposed to the weather. However, FMLs do not interact the same way with these factors; for instance, unsaturated polymers will be not affected by the ozone which can cause cracking in polymers such as neoprene and butyl rubber. Infrared radiation interacts indirectly by raising the temperature of an FML and thereby increasing the rate of oxidation and loss of volatile constituents from the FML compound. The consequent effects on an FML can include hardening, crazing or cracking of the FML surface, and reduction of physical properties, such as tensile and tear resistance. Infrared radiation can thus cause an FML to have less resistance to mechanical and abrasive damage. Effects at the air-water interface can be more pronounced because of the constant presence of chemicals in the water plus the oxygen and increased temperature at the surface. Some of these stresses are simulated in tests such as the tub test and in weathering tests.

5.3.2 Physical Stresses

A variety of physical stresses are encountered by FMLs and the other construction materials used in liner and drainage systems. These stresses, which can be independent of any chemical stresses, take place primarily during construction and during the early service life of a waste facility when the waste liquid is not in contact with the FML or the other construction materials. In the case of FMLs, some of the potential physical stresses that can be encountered are:

- Stresses during installation due to the laying out of the FML on the ground.
- Stresses during placement of a soil cover on an FML.
- Stresses due to dropped tools, etc., which could result in puncture.
- Stresses due to traffic.
- Shrinkage stresses at toes of slopes due to heating of the FML and inadequate allowance for shrinkage.
- Low temperature stresses due to inadequate allowance for thermal contraction.
- Stresses over irregularly shaped surfaces due to large aggregates next to the surface of the FML (Figure 5-10).
- Distortion of an FML placed on a geonet due to inadequate thickness or stiffness.

- Biaxial stresses which may cause rupture at low elongations, particularly of semicrystalline FMLs.

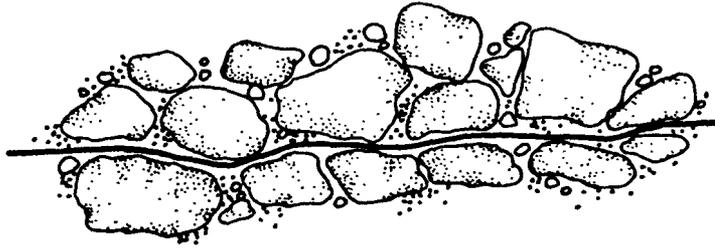


Figure 5-10. Schematic showing stresses in an FML that would be caused by large aggregates in cover and subgrade and compressive loading.

The effects of load can reduce the drainage capacity of both geotextiles and geonets, since both of these materials will show significant reductions in transmissivity with increasing overburden. Similar effects can be encountered in the improper sizing of drainage pipes.

Other physical stresses that are of importance are abrasion and frictional effects. Abrasion of FMLs can take place during the installation of a cover, and a lack of friction between the components in a layered system can cause instability and slippage of the soil cover on an FML.

An important physical stress that affects all of the polymeric materials that are used in the construction of waste storage and disposal facilities is the effect of creep under constant or variable load. Creep is a time effect which can cause puncture or rupture in an FML placed on an irregular surface or cause compression or collapse of geotextiles or geonets after long-term exposure effectively reducing their drainage capabilities. Polymeric materials under constant load are subject to fatigue failures such as have been encountered in pipes (Lustiger, 1986).

Some of the physical stresses that have been simulated in performance-type tests are described and discussed in this chapter.

5.3.3 Combination of Chemical and Physical Stresses

Once a waste storage and disposal facility is in service, FMLs and other materials of construction in the facility are under both chemical and physical stresses. The effects under chemical and physical stresses can combine. For example, the effects of creep under load can be highly aggravated by the effects of softening due to absorption of components from the waste. This would be particularly apparent with geonets and geotextiles that would be used in the drainage systems. It also may affect the FML that is placed over geonets. Simulation tests of this condition are presently being performed by Southwest Research Institute. This kind of data is being requested by some regional offices of the EPA as a part of the Part B applications.

Other ways in which the combined chemical and physical stresses can affect FMLs include the following:

- The absorption of organics and subsequent swelling of the FML can cause it to increase in permeability.
- Unsaturated polymers such as butyl rubber and neoprene exposed simultaneously to mechanical stresses and ozone can crack.
- Improperly formulated semicrystalline FMLs under mechanical stresses when in contact with some chemicals can crack by environmental stress cracking.

5.3.4 Biological Stresses

In general, the polymeric compositions that are being used in the construction of waste storage and disposal facilities have shown a very high resistance to biodegradation, as is discussed in Chapter 4. Two types of biological stresses have been observed:

- Biodegradation of monomeric plasticizers has occurred in compositions compounded with these plasticizers, particularly in some PVCs.
- Fungal growth on the surface of FMLs in wastewater lagoons has occurred at the air-water interface. The fungal growth has dried on the FML and caused the FML to shrink and crack starting at the surface.

The compounding of PVCs for FMLs can avoid for extended time the deterioration by biodegradation of plasticizers through the use of biocides and the proper selection of plasticizer. The potential fungal growth on the components of a leak detection and/or drainage system is of concern because oxygen is present in the system.

5.4 EFFECTS OF CHEMICAL STRESSES ON FMLS AND ANCILLARY CONSTRUCTION MATERIALS

The chemical compatibility of the materials used in the construction of waste storage and disposal facilities with the wastes to be contained was of major concern when the concept of lining such facilities was first considered in the late 1960s. Although there had been considerable use of liners in the abeyance and storage of water, there was concern about the effect various components of a waste liquid could have on an FML. Consequently, the EPA undertook several research programs to develop information needed to establish the adequacy of various FMLs and other materials for use in the construction of disposal facilities. In addition, other organizations also initiated research programs to determine the adequacy of liner materials for wastes generated by a specific industry.

In this section, results of several of these programs involving MSW, hazardous and toxic wastes, wastes from coal-fired power plants, and various industrial liquids and wastes are reported. In these research programs attempts were made to simulate conditions that would exist in the facilities and to design tests that would predict the performance of the lining materials being tested. In particular, there was interest in the permeability of FMLs to various organic chemicals, both in solutions and as neat chemicals. Many of these FMLs were subjected to immersion-type tests with specific chemicals and others to tests with simple aqueous solutions. An outcome of the testing was the development of a liner-waste compatibility test by the EPA, i.e. Method 9090 (EPA, 1986), which is described and discussed in this section.

5.4.1 Simulation Tests of FMLs

5.4.1.1 Exposure to MSW Leachate in Landfill Simulators--

To simulate the conditions of one-sided exposure of FMLs to MSW landfill leachate, Haxo et al (1982 and 1985a) placed 2-ft diameter liner specimens under 8 ft of ground refuse in landfill simulators (Figure 5-11). An individual simulator consisted of a 2-ft diameter steel pipe, 10 ft in height, placed on an epoxy-coated concrete base (Figure 5-12). The six polymeric FMLs that were exposed as liners in the simulators were based on the following polymers:

- Butyl rubber (IIR).
- Chlorinated polyethylene (CPE).
- Chlorosulfonated polyethylene (CSPE).
- Ethylene propylene rubber (EPDM).
- Low-density polyethylene (LDPE).
- Polyvinyl chloride (PVC).

Note: In this experiment, two sprayed-on FMLs and four admixed liner materials were concurrently exposed and tested. Results of these tests are reported in Sections 5.9 and 5.10, respectively.

The FML specimens were sealed in the simulator bases with epoxy resin so that leachate could not bypass the liners. Each FML specimen had a seam through the center which was made either by the manufacturer or in the laboratory in accordance with the standard practice recommended by the supplier. Approximately 1 yd³ of ground MSW was compacted above each liner in approximately 4-in. lifts to yield a density of 1240 lb yd⁻³ at a 30% water content. The refuse was covered with 2 ft of soil and 4 in. of crushed rock.

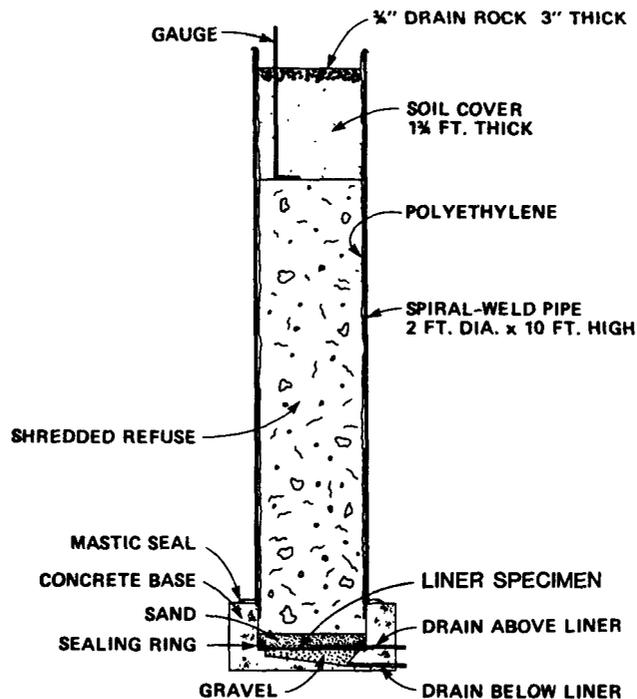


Figure 5-11. Landfill simulator used to evaluate FMLs specimen exposed to MSW landfill leachate (Source: Haxo et al, 1982).

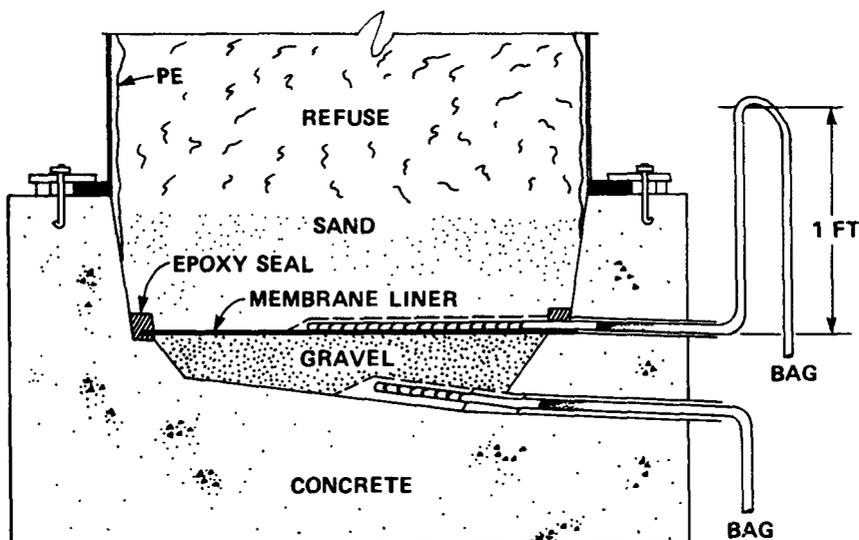


Figure 5-12. Base of the landfill simulator in which the FMLs were exposed. The refuse at the bottom of the column was anaerobic. The leachate was maintained at a 1-ft head by U-tubes. Plastic bags were sealed at both outlets. Strip specimens of FMLs were buried in the sand above the liner for exposure to leachate (Source: Haxo et al, 1982).

Tap water was introduced at the rate of 25 in. per year. Leachate generated in each cell was ponded above the specimen at a 1-ft head by continual draining into a collection bag. The simulators were designed to collect any leachate that seeped through the liner specimens.

In addition to the FML specimens exposed as liners, 2.5 x 22-in. specimens were buried in the sand above the liner specimens. Because leachate was ponded to a depth of 1-ft above the liners, the buried specimens were totally immersed throughout their exposure. These specimens were included in the study to increase the number of FMLs being tested and to compare the effects of two-sided exposure with the effects of one-sided exposure.

Two specimens of each of the FMLs tested were exposed in the simulators. The simulators exposing the first set of specimens were dismantled at the end of 12 months, and the simulators exposing the second set were dismantled at the end of 56 months. The specimens removed from the simulators were tested for physical and analytical properties. These tests are listed in Table 5-6.

The average composition of the leachate produced in the simulators at the end of 12 months, when the first set of FML specimens was recovered and tested, is shown in Table 5-7. The strength of the leachate, as measured by total solids, nonvolatile solids, and total volatile acids in the simulators decreased with time, as is shown in Figures 5-13 and 5-14. Initially, the composition of the leachate generated by the simulators was fairly uniform. However, as the concentrations of the dissolved salts and organic and acids in the leachates decreased with time, variations developed in their relative concentrations in the different simulators.

None of the FML specimens allowed any seepage. The epoxy seals in three of the bases, however, failed during the last year of operation of the simulators. The absence of seepage collected below the liners, except in cases where the epoxy sealing ring disintegrated, confirms the very low permeability of FMLs to MSW leachate. The results also show that the seams in the FML specimens were adequate for these exposure conditions.

The exposed FML specimens were cut from the bases while they were still wet and sealed in PE bags to keep them in a moist condition until they were tested. All tests were made on samples as taken from the bases, i.e. none of the samples was dried prior to testing. In all of the bases from which the specimens were cut, the square-woven glass fabric and gravel below the FML were in an "as new" condition, except in the base that contained the CSPE FML, where a small area of the glass fabric was stained. Close examination under magnification of the sheeting immediately above the stain showed that a small piece of foreign material existed in the liner compound, which resulted in a pinhole.

The results of the analytical and physical testing of the FMLs before and after exposure are presented in Table 5-8. All tests on exposed samples were made as soon as possible after removal from service. This procedure determines the properties of the FMLs as they existed in the actual service environment.

TABLE 5-6. TESTING OF POLYMERIC FMLS
Before and After Exposure to Leachate Produced
in the MSW Landfill Simulator

Thickness
Tensile properties, ASTM D412*
Hardness, ASTM D2240
Tear strength, ASTM D624, Die C
Water absorption at room temperature and 70°C, ASTM D570 (unexposed only)
Seam strength, in peel and in shear
Puncture resistance, Federal Test Method Standard No. 101C, Method 2065
Water vapor transmission, ASTM E96 (unexposed only)
Specific gravity and ash (unexposed only)
Volatiles, Matrecon Test Method 1 (Appendix G)
Extractables, Matrecon Test Method 2 (Appendix E)

*The references at the end of this chapter include the ASTM standards used in this chapter, along with the title of the standard.

TABLE 5-7. ANALYSIS OF LEACHATE
FROM MSW SIMULATOR^a

Test	Value
Total solids, %	3.31
Volatile solids, %	1.95
Nonvolatile solids, %	1.36
Chemical oxygen demand (COD), g L ⁻¹	45.9
pH	5.05
Total volatile acids (TVA), g L ⁻¹	24.33
Organic acids, g L ⁻¹ :	
Acetic	11.25
Propionic	2.87
Isobutyric	0.81
Butyric	6.93

^aAt the end of the first year of operation when the first set of FML specimens were recovered.

Source: Haxo et al, 1982, p 49.

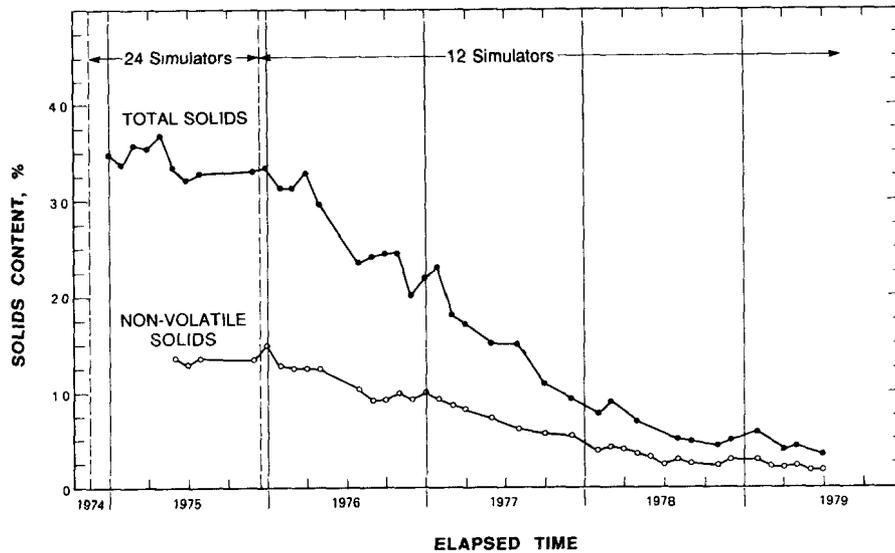


Figure 5-13. Average solids content of the leachates produced in the MSW simulators, November 1974 through July 1979. The data for November 1974 through November 1975 are the averages for the leachates from 24 simulators. Twelve simulators were disassembled in November 1975 and, consequently, the data for December 1975 through July 1979 are the averages for the leachates from the 12 remaining simulators (Source: Haxo et al, 1982, p 50).

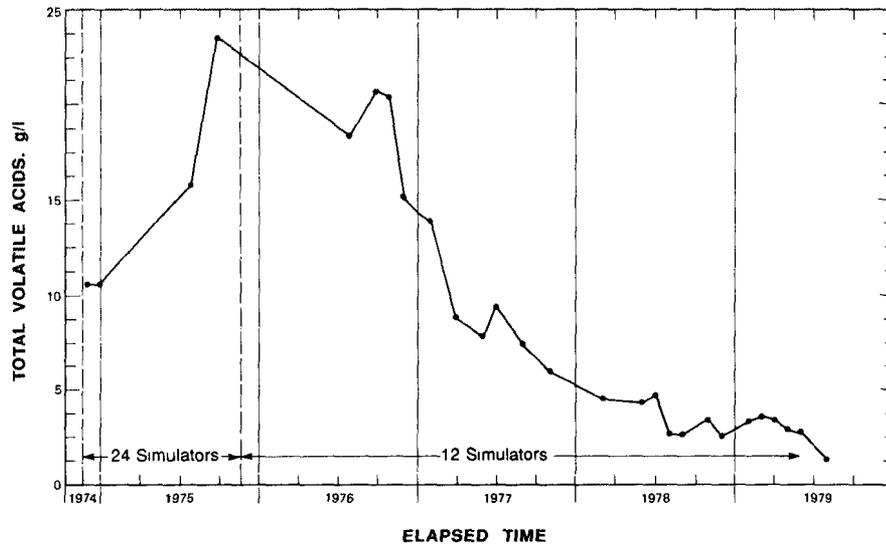


Figure 5-14. Average TVA, as acetic acid, of the leachates produced in the MSW simulators, November 1974 through July 1979. The data for November 1974 through November 1975 are the averages for the leachates from 24 simulators. The data for December 1975 through July 1979 are the averages for the leachates from 12 simulators (Source: Haxo et al, 1982, p 50).

TABLE 5-8. EFFECT ON PROPERTIES OF POLYMERIC FMLS AFTER 12 AND 56 MONTHS OF EXPOSURE TO LEACHATE IN MSW LANDFILL SIMULATOR

Item	Test method ^d	Exposure time, months	Butyl rubber	CPE	CSPE	EPDM	LDPE	PVC
Type of compound ^b	...	...	XL	TP	TP	XL	CX	TP
FML number ^c	...	...	7	12	6R	16	21	17
<u>Analytical properties</u>								
Volatiles (2 h at 105°C), %	MTM-1	0	...	0.10	0.29	0.50	0.00	0.09
	...	12	2.02	6.84	12.78	5.54	0.02	3.55
	...	56	2.37	7.61	13.90	5.74	1.95	2.08
Extractables after removal of volatiles, %	MTM-2	0	11.0	7.5	3.8	31.8	...	37.3
		56	9.8	5.1	3.4	28.3	3.37	34.4
Solvent ^d	...	...	MEK	n-heptane	acetone	MEK	MEK	CCl ₄ + CH ₃ OH
<u>Physical properties</u>								
Thickness, mil	...	0	63	32	36	51	12	21
		12	64	35	38	51	11	21
		56	64	37	37	49	10	22
Tensile strength ^e , psi	ASTM D412	0	1435	2275	1765	1480	2145	2580
		12	1395	1810	1640	1455	2465	2350
		56	1465	1960	2110	1460	2585	2740
Elongation at break ^e	ASTM D412	0	400	410	250	415	505	280
		12	410	400	300	435	505	330
		56	405	385	235	375	540	340
Set after break ^e , %	ASTM D412	0	17	430	115	12	370	73
		12	14	210	105	12	430	57
		56	12	160	60	6	410	62
Stress at 200% elongation ^e , psi	ASTM D412	0	695	1330	1525	755	1260	1965
		12	685	1090	1245	740	1205	1550
		56	750	1140	1825	800	1325	1810
Tear strength (Die C) ^e , ppi	ASTM D624	0	175	255	f	180	390	335
		12	200	320	...	195	495	450
		56	185	170	...	130	405	285
Hardness, Durometer points, 10-second reading	ASTM D2240	0	51A	77A	79A	54A	...	76A
		12	50.5A	65.5A	64A	51.5A	...	64A
		56	51A	70A	70A	51A	...	70A
Puncture resistance ^g	FTMS 101C, Method 2065							
Maximum force-average, lb		0	44.8	47.0	32.9	39.4	13.9	25.8
		12	49.5	49.8	57.0	40.1	14.8	30.1
		56	50.0	51.8	58.2	41.5	17.1	31.3
Deformation at puncture, in.		0	1.22	1.04	0.60	1.44	0.76	0.69
		12	1.20	0.98	0.88	1.18	0.80	0.70
		56	1.25	0.98	0.86	1.19	1.24	0.84

continued . . .

TABLE 5-8. CONTINUED

Item	Test method	Exposure time, months	Butyl rubber	CPE	CSPE	EPDM	LDPE	PVC
<u>Seam strength</u>								
Location of seam preparation	Lab	Lab	Lab	Factory	Lab	Factory
Bonding system	Adhesive (LVT) ^h	Solvent THF:Toluene 50:50	Cement	Adhesive (LVT) ^h	Heat	Cement
Peel strength, average, ppi	...	0	3.8	10.0	>30.0 ⁱ	5.4	>15.6 ^{i,j}	4.0
		12	2.9	5.2	3.4	2.0	...	5.1
		56	3.4	2.9	1.8	7.1	>12.0	5.6
Shear strength, ppi	...	0	30.0	>57.0 ⁱ	>50.0 ⁱ	44.5	>20.2 ⁱ	>2.72
		12	42.0	>35.0	40.2	24.3	>11.4 ^{j,k}	>25.6 ⁱ
		56	17.0	17.0	10.0	18.0	11	22 ⁱ

^aMTM = Matrecon Test Method.

^bXL = Crosslinked; TP = thermoplastic; CX = semicrystalline thermoplastic.

^cContractor's serial number. R indicates liner is fabric reinforced.

^dSolvents used in extraction: MEK = methyl ethyl ketone; CCl₄+CH₃OH = 2:1 blend of carbon tetrachloride and methyl alcohol.

^eAverage of values in machine and transverse directions.

^fTest method not applicable to fabric-reinforced materials.

^gRate of penetration of probe: 20 inches per minute.

^hLow temperature curing cement.

ⁱBreak in specimen outside of seam.

^jSeam failed at initial peak.

^kSeam in the polyethylene liner used in the steel pipes; tabs in the liner specimens mounted in base were too short.

To estimate the amount of MSW leachate absorbed by the FML specimens, the volatiles contents of samples of the exposed materials were measured. The results indicated that the CSPE, CPE, and EPDM FMLs, in this order, had absorbed the greater amounts of leachate. The LDPE, PVC, and butyl liners had the lower volatiles contents and absorbed lesser amounts of leachate.

The extractables contents of the exposed FML specimens were measured to determine the nonvolatile organics in the FML compound and the effect of exposure on the composition of the FMLs. By comparing the extractable contents of an exposed specimen that has been dried with the extractable contents of the unexposed FML, the amount of plasticizer or other ingredients in the compound that has been extracted by the leachate can be calculated. In all cases, the extractables after 56 months were about 10% lower than the original extractables, indicating loss in the original plasticizer contents.

The tensile properties of the FMLs varied; the tensile strength ranged approximately from 1400 to 2500 psi. The changes with exposure time were only modest and many may have been within experimental error, though several showed trends toward increasing values probably a result of either loss of plasticizer or, in the case of the CPE and CSPE FMLs, crosslinking. Tests which reflect the stiffness of the materials, such as modulus (e.g. stress at 200% elongation) and hardness showed a minimum at 12 months. These minima probably reflect the changes in the composition of the leachate with time; at 12 months the leachate concentration showed significantly higher organic content than it did at 56 months. In all cases tear strength and puncture resistance remained at satisfactory levels over the 56 months of exposure.

Though the FMLs showed good retention of properties during exposure, there was a significant drop in several cases in the seam strength of the materials, particularly in the CPE, CSPE, and EPDM specimens; however, this loss of seam strength did not result in any seepage or leakage through the specimens. The fact that no leakage occurred may have been due to the lack of uniaxial or biaxial stress on the specimens. The simulators were designed principally to assess compatibility. Stressing of the specimens was avoided because of doubts that stress could be controlled.

Overall, the net changes in the physical properties of the FMLs resulting from 56 months of exposure were relatively minor. All of the FMLs softened to varying degrees during the first 12 months, probably the result of absorption of organic constituents of the leachate. In the interval of time to 56 months, the PVC, CSPE, and CPE FMLs rehardened slightly, possibly indicating, in the case of the PVC FML, loss of plasticizer and, in the case of the CSPE and CPE FMLs, crosslinking of the polymers. They all recovered most of their tensile properties that were lost due to the initial softening. These three FMLs were all thermoplastic and uncrosslinked.

The results of this experiment are indicative of the concentration effect and an equilibrium in the swelling with changing concentration of the organics. Of the six polymeric FMLs, the LDPE best maintained original properties during the exposure period, as is shown in Table 5-8; it also absorbed the least amount of leachate. However, this FML, which was 10 mils

in thickness, had too low a puncture resistance for use in lining a landfill. This deficiency was confirmed by the difficulties encountered in its performance as a lining of the steel pipes of the simulators, in the preparation of the primary liner specimens, and in the fabrication and use of the LDPE leachate collection bags. The butyl rubber and EPDM FMLs, which were cross-linked changed slightly more in physical properties than did the LDPE FML during the exposure period.

A comparison of the swelling of FMLs in water at room temperature and in the leachate generated in the simulators is presented in Table 5-9. The data for most of the FMLs showed that the swelling in leachate was significantly higher than that in water in spite of the dissolved inorganic constituents in the leachate. This greater swelling was probably due to the absorption of organic constituents in the leachate. The neoprene and CPE FMLs, both of which are chlorine-containing polymers, swelled less in leachate than in water. As MSW leachate generally contains salt, this behavior reflects a commonly observed effect of such polymers when they are immersed in aqueous salt solutions as compared with immersion in water. The salt concentration depresses the absorption of water by chlorinated elastomeric-type polymers.

5.4.1.2 Exposure to Hazardous Wastes in One-Sided Exposure Cells--

An exploratory experimental research project was conducted (1975 - 1983) by Haxo et al (1985b and 1986) to assess the relative effectiveness and durability of a wide variety of liner materials when exposed to nine different wastes which were deemed to be hazardous by EPA in Cincinnati. The liner materials were placed in a variety of exposures that simulated different aspects of service in on-land waste storage and disposal facilities. These exposures included immersion tests, pouch tests, and tub tests, the results of which are described in separate sections in this chapter, and exposure in one-sided exposure cells. The materials studied included compacted soil, polymer-treated bentonite-sand mixtures, soil cement, hydraulic asphalt concrete, sprayed-on asphalt, and 31 FMLs which were based on PVC, CPE, CSPE, EPDM, neoprene, butyl rubber, ELPO, and PEL. Four semicrystalline polymeric sheetings (PB, LLDPE, HDPE, and PP), though not compounded for use as liners, were included in the study because of their known chemical resistance and use in applications requiring good chemical and aging resistance. HDPE FMLs were not commercially available in the United States at the time the project was initiated. The results of exposing the admixed and sprayed-on liners are discussed in Sections 5.9 and 5.10, respectively.

Eight polymeric FMLs were subjected to one-sided exposure in test cells to nine actual waste liquids, including two acidic wastes, two alkaline wastes, three oily wastes, a blend of lead wastes, and a pesticide waste. Analyses of the various wastes are presented in Appendix J.

Each individual test cell functioned as a permeameter by allowing collection of seepage that might occur below the liner specimen. Exposure in the cell simulated the exposure of a liner at the bottom of a pond. Each cell exposed a test specimen to approximately 1 cu ft of waste at a depth of 1 foot. The cells designed to expose the FML samples are presented schematically in Figure 5-15.

Exposure specimens of each FML were fabricated in accordance with the design shown in Figure 5-16. When pieces A and B were seamed together, a 1.5-in. strip of polyethylene was placed along the edge of the seam on the pull tab to prevent bonding of surfaces in this area so that the seam could be tested in peel. Piece C was butted against the seam edge and tacked in place as a spacer to produce a double thickness around the cell flange area.

All of the specimens featured a seam that could be tested in both shear and peel modes. Seams were made in accordance with the instructions of the specific membrane supplier and, in some cases, with his materials. As most seams in fabricated liners are parallel to the machine direction of the sheeting, the seams fabricated in the test specimens were parallel to the machine direction. All seams were 2-in. wide. For fabric-reinforced FMLs, the seams were fabricated so that the edge of the top piece ("B") that faced the waste was a selvage edge. This avoided exposing the cut ends of the reinforcing fabric directly to the waste liquid. The underside of the FML had a 1.5-in. tab left free for peel testing.

Before fabricating the liner specimens for mounting in the long-term exposure cells, sample seams were made and tested. If the sample seams were satisfactory, fabrication of the specimens began. Seams of most materials were considered satisfactory if, when tested in shear, they did not fail in the adhesive. For crosslinked liner materials, whose seams intrinsically fail in the adhesive, the seams were considered satisfactory if they reached strength levels previously determined to be acceptable. If seams were unsatisfactory, a second set of sample seams was made and tested. In some cases, cleaning the liner surface before seaming had been inadequate; in others, insufficient adhesive had been applied. The EPDM and butyl rubber FMLs came from the same supplier, and were seamed with the same adhesive system, which was a low-temperature vulcanizing system and which included a two-part adhesive, gum tape, and a caulking compound. Figure 5-17 presents an unassembled exposure cell, with an FML specimen, before assembly. Table 5-10 shows the combinations of FMLs and wastes that were placed in exposure.

Testing of the FMLs before and after exposure to the hazardous wastes was performed in accordance with the methods listed in Table 5-11. The exposure times for each FML-waste combination are presented in Table 5-12. The results of testing the exposed FMLs are summarized in Tables 5-13 through 5-16, which present the results of determining the percent volatiles, percent extractables, percent retention of stress at 100% elongation, and percent retention of elongation at break of the exposed samples. The data show the effect of the waste at each exposure time on each of these properties. They also show both the variation in magnitude of the effects on different FMLs by a given waste and the different effects of the different wastes on a given FML.

Information on the seams and on the retention of seam strength are given in Tables 5-17 through 5-19. Table 5-17 presents information on the type of seaming procedures along with information on the fabricator of the seams. Table 5-18 presents the results of testing the seam strength of the

TABLE 5-9. COMPARISON OF WATER AND MSW LEACHATE ABSORPTIONS
BY POLYMERIC FMLS IN ONE YEAR AT ROOM TEMPERATURE

Polymer	FML number ^a	Weight gain after immersion, %	
		In tap water	In MSW leachate ^b
Butyl rubber	7 ^c	1.60	1.87
	22	1.70	2.54
	24	1.10	1.27
Chlorinated polyethylene	12 ^c	13.1	12.5
	13R	19.6	14.3
	23	15.5	11.8
Chlorosulfonated polyethylene	3	17.4	27.38
	4R	18.0	25.78
	6R	9.20	18.85
	14R	11.2	9.6
Ethylene propylene rubber	8	1.40	6.76
	16 ^c	4.80	6.08
	25	1.50	6.37
	26	1.60	10.4
Neoprene	9	22.7	22.0
Polybutylene	20	0.25	0.43
Polypropylene	27	0.28	0.70
Polyvinyl chloride	10	1.85	7.33
	11	1.85	5.42
	15	2.10	5.16
	17 ^c	1.85	3.50
	19	0.60	0.92

^aMatrecon identification number; R = fabric-reinforced.

^bSample exposed in MSW simulators in sand above FMLs. All data calculated from volatiles data. Volatiles of unexposed FML was assumed to be zero.

^cSample of FML also mounted in MSW landfill simulator bases.

Source: Haxo, 1977, p 156.

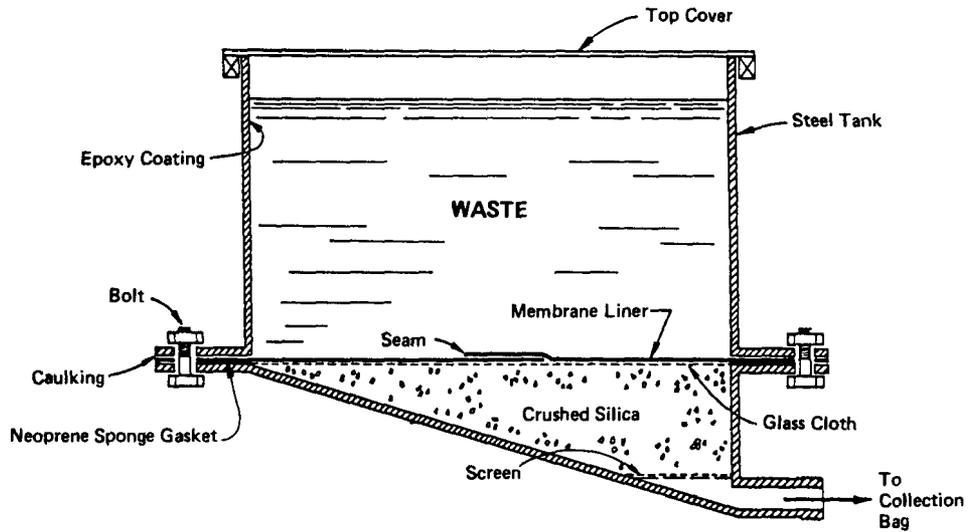


Figure 5-15. Design of cells for long-term exposure of FMLs to different hazardous wastes. The area of the liner specimens in direct contact with the wastes measured 10 x 15 inches. (Source: Haxo et al, 1985b, p 76).

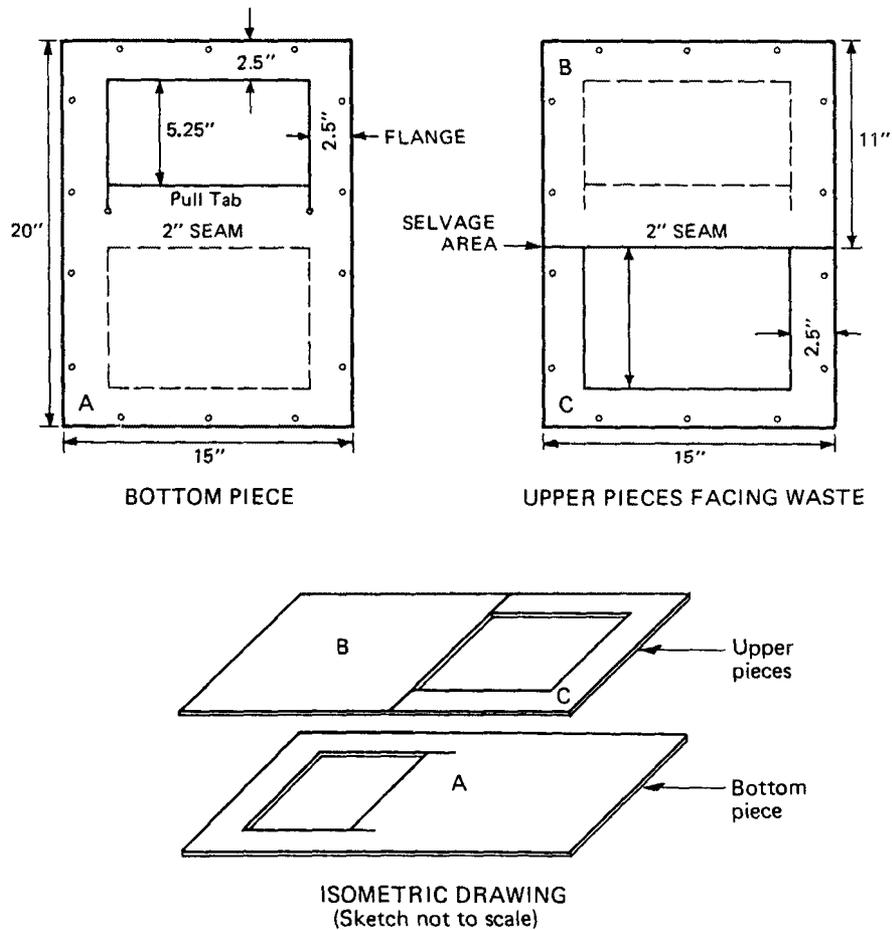


Figure 5-16. FML test specimens for long-term exposure in one-sided exposure cells. (Source: Haxo et al, 1985b, p 71).

TABLE 5-10. COMBINATIONS OF POLYMERIC FMLS AND HAZARDOUS WASTES TESTED IN ONE-SIDED EXPOSURE CELLS

Polymer	FML number ^b	Number of cells	Wastes ^a								
			Acidic		Alkaline		"Lead Waste" (W-14)	Oily			Pest-icide "Weed Killer" (W-11)
			"HFL" (W-10)	"HNO ₃ -HF-HOAc" (W-9)	"Slop Water" (W-4)	"Spent Caustic" (W-2)		"Slurry Oil" (W-15)	"Oil Pond 104" (W-5)	"Weed Oil" (W-7)	
Butyl rubber	57	8	...	2	...	2	2	...	...	...	2
Chlorinated polyethylene	77	10	...	2	...	2	2	...	2	...	2
Chlorosulfonated polyethylene	6	10	...	2	...	2	2	...	2	...	2
Elasticized polyolefin	36	15	1	2	1	2	2	2	2	1	2
Ethylene propylene rubber	26	8	...	2	...	2	2	...	...	...	2
Neoprene	43	8	...	-	...	2	2	...	2	...	2
Polyester elastomer	75	12	...	2	...	2	2	2	2	...	2
Polyvinyl chloride	59	15	1	2	1	2	2	2	2	1	2

^aMatrecon waste serial number shown below identification. Analyses of wastes are summarized in Appendix J.

^bMatrecon FML serial number.

Source: Haxo et al, 1985b, p 106.

TABLE 5-11. TESTING OF POLYMERIC FMLS EXPOSED TO HAZARDOUS WASTES

Test	Unexposed FML	Exposed FML
<u>Analytical properties</u>		
Specific gravity, ASTM D297/D792	Yes	No
Volatiles, MTM-1 (Appendix G)	Yes	Yes
Ash, ASTM D297, Section 35	Yes	No
Extractables, MTM-2 (Appendix F)	Yes	Yes
Water absorption or extraction at room temperature and 70°C, ASTM D570	3 at each temperature	No
<u>Physical properties</u>		
Thickness	Yes	Yes
Tensile properties ^a , ASTM D412	5 in each direction	3 in each direction
Hardness, ASTM D2240, 5 second (Duro A; Duro D also if Duro A >80)	5 measurements	5 measurements
Tear strength ^b , ASTM D624, Die C	5 specimens in each direction	3 specimens in each direction,
Puncture resistance, FTMS 101C, Method 2065	5 specimens	2 specimens
Seam strength, in 90° peel, ASTM D413 ^c	3 specimens	3 specimens
Seam strength, in shear, ASTM D882 (modified) ^c	3 specimens	3 specimens
Water vapor permeability, ASTM E96	3 specimens	No

^aMeasured with special dumbbell which featured smaller tabs, a shorter overall length, and a shorter narrowed section in comparison with the ASTM D412 Type IV dumbbell. At the time this project was initiated, it was desired that all FMLs be tested in accordance with the same test methods. Limited testing of the fabric-reinforced FMLs was performed towards the end of the project in accordance with ASTM D751, Strip Method.

^bUnreinforced sheeting, only.

^c1-in. wide strips tested at a 2-ipm jaw separation rate.

Source: Haxo et al, 1985b, p 62.

TABLE 5-12. EXPOSURE OF POLYMERIC FMLS TO HAZARDOUS WASTES IN ONE-SIDED EXPOSURE CELLS - DAYS OF EXPOSURE

Polymeric FML Polymer	Number ^b	Wastes ^a								
		Acidic		Alkaline		"Lead Waste" (W-14)	Oily		"Weed Killer" (W-11)	
		"HFL" (W-10)	"HNO ₃ -HF- HOAc" (W-9)	"Slop Water" (W-4)	"Spent Caustic" (W-2)		"Slurry Oil" (W-15)	"Oil Pond 104" (W-5)		"Weed Oil" (W-7)
Butyl rubber	57R	...	505 1218	...	526 1249	499 1339	...	...	...	500 1258
Chlorinated polyethylene	77	...	459 1218	...	526 1249	499 1334	...	521 1358	...	500 1258
Chlorosulfonated polyethylene	6R	...	505 1218	...	526 1249	499 1343	...	521 1357	...	504 1258
Elasticized polyolefin	36	2293 ...	505 1217	2300 ...	526 2677	499 1343	327 2355	521 1357	...	494 2699
Ethylene propylene rubber	26	...	497 1147	...	526 124	499 1344	...	...	...	500 1258
Neoprene	43	...	...	...	526 1237	499 1342	...	521 1356	...	494 1257
Polyester elastomer	75	...	323 509	...	526 1237	499 1342	328 ...	521 1357	...	501 1258
Polyvinyl chloride	59	1565 ...	505 1352	1565 ...	526 1249	499 1345	327 ...	521 1356	...	500 1258

^aMatrecon waste serial number shown below identification. Analyses of wastes are summarized in Appendix J.

^bMatrecon FML serial number; R = fabric-reinforced.

Source: Haxo et al, 1985b, p 111.

TABLE 5-13. EXPOSURE OF POLYMERIC FMLS TO HAZARDOUS WASTES IN ONE-SIDED EXPOSURE CELLS - PERCENT VOLATILES^a

Polymeric FML ^c Polymer	Number	Original value, %	Wastes ^b								
			Acidic		Alkaline		Oily			Pesticide	
			"HFL" (W-10)	"HNO ₃ -HF- HOAc" (W-9)	"Slop Water" (W-4)	"Spent Caustic" (W-2)	"Lead Waste" (W-14)	"Slurry Oil" (W-15)	"Oil Pond 104" (W-5)	"Weed Oil" (W-7)	"Weed Killer" (W-11)
Butyl rubber	57R	0.29	...	5.92 11.46	...	1.75 1.37	2.79 3.53	...	...	...	4.10 4.79
Chlorinated polyethylene	77	0.14	...	7.82 13.18	...	2.32 2.79	11.58 19.20	...	3.69 10.11	...	4.99 7.91
Chlorosulfonated polyethylene	6R	0.51	...	4.69 7.18	...	4.77 5.77	1.08 11.44	...	7.51 10.25	...	8.00 9.73
Elasticized polyolefin	36	0.15	1.46 ...	3.20 5.26	10.83 ...	1.25 1.01	1.03 1.53	0.38 4.02	2.15 5.12	...	0.13 0.58
Ethylene propylene rubber	26	0.50	...	8.95 12.02	...	1.27 1.31	2.83 5.25	...	...	...	3.34 6.29
Neoprene	43	0.45	...	...	...	4.40 5.67	18.01 17.50	...	12.99 21.31	...	11.29 13.63
Polyester elastomer	75	0.26	...	0.39 4.74	...	0.65 0.89	2.63 1.72	0.40 ...	1.27 2.59	...	0.60 2.92
Polyvinyl chloride	59	0.31	9.90 ...	12.08 13.94	18.72 ...	2.34 1.85	3.34 4.43	0.29 ...	1.70 4.19	...	2.30 3.61

^aRespective durations of exposure are presented in Table 5-12.

^bMatrecon waste serial number shown below identification. Analyses of wastes are summarized in Appendix J.

^cMatrecon FML serial number; R = fabric reinforced. Full unexposed property data are presented in Appendix F.

Source: Haxo et al, 1985b, p 116.

TABLE 5-14. EXPOSURE OF POLYMERIC FMLS TO HAZARDOUS WASTES IN ONE-SIDED EXPOSURE CELLS - PERCENT EXTRACTABLES^a

Polymeric FML ^c Polymer	Number	Original value, %	Wastes ^b								
			Acidic		Alkaline		"Lead Waste" (W-14)	Oily		Pesticide "Weed Killer" (W-11)	
			"HFL" (W-10)	"HNO ₃ -HF- HOAc" (W-9)	"Slop Water" (W-4)	"Spent Caustic" (W-2)		"Slurry Oil" (W-15)	"Oil Pond 104" (W-5)		"Weed Oil" (W-7)
Butyl rubber	57R	6.36	...	...	...	...	7.75	...	...	...	5.15
			...	8.65	...	7.86	7.86	...	...	...	7.62
Chlorinated polyethylene	77	9.13	...	10.09	...	...	7.31	...	...	...	9.72
			...	9.41	...	9.10	7.24	...	17.00	...	9.41
Chlorosulfonated polyethylene	6R	3.77	...	...	...	4.77	3.52	...	...	...	4.13
			...	4.62	...	5.77	5.95	...	9.45	...	5.39
Elasticized polyolefin	36	5.50	5.40	5.40	1.70	...	5.66	13.94	13.72	...	7.14
			...	7.09	...	5.96	8.06	23.88	20.74	...	6.86
Ethylene propylene rubber	26	22.96	...	21.36	...	...	22.27	...	...	...	23.13
			...	...	...	23.95	26.01	...	...	...	25.20
Neoprene	43	13.69	...	...	...	...	12.54	...	...	...	13.25
			...	...	...	13.69	12.15	...	15.86	...	16.14
Polyester elastomer	75	2.74	...	10.77	...	3.85	2.98	9.91	5.68	...	5.15
			...	13.36	...	3.31	5.35	...	7.28	...	5.83
Polyvinyl chloride	59	35.86	34.42	16.68	10.40	34.62	33.47	39.63	32.62	...	35.27
			...	18.58	...	35.61	22.47	...	29.99	...	33.39

^aRespective durations of exposure are presented in Table 5-12.

^bMatrecon waste serial number shown below identification. Analyses of wastes are summarized in Appendix J.

^cMatrecon FML serial number; R = fabric-reinforced. Full unexposed property data are presented in Appendix F.

Source: Haxo et al, 1985b, p 117.

TABLE 5-15. EXPOSURE OF POLYMERIC FMLS TO HAZARDOUS WASTES IN ONE-SIDED EXPOSURE CELLS - PERCENT RETENTION OF ELONGATION AT BREAK^a

Polymeric FML ^c Polymer	Number	Original value, %	Wastes ^b								
			Acidic		Alkaline		"Lead Waste" (W-14)	Oily		"Weed Killer" (W-11)	
			"HFL" (W-10)	"HNO ₃ -HF- HOAc" (W-9)	"Stop Water" (W-4)	"Spent Caustic" (W-2)		"Slurry Oil" (W-15)	"Oil Pond 104" (W-5)		"Weed Oil" (W-7)
Butyl rubber	57R	42 ^d	...	60	...	60	119	...	...	...	143
			...	645	...	219	167	...	...	...	100
Chlorinated polyethylene	77	402	...	89	...	107	101	...	98	...	100
			...	89	...	88	83	...	88	...	89
Chlorosulfonated polyethylene	6R	242	...	90	...	70	107	...	103	...	112
			...	79	...	65	77	...	72	...	85
Elasticized polyolefin	36	665	98	99	88	100	92	96	86	...	101
			...	96	...	97	94	97	78	...	97
Ethylene propylene rubber	26	450	...	97	...	102	100	...	...	...	100
			...	94	...	95	106	...	...	...	104
Neoprene	43	320	...	...	...	98	76	...	86	...	93
			...	...	...	95	75	...	92	...	83
Polyester elastomer	75	575	...	<1	...	86	98	77	95	...	96
			...	4	...	86	90	...	92	...	87
Polyvinyl chloride	59	995	153	200	...	99	82	113	152	...	100
			...	249	...	115	103	...	174	...	137

^aRespective durations of exposure are presented in Table 5-12.

^bMatrecon waste serial number shown below identification. Analyses of wastes are summarized in Appendix J.

^cMatrecon FML serial number; R = fabric-reinforced. Full unexposed property data are presented in Appendix F.

^dUnexposed FML broke at less than 100% elongation.

Source: Haxo et al, 1985b, p 119.

TABLE 5-16. EXPOSURE OF POLYMERIC FMLS TO HAZARDOUS WASTES IN ONE-SIDED EXPOSURE CELLS - PERCENT RETENTION OF STRESS AT 100% ELONGATION^a

Polymeric FMLC Polymer	Number	Original value, psi	Wastes ^b								
			Acidic		Alkaline		"Lead Waste" (W-14)	Oily		"Weed Killer" (W-11)	
			"HFL" (W-10)	"HNO ₃ -HF- HOAc" (W-9)	"Slop Water" (W-4)	"Spent Caustic" (W-2)		"Slurry Oil" (W-15)	"Oil Pond 104" (W-5)		"Weed Oil" (W-7)
Butyl rubber	57R	(d)	...	...	...	...	...	...	...	...	...
Chlorinated polyethylene	77	900	...	97 113	...	82 129	56 71	...	53 62	...	94 113
Chlorosulfonated polyethylene	6R	937	...	106 112	...	165 200	85 118	...	63 96	...	90 118
Elasticized polyolefin	36	922	98 ...	92 98	97 ...	87 87	95 104	70 60	61 71	...	104 91
Ethylene propylene rubber	26	357	...	81 70	...	88 108	84 80	...	...	...	89 87
Neoprene	43	460	...	...	...	90 95	53 61	...	50 42	...	62 54
Polyester elastomer	75	2585	...	...	...	101 109	88 88	77 ...	94 85	...	95 96
Polyvinyl chloride	59	995	153 ...	200 249	...	99 115	82 103	113 ...	152 174	...	100 137

^aRespective durations of exposure are presented in Table 5-12.

^bMatrecon waste serial number shown below identification. Analyses of wastes are summarized in Appendix J.

^cMatrecon FML serial number; R = fabric-reinforced. Full unexposed property data are presented in Appendix F.

^dUnexposed FML broke at less than 100% elongation.

Source: Haxo et al, 1985b, p 119.

TABLE 5-17. SEAMS^a IN POLYMERIC FML SAMPLES EXPOSED TO HAZARDOUS WASTES IN ONE-SIDED EXPOSURE CELLS

Polymeric FML		Method of seaming	Seam width, in.	Fabricator
Polymer	number ^b			
Butyl rubber	57R	Vulcanizable adhesive furnished by supplier of liner	2	Matrecon
Chlorinated polyethylene	77	Solvent weld with mixture of 1 part toluene and 1 part tetrahydrofuran	2	Matrecon
Chlorosulfonated polyethylene	6R	Adhesive furnished by liner supplier	2	Matrecon
Elasticized polyolefin	36	Heat sealed	0.5	Supplier
Ethylene propylene rubber	26	Adhesive and gum tape furnished by supplier	2	Matrecon
Neoprene	43	Cement and lap sealant furnished by supplier of liner	2	Matrecon
Polyester elastomer	75	Heat sealed	0.5	Supplier
Polyvinyl chloride	59	Solvent weld using mixture of 2 parts tetrahydrofuran and 1 part cyclohexanone	2	Matrecon

^aAll seams were allowed to age at least a month before being tested or covered with wastes.

^bMatrecon FML serial number; R = fabric-reinforced.

Source: Haxo et al, 1985b, p 120.

TABLE 5-18. EXPOSURE OF POLYMERIC FMLS TO HAZARDOUS WASTES IN ONE-SIDED EXPOSURE CELLS - EFFECT ON SEAM STRENGTH MEASURED IN SHEAR MODE^a

Polymeric FML Polymer	Number ^c	Original value, ppi	Method of seaming	Seam strength in ppi after exposure to different wastes ^b								
				Acidic		Alkaline		Oily			Pesticide	
				"HFL" (W-10)	"HNO ₃ -HF- HOAc" (W-9)	"Slop Water" (W-4)	"Spent Caustic" (W-2)	"Lead Waste" (W-14)	"Slurry Oil" (W-15)	"Oil Pond 104" (W-5)	"Weed Oil" (W-7)	"Weed Killer" (W-11)
Butyl rubber	57R	>84.8 ^d	Cement ^e	...	>67.8 ^d >73.3 ^d	...	>74.4 ^f >78.6 ^d	64.69 >70.7 ^d	...	...	...	69.1 ^h >68.8 ^d
Chlorinated polyethylene	77	48.39	Solvent	...	27.1 ^h 39.8 ^h	...	41.5 ^h 46.0 ^h	26.3 ⁱ 26.39	...	16.49 25.59	...	>38.8 ^d >44.5 ^d
Chlorosulfonated polyethylene	6R	62.19	Cement	...	52.79 57.49	...	64.0 ⁱ >76.3 ^d	58.2 ^j 66.69	...	60.5 ^h 60.3 ^d	...	>61.3 ^d 65.7 ^h
Elasticized polyolefin	36	28.89	Heat ^k	32.49 ...	29.29 32.09	31.3 ^h ...	28.99 31.49	26.09 29.09	21.7 ^d 24.49	>19.39 18.39	...	26.59 32.59
Ethylene propylene rubber	26	39.0 ^l	Cement ^e	...	47.9 ^l ...	...	39.1 ^l 45.9 ^m	32.2 ^l 13.9 ^l	...	...	...	46.5 ^l 44.4 ^l
Neoprene	43	45.7 ⁿ	Cement ^e	...	...	...	>51.9 ^o >58.5 ^d	>31.6 ^o 27.1 ⁿ	...	24.8 ^p 14.69	...	>23.7 ^d 34.9 ^h
Polyester elastomer	75	21.29	Heat ^k	...	...	...	...	25.2 ^h >16.7 ^d	>18.8 ^d ...	28.29 >14.6 ^d	...	26.59 21.9 ^h
Polyvinyl chloride	59	>69.1 ^d	Solvent	69.29 ...	74.79 79.0 ^h	71.6 ^q ...	50.49 63.69	53.19 45.09	59.39 ...	60.99 77.19	...	46.0 ⁱ 60.49

^aStrip specimen 1-in. wide; initial jaw separation, 4 in.; rate of jaw separation, 2 ipm. All seams fabricated by Matrecon following manufacturers' recommendations, except where otherwise noted. Value for seam strength is reported in pounds-per-inch-width (ppi). A "greater than" symbol is used to indicate that the strength of the seam itself is greater than the value reported. See Table 5-12 for durations of exposure.

^bMatrecon waste serial number shown below identification. Analyses of wastes are summarized in Appendix J.

^cMatrecon FML serial number; R = fabric-reinforced.

^dSpecimens broke at clamp edge.

^eLow-temperature vulcanizing adhesive.

^fSpecimens broke outside of seam area and not in the clamped area.

^gSpecimens broke at seam edge.

^hOne specimen broke at seam edge; the other specimen broke in the clamped area.

ⁱOne specimen broke at seam edge; the other broke outside of seam area and not in the clamped area.

^jOne specimen broke outside seam area; the other delaminated in the seam area which had been separated.

^kSeam fabricated by supplier.

^lSpecimens delaminated in adhesive.

^mOne specimen broke at seam edge; other delaminated in adhesive.

ⁿSpecimens delaminated in the plane of the bond between adhesive and liner surface.

^oOne specimen broke at clamp edge; other broke outside of seam area and not in clamped area.

^pOne specimen broke at clamp edge; other delaminated in the plane of the bond between adhesive and liner surface.

^qTwo specimens broke outside seam area; one specimen broke at clamp edge; two broke at seam edge.

Source: Haxo et al, 1985b, p 121.

TABLE 5-19. EXPOSURE OF POLYMERIC FMLS TO HAZARDOUS WASTES IN ONE-SIDED EXPOSURE CELLS - EFFECT ON SEAM STRENGTH MEASURED IN PEEL MODE^a

Polymeric FML Polymer	Number ^c	Original value, ppi	Method of seaming	Seam strength in ppi after exposure to different wastes ^b								
				Acidic		Alkaline		Oily			Pesticide	
				"HFL" (W-10)	"HNO ₃ -HF- HOAc" (W-9)	"Stop Water" (W-4)	"Spent Caustic" (W-2)	"Lead Waste" (W-14)	"Slurry Oil" (W-15)	"Oil Pond 104" (W-5)	"Weed Oil" (W-7)	"Weed Killer" (W-11)
Butyl rubber	57R	8.0 ^d	Cement ^e	...	3.2 ^f 4.5 ^f	...	8.5 ^f 4.1 ^f	7.8 ^f 5.3 ^f	...	...	...	10.9 ^f 3.6 ^f
Chlorinated polyethylene	77	21.49	Solvent	...	17.99 19.09	...	21.99 21.0 ^h	17.39 13.79	...	14.3 ⁱ 11.49	...	20.09 16.29
Chlorosulfonated polyethylene	6R	23.2 ^j	Cement	...	14.1 ^f 12.5 ^k	...	21.3 ^f 28.4 ^f	26.4 ^j 21.5 ^k	...	16.5 ^f 15.0 ^f	...	21.3 ^f 15.1 ^f
Elasticized polyolefin	36	21.0 ^l	Heat ^m	22.6 ^l ...	21.5 ^l 22.0 ^l	22.0 ^l ...	19.8 ^l 22.0 ^l	19.8 ^l 22.2 ^l	18.7 ^l 18.6 ^l	>14.5 ^l 14.9 ^l	...	20.9 ^l 23.2 ^l
Ethylene propylene rubber	26	4.9 ^k	Cement ^e	...	5.9 ^k ...	...	4.5 ^k 5.4 ^k	3.5 ^k 2.3 ^k	...	...	...	5.0 ^k 5.0 ^k
Neoprene	43	8.2 ⁿ	Cement ^e	...	...	...	8.8 ⁿ 10.8 ⁿ	3.3 ⁿ 2.2 ⁿ	...	2.1 ⁿ 3.6 ⁿ	...	7.6 ⁿ 4.3 ⁿ
Polyester elastomer	75	20.89	Heat ^m	...	...	...	...	17.4 ^o 18.3 ^p	18.2 ^l ...	18.8 ^l 16.29	...	20.3 ^l 19.5 ^l
Polyvinyl chloride	59	15.29	Solvent	23.9 ^r ...	28.4 ^s 34.09	9.8 ^r ...	21.49 14.89	19.0 ^s 16.4 ^r	20.39 ...	23.1 ^s 22.0 ^r	...	18.19 23.0 ^r

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^aStrip specimen 1-in. wide; initial jaw separation, 2 in.; rate of jaw separation, 2 ipm. Value reported in pounds-per-inch-width (ppi) is average after initial peak, except where otherwise noted. All seams fabricated by Matrecon following manufacturers' recommendations, except where otherwise noted. See Table 5-12 for durations of exposure.

^bMatrecon waste serial number shown below identification. Analyses of wastes are summarized in Appendix J.

^cMatrecon FML serial number; R = fabric-reinforced.

^dSpecimens delaminated in the adhesive.

^eLow-temperature vulcanizing adhesive.

^fSpecimens broke by a combination of delamination of the adhesive and delamination of the lining material.

^gSpecimens delaminated in the plane of the bond between the two liner surfaces.

^hSpecimens initially delaminated in the plane of the bond between the two liner surfaces, then broke at the line of peel in the course of the test.

ⁱOne specimen broke at the line of peel shortly after it began to peel; the other delaminated in the plane of the bond between the two liner surfaces.

^jOne specimen delaminated in the lining material; the other delaminated in the adhesive.

^kSpecimens delaminated in the adhesive.

^lSpecimens broke at the line of peel after peeling approximately 0.1 in. Values reported are maximum stresses immediately before break.

^mSeam fabricated by supplier.

ⁿSpecimens delaminated in the plane of the bond between adhesive and liner surface.

^oSpecimens ripped uncontrollably once peel was initiated. Value reported is maximum stress.

^pOne specimen broke at jaw bite; the other broke at the line of peel after peeling approximately 0.1 in.

^qSpecimens broke at jaw bite.

^rSpecimens initially delaminated in the plane of the bond between the two liner surfaces, then ripped uncontrollably.

^sOne specimen delaminated in the plane of the bond between the two liner surfaces; the other initially delaminated of the plane of the bond between the two surfaces, then ripped uncontrollably.

Source: Haxo et al, 1985b, p 122.

specimens measured in shear after exposure, together with data on the unexposed FMLs. Table 5-19 presents results of testing the strength of the seams in the peel mode. All the data show the strength values in pounds-per-inch width (ppi) and the locus of failure of the adhesion test specimen.

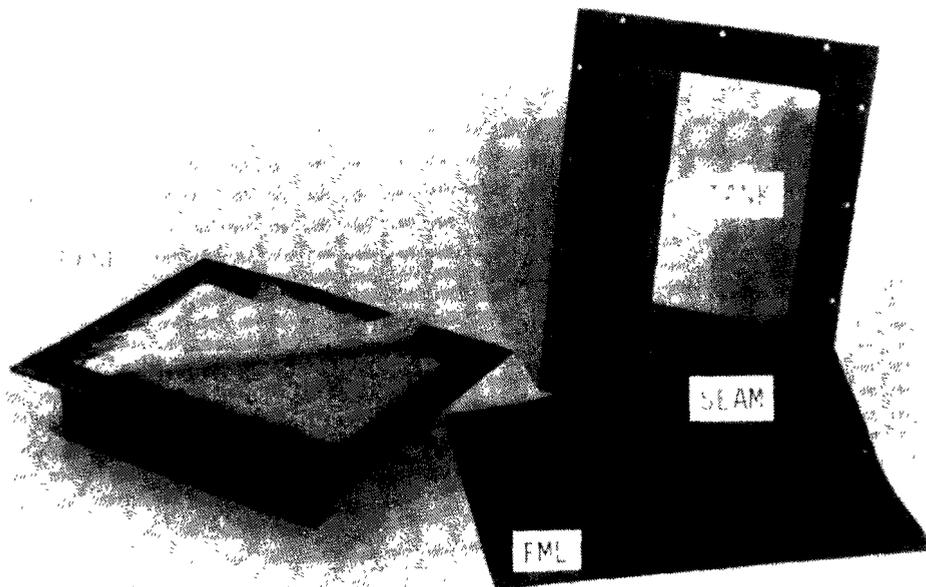


Figure 5-17. Unassembled exposure cell used for FML specimens. Shown are the tank, the base filled with silica gravel, and an FML specimen. (Source: Haxo et al, 1985b, p 72).

The responses of the FMLs varied greatly to the individual wastes, particularly to those waste liquids with oily constituents. The effects varied from essentially no change during the exposures to complete failure. The screening tests eliminated several of the polymeric FMLs from exposures to oily wastes in the primary cells. The varied responses of the FMLs occurred not only among the different polymer types but also within a single type because of compound variations, e.g. plasticizer type and amount, cross-linking, and fabric reinforcement. The results demonstrate the importance of determining FML and waste compatibility during the selection and design process.

The results of testing the exposed specimens are discussed in subsequent subsections by individual FML.

5.4.1.2.1 Butyl rubber--The butyl rubber FML (No. 57R) was reinforced with a nylon scrim which had a 22 x 11 epi thread count. It had a nominal thickness of 31 mils and a vulcanized coating compound with a high ash content which reflected the use of inorganic fillers in the compound. Overall, except for peel adhesion, the butyl rubber specimens showed good retention of their original properties on exposure to the four wastes it was exposed to (Table 5-10). The effect of time was not large. The waste which

caused the greatest change, perhaps, was the acidic waste "HNO₃-HF-HOAc", in which the butyl increased in volatiles content significantly and appeared to soften. The butyl FML was not tested with the oily wastes because the preliminary compatibility testing indicated that these wastes would have caused significant softening and loss of tensile strength.

5.4.1.2.2 Chlorinated polyethylene (CPE)--The CPE FML (No.77) was an unreinforced thermoplastic sheeting with a 30-mil nominal thickness. It had an ash content of 12.56% and an extractables content of 9.13%. The CPE FML appeared to perform satisfactorily with the inorganic aqueous solutions but showed significant losses in properties after exposure to the oily wastes. The CPE specimens showed significant increases in volatiles content in the acidic, lead, and pesticide wastes, probably reflecting the absorption of water (Table 5-13). The increase during exposure to "Oil Pond 104" waste was probably due to absorption of oil as well as water. The smallest increase in volatiles was in the specimen exposed to the "Spent Caustic" waste. The modulus in all cases showed an initial drop and then an increase, indicating initial swelling followed by crosslinking (Table 5-16). However, there were losses in modulus in the lead waste and in the oily waste. The only significant increase in the extractables during exposure was in the sample exposed to the oily waste, "Oil Pond 104" (Table 5-14).

5.4.1.2.3 Chlorosulfonated polyethylene (CSPE)--The CSPE FML (No. 6R) was reinforced with a nylon scrim that had a thread count of 8 x 8 epi. The FML had a nominal thickness of 30 mils. The CSPE compound was a "potable" grade compound which contained 3.28% ash and had an extractables content of 3.77%.

The results of exposing the CSPE FML to the five wastes that it was exposed to indicated that this FML tended to absorb water and also some oil when exposed to wastes containing oily constituents. The effect of aging and exposure to wastes showed an increase in modulus and a decrease in elongation at break, both of which are probably due to crosslinking of the polymer (Tables 5-15 and 5-16). All of the CSPE specimens increased significantly in volatile contents in all the wastes (Table 5-13). Though volatiles of the CSPE liner increased in the spent caustic and pesticide wastes, the magnitude appeared to be leveling off at the time the second set was removed. The extractables changed only modestly during the exposure (Table 5-14). The highest extractables content measured after exposure was for the specimen that had been exposed to "Oil Pond 104" waste; in this case, the extractables increased from 3.77 to 9.45%.

The greatest loss in seam strength was with the seams exposed to the acidic waste; these losses probably reflect the loss in strength of the nylon fabric. It should be noted that since work on this project was initiated, there has been a shift from nylon to polyester as the reinforcing fabric that is used in the manufacture of fabric-reinforced FMLs. It should also be noted that "industrial-grade" CSPE is now used for service of this type and it has a much lower water absorption than "potable-grade" CSPE.

5.4.1.2.4 Elasticized polyolefin (ELPO)--The ELPO FML (No. 36) contained a small amount of crystallinity and had a nominal thickness of 20 mils, a specific gravity of 0.938, an ash content of 0.9%, and an extractables content of 5.5%.

The ELPO specimens had only small increases in volatiles content and showed good retention of properties in those wastes that were predominantly water; for example, the pesticide, the lead, and the "Spent Caustic" wastes. The specimens exposed to those wastes that contained oily constituents, particularly the "Oil Pond 104" waste and the "Slurry Oil" waste, increased in volatiles and extractables contents, which resulted in major drops in tensile strength and modulus and softening of the sheeting. There were also a significant increases in volatiles content by the specimens exposed to the acidic waste, "HNO₃-HF-HOAc", and the alkaline waste, "Slop Water".

5.4.1.2.5 Ethylene propylene (EPDM)--The EPDM rubber FML (No. 26) was crosslinked and had a nominal thickness of 30 mils. It had a specific gravity of 1.169, an ash content of 7.67%, and an extractables content of 22.96%. The high extractables content shows the high oil content that is common to many EPDM compounds. This FML was not tested with the oily wastes based on results of the preliminary compatibility tests and the oil sensitivity of this type of rubber. The EPDM FML was affected only moderately by the four wastes to which it was exposed. Of the four wastes, the acidic waste appears to have been the most aggressive toward the EPDM compound; the effects, however, were not large. The seam strength was low before exposure and decreased with exposure, indicating inadequacy of the seaming method.

5.4.1.2.6 Neoprene--The neoprene FML (No. 43) that was tested was crosslinked and not fabric-reinforced. It had a nominal thickness of 31.3 mils, a specific gravity of 1.477, an ash content of 12.3%, and an extractables content of 13.69%.

Because neoprene is generally considered to be an oil-resistant rubber, it was exposed to the oily wastes, as wastes of this type are aggressive to many of the lining materials. All the neoprene specimens increased substantially in volatiles content in all of the wastes, increasing from 0.45% to 11.29 - 21.31%, except in the "Spent Caustic," in which the values increased to 5.67%. On the other hand, the extractables content changed little even for the specimens exposed to the oily wastes. Consequently, it appears that most of the liquid absorbed by the neoprene specimens was water. The neoprene specimens exposed to the lead waste, the "Oil Pond 104" waste, and the pesticide waste softened considerably and had a low retention of stress at 100% elongation (Table 5-16). This is probably the result of absorbing water. The specimens exposed to the "Spent Caustic" waste softened little and retained their elongation best, probably the result of the high dissolved solids content of the wastes. Low absorption of highly concentrated brines is characteristic of neoprene compounds.

The oil resistance normally associated with neoprene was not apparent in these tests. Figure 5-18 shows the swelling that occurred in a neoprene sample that had been exposed to the "Lead Waste."

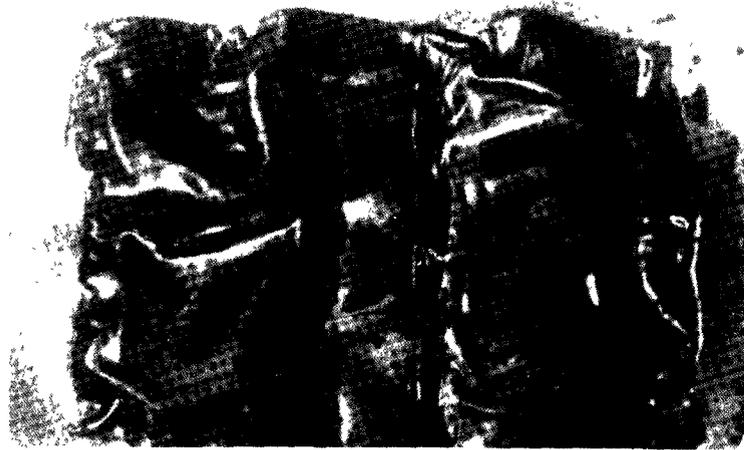


Figure 5-18. Two photographs of the recovered neoprene FML (No. 43) that had been exposed to the lead waste for 499 days. Fig. 5-16a shows the exposed FML in the test cell after it had been cleaned. Fig. 5-16b shows the exposed FML specimen after removal from the cell.

5.4.1.2.7 Polyester elastomer (PEL)--The polyester elastomer FML (No. 75), a developmental product with a thickness of 7 mils, was based on a semicrystalline polymer that melts in the 188° to 207°C range. It had a specific gravity of 1.236, an extractables content of 2.74%, and an ash content of 0.38%. A thermogravimetric analysis of this FML indicated that it contained 91% polymer, 3% plasticizer, and 6% carbon black. The PEL sheeting was included in this project because of its reported resistance to hydrocarbons and other oily materials. This was the only FML in the program that failed by cracking and leaking on exposure to a waste, in this case, the acidic waste "HNO₃-HF-HOAc". This shows the sensitivity of this polymer to acidic materials which caused it to degrade by hydrolysis. Exposure in the oily wastes caused the PEL to decrease significantly in its physical properties particularly after exposure to the "Slurry Oil" waste. This FML had its best retentions in the pesticide and the "Spent Caustic" wastes. New versions of this type of FML are now available with improved properties for liner applications.

5.4.1.2.8 Polyvinyl chloride (PVC)--The PVC FML (No. 59) had a nominal thickness of 30 mils, a specific gravity of 1.280, an ash content of 6.97%, and an extractables content of 35.86%. The high extractables, largely plasticizer, is equivalent to about 60 parts per 100 g of PVC resin.

The PVC FML showed considerable variation in its response to the different wastes to which it was exposed. The variation was largely related to the amount of swell and the loss of plasticizer that took place during the exposure. The volatiles increased for all of the exposed specimens except for the specimen that was in contact with the "Slurry Oil" waste (Table 5-13). In most cases, the amount did not increase greatly after the initial exposure time. However, the increase was substantially greater for the second specimens of this FML tested after exposure to "Slop Water" and the strong acid, "HNO₃-HF-HOAc." The extractables of the exposed specimens varied considerably (Table 5-14); all, however, tended to be lower than the original value, indicating loss of plasticizer. The specimen exposed to the "Slop Water" had the lowest extractables content, indicating a major loss of plasticizer. The specimens in the acidic waste also had a significant loss. The extractables content of the specimens exposed to the lead waste and to "Oil Pond 104" waste also dropped during exposure, indicating some loss of the plasticizer to the oily wastes. The effects of the exposure on physical properties was also severe in some cases. The specimens that had been exposed to the "Slop Water" lost almost all of their elongation and became very hard (Table 5-15). The specimen that had been in contact with the acidic waste, "HNO₃-HF-HOAc," lost in elongation and more than doubled in stress at 100% elongation (Table 5-16). The specimens exposed to "Oil Pond 104" waste and the weaker acidic waste, "HFL," also increased significantly in modulus.

5.4.1.3 Exposure to Wastes from Coal-Fired Electric Power Plants--

A similar study to that described in the previous section is being carried out for the Electric Power Research Institute by Haxo et al (1987), using the same type of exposure cell to simulate conditions in impoundment facilities.

Eight polymeric FMLs are being exposed to eight different wastes or test fluids. The eight FMLs are:

- Butyl rubber.
- Chlorinated polyethylene.
- Chlorosulfonated polyethylene (two compositions: a potable and an industrial grade).
- Ethylene propylene rubber.
- High-density polyethylene.
- Polyvinyl chloride (two compositions).

Eight types of wastes were selected for the long-term primary exposure program: three fly ashes of different pHs, a flue-gas desulfurization sludge, a flue gas desulfurization sludge/fly ash/lime mixture, an acidic boiler-cleaning waste, an acidic air-preheater cleaning waste, and an alkaline waste brine from water treatment. These eight wastes, which are typical of waste streams found in coal-fired power plants, may contaminate the groundwater or are potentially aggressive to FMLs. Each waste was analyzed for chemical constituents. On the basis of these analyses, the boiler-cleaning and air-preheater wastes appeared to be the most aggressive to liners. They were, therefore, used in the liner-waste compatibility immersion tests. Several polymeric FMLs have been immersed in a flue-gas desulfurization sludge not used in the primary exposure program and in leachate from the alkaline fly ash. Two other test liquids, 5% brine and deionized water, were also used in exposure tests with polymeric FMLs.

Because some organic compounds can potentially have adverse effects in FML liner systems, the presence of dissolved organics in the waste streams was of special concern. However, none of the eight wastes used in this project contain significant amounts of organics.

5.4.1.4 Exposure in Tub Tests--

As part of the research program described in Section 5.4.1.2, Haxo et al (1985b and 1986) exposed samples of polymeric FMLs in tub tests under conditions that simulated some that exist in a lined surface impoundment in which the liner is in contact with the waste liquid and is not covered with soil. The effects of exposure to sun, temperature changes, ozone, and other weather factors could be assessed together with the effect of a given waste on a specific FML. The level of the waste was allowed to fluctuate so that an area of FML was subjected intermittently to the both the waste and the weather. This alternating of conditions, which is encountered in surface impoundments, is especially harsh on lining materials. A detailed description of the tub test procedure is presented in Appendix H.

The tubs used in this study were constructed of 0.75-in. exterior grade plywood with sides sloping outward at a 1 horizontal:2 vertical slope

(Appendix H, Figure H-1). The inside base measured 7 x 12 in., and the opening at the top measured 19.75 x 24.5 inches. The tub depth was 10 inches.

An exposure test specimen consisted of a 40 x 48-in. sheet which, in most cases, incorporated a seam through the center. In this way the seam durability as well as that of the FML was assessed. The test specimens were draped over the tubs and folded to fit the inside corners and edges of the tubs; the excess material was allowed to hang freely over the edges. In this manner, there was a considerable number of folds and sharp angles in the liner while it was exposed, particularly over the corners of the tubs (Appendix H, Figure H-2). If the FML was sensitive to the waste or to ozone, cracking or crazing would develop.

The tubs were filled from 3/4 to 7/8 with the wastes. Approximately 4.5 gal of waste was required to fill each tub. The tubs were placed in a lined shallow basin to prevent waste overflow or leaks from contacting the roof top.

During the exposure, the liners were inspected visually on a regular basis for cracking, opening of seams, and other forms of deterioration. The tubs were covered during rainy periods. The liquid levels and temperatures were measured and recorded at regular intervals. The levels were allowed to fluctuate about 4 inches. Water was added when levels became too low due to evaporation. The shallowness of the tubs and the dark color of the FMLs resulted in high heat absorption when the tubs were exposed to sunlight; the liners and the wastes were quite warm on sunny days. The air and waste temperatures were monitored regularly; waste temperatures ranged from 10° to 66°C (Haxo et al, 1985b, p 160).

During much of the year, the oily wastes accumulated water (from dew) at the bottom of the tubs which did not evaporate significantly. An oil-water mixture had to be pumped from the bottom of the tubs to maintain liquid levels and prevent the oily wastes from overflowing. The oil-water mixture was removed and analyzed for pH, electrical conductivity, percent solids, and other parameters as appropriate. During rainy periods, water in the catch basin was also monitored for pH and conductivity to determine whether there was any leakage from the tubs containing highly acidic or highly alkaline wastes.

The seven FML-waste combinations that have been removed from exposure are shown in Table 5-20. These seven combinations include a range of six different FMLs and three different wastes. Three tub liners, including two liners of the same FML (ELPO) exposed to the same waste ("Oil Pond 104"), were removed from service because the liners had failed in the waste-air interface area due to cracking at a fold. The tub lined with a neoprene FML containing the waste liquid "Oil Pond 104" also failed and was subsequently removed from service. The results of testing these three liners were reported in Haxo et al (1985b). The procedures used in testing the liners removed from service are presented in Appendix H. An analysis of the wastes used in these tests is presented in Appendix J.

TABLE 5-20. COMBINATIONS OF POLYMERIC FMLS AND WASTES REMOVED FROM EXPOSURE TUB TEST AND EXPOSURE TIMES IN DAYS

Polymeric FML Polymer Number ^a		Waste identification		
		Acidic "HNO ₃ -HF-HOAc" (W-9) ^b	Alkaline "Spent Caustic" (W-2) ^b	Oily "Oil Pond 104" (W-5) ^b
CPE	77	...	Tub 9 (2774 days)	...
CSPE	6R	Tub 10 (2697 days)	...	...
ELPO	36	...	...	Tub 1 ^c ,1A ^c (506 days) (1308 days)
EPDM	8	Tub 11 (2046 days)	Tub 7 (2479 days)	...
Neoprene	82	...	...	Tub 6 ^c (2008 days)
PVC	11	Tub 12 (2629 days)	...	...

^aMatrecon FML serial number; R = fabric-reinforced.

^bMatrecon waste serial number. See Appendix J for analyses of the wastes.

^cResults of testing these tubs were presented in Haxo et al (1985b).

5.4.1.4.1--Testing of first failed ELPO liner exposed to "Oil Pond 104" waste--ELPO had not been recommended for oily applications; however, it had functioned satisfactorily in preliminary compatibility tests. The first ELPO liner exposed to "Oil Pond 104" waste failed after 506 days of exposure at a crack in a fold at the air-waste interface at the waste surface on the north sloping side of the tub. The liner appeared to have swelled considerably in this area. On removal from the tub, physical tests were performed at four exposure locations:

- Under the waste at the bottom of the tub.
- In the waste-shade zone on the south side.
- In a shade zone only where the sheeting was draped over the north edge.
- In a waste-sunlight zone on the north slope.

The waste-sunlight zone encountered the most severe exposure environment for the liner material.

5.4.1.4.2 Recovery and testing of the second failed ELPO liner exposed to "Oil Pond 104" waste--The second ELPO liner, which did not have a seam, replaced the first liner that had failed. This liner failed after 1308 days of exposure in much the same fashion as the first. It cracked at a fold at the air-waste interface.

On removal from the tub, this FML showed considerable distortion and swelling at the air-waste interface area. Test specimens were cut from the liner in accordance with the pattern shown in Figure 5-19. A 1-in. strip was removed from across the north-south axis of the tub liner. The thickness of the strip was measured along its length with a roller type gauge, and the results are presented in Figure 5-20.

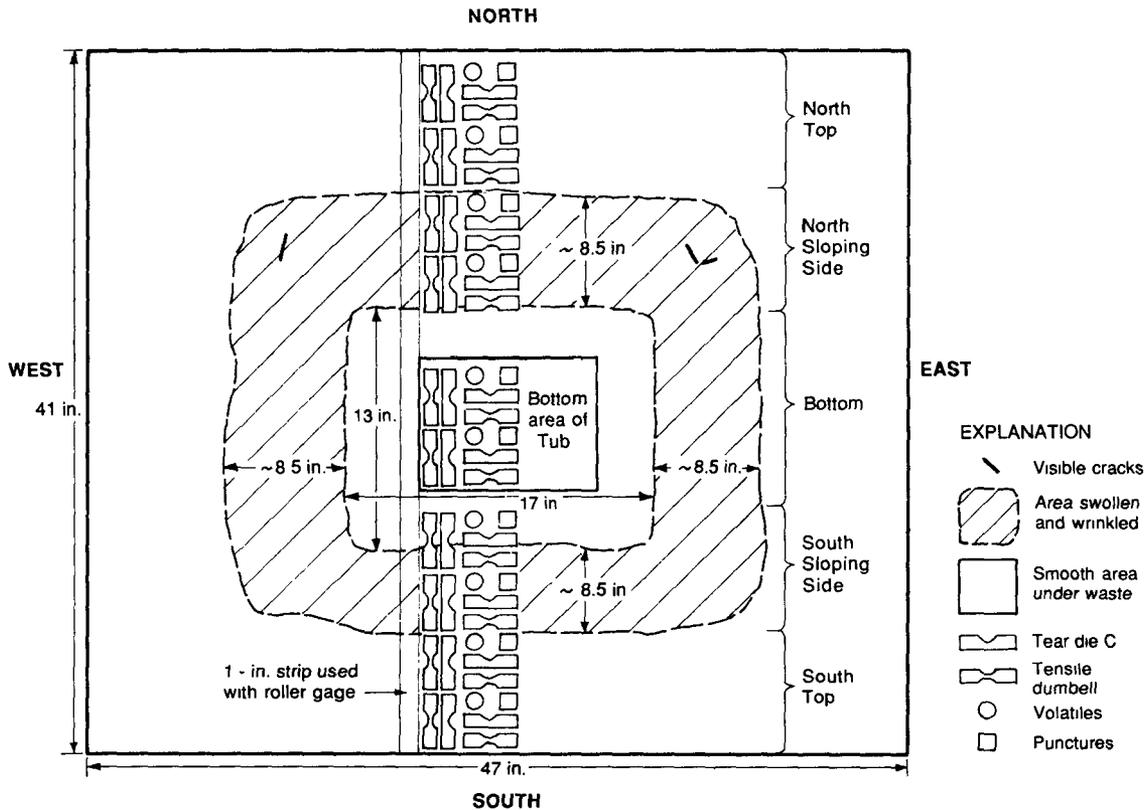


Figure 5-19. Drawing of exposed ELPO liner showing locations where the test specimens were cut and the orientation with respect to the tub and to the north. Location of strip for measuring thickness across specimens is also shown. (Source: Haxo et al, 1985b, p 163).

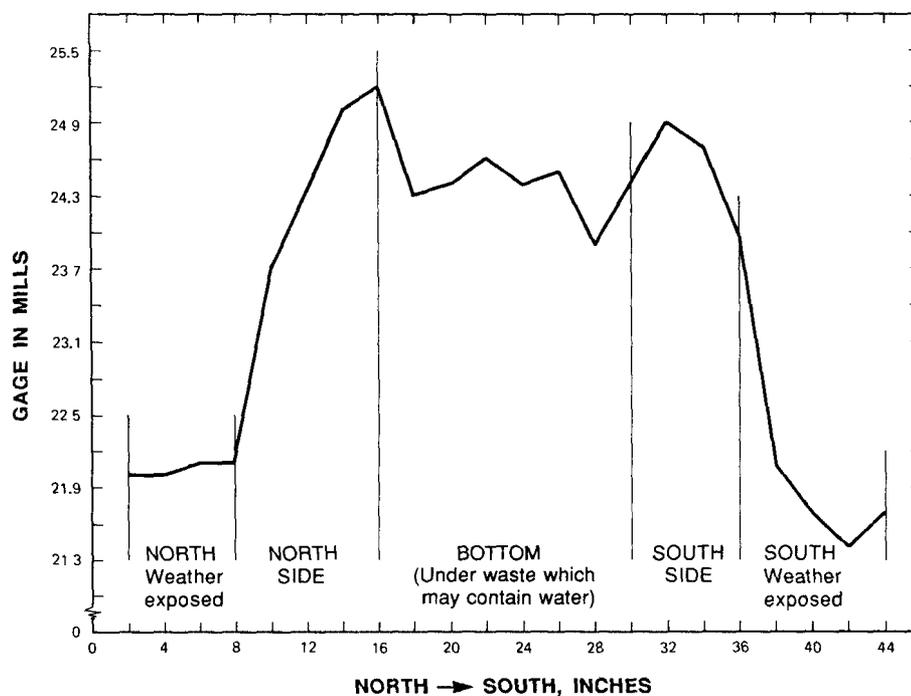


Figure 5-20. Thickness of strip of exposed ELPO liner cut across the width of the liner in north-south direction. (Source: Haxo et al, 1985b, p 163).

The test results for the liner samples taken from the different locations are presented in Table 5-21 together with the results of testing the unexposed FML. As in the case of the first failed ELPO liner, the effects of the absorption of the oil are large. The specimens taken from the north interface had an extractables content of almost 33% in comparison with the 5.5% extractables content of the unexposed FML. Retention of the tensile strength of the FML at the interface area on both the north and south sides was low. The tensile strength as a function of the thickness of the exposed FML is shown in Figure 5-21. The data on all of the individual tensile determinations have been included in the plot.

5.4.1.4.3 Testing of the neoprene liner exposed to "Oil Pond 104" waste--The neoprene liner, which failed in the seam, was the third to fail in the oily waste, "Oil Pond 104." The results of testing the liner are presented in Table 5-22. The FML absorbed a significant amount of oily waste as is shown by the increase in extractables in the areas where the liner was in contact with the waste.

As in the case of the two ELPO liners, the extractables of the sheeting exposed at the bottom of the tub was lower than that of the sheeting exposed on the sides at the air-waste interface area. This may be an indication either that exposure was more severe at the interface or that enough water was in the waste at the bottom of the tub to reduce swelling. The retention of physical properties is inversely related to the degree of swelling by the oily waste.

TABLE 5-21. PROPERTIES OF SECOND ELPO LINER EXPOSED TO AN OILY WASTE ("OIL POND 104") FOR 1308 DAYS IN TUB ON LABORATORY ROOF IN OAKLAND, CA

Variation in Location in Tub

Property	Properties of unexposed FML	Location in tub			
		North at top	North at inter-face	Waste only	South at inter-face
<u>Analytical properties</u>					
Volatiles, %	0.15	1.65	6.2	8.6	8.4
Extractables, %	5.50	7.54	32.7	20.7	23.0
<u>Physical properties^a</u>					
Thickness, mil	23	22.5	25.8	24.6	125.8
		<u>Retention, %</u>			
Tensile at break	2620 psi	84	29	48	37
Elongation at break	665%	80	63	89	83
Stress at 100% elongation	925 psi	97	49	63	59
Stress at 200% elongation	1020 psi	95	47	61	56
Tear strength	380 ppi	94	41	56	48
Puncture resistance:					
Stress	26.3 lb	119	71	68	69
Elongation	0.97 in.	144	132	118	116

^aTensile and tear values are averaged for both directions.

Source: Haxo et al, 1985b, p 164.

The results of testing the seam in the tub liner are presented in Table 5-23. The seam was made with a low-temperature vulcanizing cement. The top edge of the seam was caulked over with a lap sealant. The seam under the waste had a much lower seam strength than the seam that had not been in contact with the waste.

5.4.1.4.4 Summary of results of testing other FMLs exposed in roof tubs--The results of testing the other FMLs exposed in the roof tubs are summarized in Table 5-24.

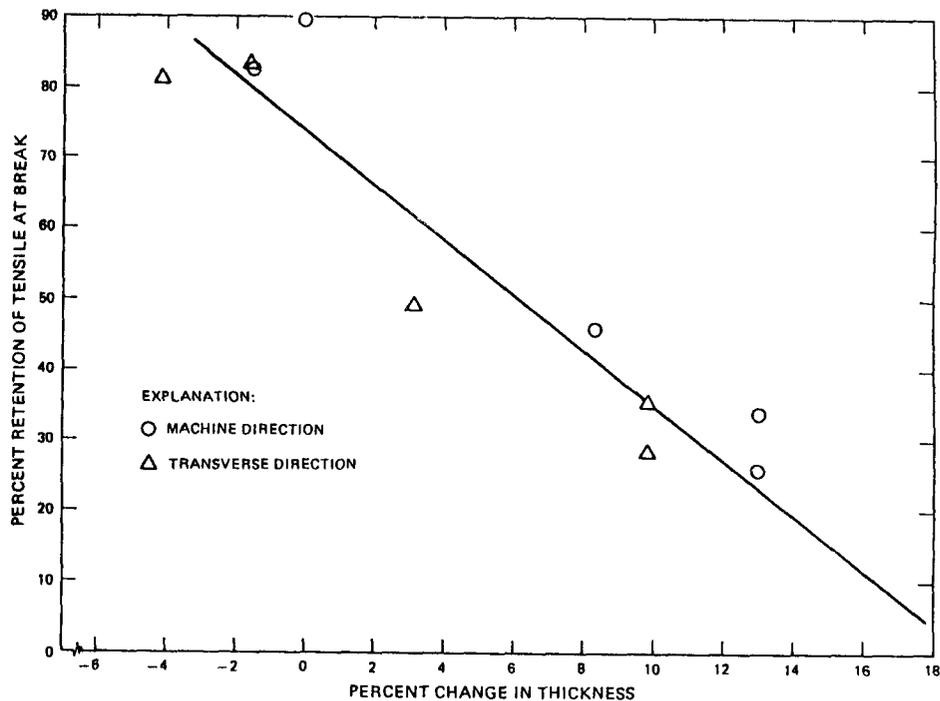


Figure 5-21. Retention of tensile strength of ELPO exposed in the oily waste, "Oil Pond 104," for 1308 days, as a function of change in thickness due to swelling. (Source: Haxo et al, 1985b, p 164).

5.4.1.4.5 Discussion of results--The results of the roof tub tests show the importance of location within a facility on the effects of exposure on an FML. The aging that occurs at the different locations can vary considerably, particularly if there is stratification of the wastes. The cracking in the PVC 11 FML exposed to the acidic waste and the EPDM 8 FML exposed to the alkaline waste was due to exposure to the weather. It should also be noted that these were areas where the liners were folded, that is, in place where the FML samples were under constant stress. The cracking of the EPDM 8 FML was probably ozone cracking, an unusual effect in EPDM sheeting. The cracks that developed in the ELPO 36 liners at the air-waste interface were also at folds. The neoprene 82 and ELPO 36 FMLs had their most significant losses in properties at the air-waste interface on the south-facing slope. The CSPE 6R liner also developed a leak and two blisters at the air-waste interface. The neoprene 82 FML failed in the seam area exposed to oily waste, and the seam in the EPDM 8 FML had begun to delaminate in the area exposed to the acidic waste. Adhesives were used in making both seams. These results indicate the difficulties involved in seaming crosslinked FMLs and the necessity of compatibility testing of seams.

5.4.1.5 Simultaneous Exposure to Simulated Tailings and Stress--

Mitchell and Cuello (1986) performed simulation exposure tests on three different FMLs at three different temperatures in specially designed exposure

TABLE 5-22. PROPERTIES OF A NEOPRENE FML^a EXPOSED TO AN OILY WASTE ("OIL POND 104")
FOR 2008 DAYS IN TUB ON LABORATORY ROOF IN OAKLAND, CA

Samples Taken From Different Locations in Tub

Property	Direction of test	Properties of unex- posed FML	Position in tub				
			South top	South slope	Bottom	North slope	North top
<u>Analytical properties</u>							
Extractables, %		13.43	12.28	30.09	25.33	28.94	12.71
Volatiles Loss over desiccant at 50°C, %		...	0.6	5.1	6.5	2.1	0.5
<u>Physical properties</u>							
Thickness (average), mil		61	63	75	77	75	65
			<u>Retention, %</u>				
Tensile at break	Machine	1835 psi	89	51	41	31	85
	Transverse	1675 psi	89	39	45	43	92
Elongation at break	Machine	390%	71	84	79	96	74
	Transverse	410%	70	79	75	89	70
Stress at 100% elongation	Machine	405 psi	152	40	29	16	154
	Transverse	360 psi	146	28	34	29	161
Stress at 200% elongation	Machine	875 psi	135	52	44	24	132
	Transverse	705 psi	144	42	54	41	155
Tear resistance	Machine	185 ppi	88	36	31	36	84
	Transverse	180 ppi	89	35	29	30	81
Puncture resistance							
Thickness		60.5 mil	105	126	129	131	107
Maximum force-average		53.9 lb	97	54	64	32	102
Deformation at puncture		1.2 in.	51	84	81	73	68
Hardness, durometer points 5-second reading		57A	<u>Change in points</u>				
			+7A	-31A	-29A	-33A	+8A

^aCrosslinked 60-mil neoprene FML without fabric reinforcement (Matrecon No. 82).

Source: Haxo et al, 1985b, p 165.

columns, which attempted to simulate conditions at the bottom of a tailings pond. A schematic of the exposure column is presented in Figure 5-22. The columns were made of 0.61-m (24-in.) stainless steel pipe. FML samples in which seams were incorporated were placed over a sand subgrade and sealed between the flanges of the column. The FMLs were covered with a 25-cm layer of fine silica sand to simulate tailings. Seventy liters of simulated leachate were added to each column. The load created by tailings was simulated by a press. Air pressurization of the test column was used to maintain a load equivalent to approximately a 5 to 6-m head of water on the sand above the FML. The temperature of the columns was maintained by fluid circulating in copper coils around the column exteriors. Operation of the columns included continuous temperature recording and daily monitoring of pH, liquid level, and air pressure. If the pH rose above 2.5, sulphuric acid was added to keep the pH between 2.0 and 2.5. The leachate was circulated several hours a day on weekdays. The column presses were loaded biweekly and locked into position.

TABLE 5-23. SEAM STRENGTH OF NEOPRENE 82 FML SAMPLE AFTER 2008 DAYS OF EXPOSURE IN TUB CONTAINING OILY WASTE, "OIL POND 104"

Mode of test	Location in tub of sample tested		
	East top	Bottom	West top
Shear			
Maximum, ppi	58.8	8.1	55.1
Locus of break	AD-LS ^a	AD-LS ^a	AD-LS ^a
Peel, ppi			
Maximum ^b , ppi	9.2	1.6	8.2
Average, ppi	6.5	0.8	5.5
Locus of break	AD-LS ^a	AD-LS ^a	AD-LS ^a

^aAD-LS = Delamination between adhesive and liner surface.

^bMaximum peel strength occurred at caulked edge.

Source: Haxo et al, 1985b, p 166.

Samples of HDPE, PVC, and CSPE FMLs were exposed in the columns at three different temperatures for 18 weeks. In the original experimental design, all FMLs were to be exposed at 18°, 48°, and 78°C. However, the combination of stress and elevated temperature apparently caused the CSPE FML exposed at 78°C to fail. A second CSPE FML sample was brought up to an elevated temperature (<70°C) over a period of several weeks to allow the compound to crosslink. Pressure was not exerted until the operating temperature was reached.

TABLE 5-24. SUMMARY OF THE RESULTS OF THE ROOF TUB EXPOSURES

Polymer type	FML number ^a	Waste ^b	Length of exposure, days	Comments
Ethylene propylene rubber	8	"HNO ₃ -HF-HOAc"	2046	Moderate effects on properties of FML. Lap sealant on seam under waste had cracked and half of seam had delaminated.
Ethylene propylene rubber	8	"Spent Caustic"	2479	Moderate effects on properties of FML. Cracks in fold at top edge of tub.
Polyvinyl chloride	11	"HNO ₃ -HF-HOAc"	2629	Severe effects on properties. Hardening and loss of flexibility in area above waste. Loss of properties and swelling in area under waste. Weather-cracking along fold at top edge of liner.
Chlorosulfonated polyethylene	6R	"HNO ₃ -HF-HOAc"	2697	Moderate effects on properties given crosslinking of polymer. Severe swelling in areas in contact with waste. Failure of reinforcing fabric (nylon). Blisters and a leak at air-waste interface.
Chlorinated polyethylene	77	"Spent Caustic"	2774	Moderate effects on properties.

^aMatrecon FML serial number; R = fabric-reinforced.

^bAnalyses of wastes are summarized in Appendix J.

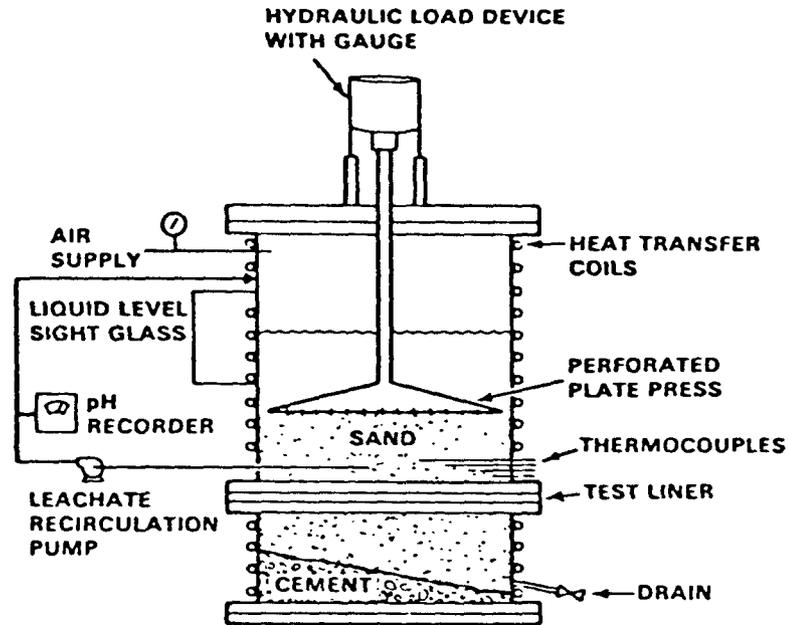


Figure 5-22. Schematic of accelerated aging column. (Source: Mitchell and Cuello, 1986, p 19).

After exposure, the FML samples were tested for analytical and physical properties. The analytical tests were selected specifically for the particular type of FML in order to determine whether the type of degradation to which that particular polymer was prone had occurred. For example, the HDPE samples were tested by differential infrared transmission analysis (to detect any carbonyl formation), by DSC (to detect changes in crystallinity), and by gel permeation chromatography (to determine molecular weight averages). The results of the DSC determination indicate that the accelerated test at 78°C appears to have affected the degree of crystallinity, as is shown in Table 5-25. The results of the molecular weight determinations were inconclusive. It should be noted that all samples were allowed to dry before physical and analytical testing.

5.4.1.6 Exposure in Pouch Tests--

The pouch test described in Chapter 4 (Section 4.2.2.4.1) in the discussion of the permeability of FMLs and in Appendix D. This test simulates some of the conditions that an FML might encounter as a liner in a waste storage or disposal facility (Haxo and Nelson, 1984; Haxo et al, 1982, 1984, and 1985b). It appears to be not only a means of assessing the permeability of FMLs but also a means of assessing the durability of FMLs in contact with wastes. The pouch can be filled with a waste liquid or leachate and the test can be allowed to run for extended periods of time after which the pouch is dismantled, the contained fluid weighed and analyzed, and the pouch walls analyzed and tested for physical properties.

Only pouches fabricated from thermoplastic and semicrystalline thermoplastic FMLs can be tested by this procedure because of the difficulties

involved in making adequate narrow-width seams with crosslinked FMLs. The pouch test depends on the preparation of leak-free pouches. A seam should not allow liquids to leak through it (e.g. through pinholes at the edge of the seam), thereby by-passing the membrane and resulting in a high transmission value.

TABLE 5-25. RESULTS OF DSC ANALYSES OF VIRGIN AND AGED HDPE FML SAMPLES

Sample	Depth, μm	ΔH_f , cal/g	Crystallinity, %
Virgin	18	35.51	51.9
	36	35.61	52.1
	51	35.69	52.2
	77	36.14	52.8
18°C	33	34.39	50.3
	51	35.24	51.5
	74	35.96	52.6
	97	35.29	51.6
47°C	18	36.40	53.2
	36	36.49	53.3
	53	36.31	53.1
	71	36.57	53.5
	89	36.88	53.9
	107	36.23	53.0
	127	37.00	54.1
76°C	20	37.87	55.4
	41	39.00	57.0
	58	39.19	57.3
	76	39.14	57.2
	23	37.18	54.4
	38	36.99	54.1
	53	37.74	55.2
	74	37.60	55.0

^aSource: Mitchell and Cuello, 1986, p 15.

The driving force for the movement of a given constituent through the pouch wall is its relative concentration on both sides of the wall. Each constituent in a mixture will tend to move through the pouch wall from a higher concentration of the specific species to a lower concentration of that species. For example, immersing a pouch filled with a waste liquid in DI water creates a significant concentration difference that will cause water to move into the pouch and constituents of the contained waste liquid which are soluble in the pouch wall to move out of the pouch into the outer water

where the concentration is lower. These effects are illustrated schematically in Figure 5-23 for a pouch filled with an aqueous waste or test liquid and immersed in water.

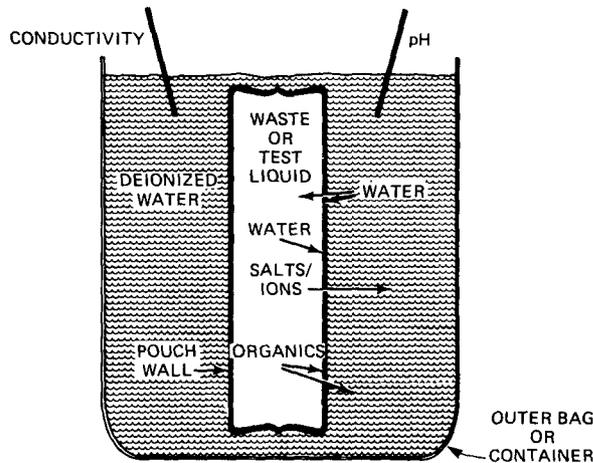


Figure 5-23. Pouch assembly showing the movement of constituents during the pouch test. In the case illustrated by this drawing, the pouch is filled with an aqueous waste or test liquid and immersed in deionized water. Arrows indicate the flow of specific constituents.

5.4.1.6.1 Tests of FML pouches containing MSW leachate--The pouch test was used to assess the permeability of six polymeric FMLs to MSW leachate (Haxo et al, 1982). An analysis of the leachate placed in the pouch is presented in Table 5-26. The results of the tests are summarized in Table 5-27.

TABLE 5-26. CHARACTERISTICS OF LEACHATE IN POUCHES

Property	Value
Total solids, %	2.0
Total volatile solids, %	1.1
Chemical oxygen demand, g L ⁻¹	35.7
Total volatile acids, g L ⁻¹	15.2
pH	5.15
Conductivity, $\mu\text{mho cm}^{-1}$	11,500

Source: Haxo et al, 1982, p 98.

TABLE 5-27. TESTS OF FML POUCHES^a FILLED WITH MSW LEACHATE
Transmission of Water and Ions Through Pouch Walls

Polymer	FML number	Original values			Values at 70 days			Values at 500 days		
		pH ^b	Conduc- tivity ^b , μmho cm ⁻¹	Weight of filled bag, g	pH ^b	Conduc- tivity ^b , μmho cm ⁻¹	Weight increase ^c , g	pH ^b	Conduc- tivity ^b , μmho cm ⁻¹	Weight increase ^c , g
CPE	77	5.7	5.2	170.91	5.8	29.7	1.68	6.5	124.0	4.74
ELPO	36	5.1	4.3	142.63	5.0	9.82	-0.07	4.5	17.8	0.22
PEL	75	4.0	20.5	112.25	3.5	73.0	0.58	6.4	50.0	2.95
PVC	11	5.8	6.0	166.88	4.4	30.9	0.41	6.0	32.0	1.12
PVC	17	5.0	13.3	138.28	2.9	310.1	0.33	2.8	325.0	1.37
PVC	59	5.7	5.9	170.14	3.8	61.5	0.97	6.3	23.2	1.21
Blank	...	5.5	1.33	...	5.7	1.75	...	4.3	11.6	...

^aArea of each pouch exposed to MSW leachate was approximately 560 cm²; each pouch contained 100 mL of MSW leachate.

^bpH and conductivity of water outside the pouches containing MSW leachate.

^cWeight increase of pouches containing MSW leachate.

Source: Haxo et al, 1982, p 99.

After 500 days of exposure, test results indicated that there was movement through the FMLs by both the water and the dissolved constituents of the MSW leachate. An increase in electrical conductivity occurred, indicating potential permeation of ions from the leachate into the deionized water. The odor of butyric acid in the outer water indicated the transmission of this constituent of the leachate. There was an increase in the weight of the pouches containing leachate, indicating transmission of water into the pouches. Of the six FMLs tested, the ELPO yielded the lowest transmission of water and dissolved components, and the PVC 17 appeared to be the most permeable.

5.4.1.6.2 Tests of FML pouches containing hazardous waste liquids--In pouch tests run with actual hazardous wastes (Haxo et al, 1985b), a total of 56 different FML-waste combinations, including 11 different FMLs and 10 different waste liquids, were tested. Selected results of these tests are summarized in Tables 5-28 through 5-30, which present data for the following:

- Exposure times in number of days that the individual pouches were in test (Table 5-28).
- Electrical conductivity of the outer water in the pouch assembly at the conclusion of the tests or before any leaks were noted (Table 5-29).
- Change in weight of the waste in the pouches at the conclusion of the tests (Table 5-30).

Analyses of the wastes used in this study are presented in Appendix J.

As these tests were exploratory in nature, only one pouch was tested for each liner-waste combination with the exception of the ELPO pouches containing the alkaline waste "Slop Water." Pouches were removed from test either after the pouches failed (i.e. broke), or after an arbitrary prolonged exposure. Many pouches failed in the seams. Even though some of the seam failures were related to exposure, these failures are indicative of the problems involved in fabricating the pouches and do not necessarily reflect on the seaming techniques used by manufacturers, fabricators, or installers, whether in the factory or in the field.

The results of these tests indicate the range of responses among the different FMLs to a single waste and with the same FML to the different wastes. For example, of the pouches containing the acidic wastes, the ELPO pouches exhibited the lowest transmission of water (as determined by change in weight of the pouch contents at the end of test; see Table 5-30) and the lowest transmission of ions into the outer water (Table 5-29); however, among the pouches containing the alkaline "Slop Water," the ELPO pouches had the highest or second highest transmission rates to both water and ions.

To give an example of a complete test, the results of testing the pouches containing the highly alkaline wastewater "Slop Water" are discussed in detail in the following paragraphs.

TABLE 5-28. POUCH TESTS OF POLYMERIC FMLS WITH DIFFERENT WASTE LIQUIDS

Exposure Time in Days

Pouch		Waste liquid									
		Acidic		Alkaline		Indus- trial	Oily			Pest- icide	
		"HFL" (W-10)	"HNO ₃ - HF- HOAc" (W-9)	"Stop Water" (W-4)	"Spent Caustic" (W-2)		"Basin F" (W-16)	"Lead Waste" (W-14)	"Slurry Oil" (W-15)		"Oil 104" (W-5)	"Weed Oil" (W-7)	"Weed Killer" (W-11)
Polymer	Number ^a										
Chlorinated polyethylene	86 (22)	1895	1887	625 <65> ^b	2420	...	...	...	1485	1896	...
Chlorosulfonated polyethylene	6R (31)	...	...	...	...	...	...	...	1494	...	...
	55 (35)	...	...	...	...	1953	...	...	1485	...	...
	85 (33)	...	1887	2516	2468	...	...	...	...	...	...
Elasticized poly- olefin	36 (22)	1895	1887	790 <753> 1725 ^d	2420	1903	1354 <277>	^c	1485	1896	2250
Polybutylene	98 (8)	1895	625 <552>	2516	2468	1952	^c	1847 <1734>	1485	1896	2250
Polyethylene, low-density	21 (10)	1895	...	...	...	1953	...	...	1494	1896	...
Polyvinyl chloride	17 (20)	1885	...	...	...	1357 <227>	...	...	1484	1882	...
	19 (22)	1895	1887	930 <872>	2420	1952	^c	^c	1485	1775 <1681>	2250
	88 (20)	...	1887	625 <65>	2468	...	...	...	...	...	...
	93 (11)	1767 <1648>	...	...	...	...	...	...	248 <9>	1497 <62>	...

^aMatrecon FML number and thickness in mils (in parentheses).^bNumber in brackets <> is the number of days pouch was monitored before a rise in electrical conductivity or a significant loss in weight, i.e. a possible leak, was noted.^cStill in test as of February 26, 1985.^dAfter first pouch swelled and broke at a seam, a second pouch was put into test to confirm results obtained on first pouch.

TABLE 5-29. POUCH TESTS OF POLYMERIC FMLS WITH DIFFERENT WASTE LIQUIDS
Electrical Conductivity (in $\mu\text{mho/cm}$) of Outer Water at Conclusion of Test or Before Leakage from Pouch^a

Pouch composition		Waste liquid									
		Acidic		Alkaline		Indus- trial	Oily			Pest- icide	
		"HFL" (W-10)	"HNO ₃ - HF- HOAc" (W-9)	"Slop Water" (W-4)	"Spent Caustic" (W-2)		"Basin F" (W-16)	"Lead Waste" (W-14)	"Slurry Oil" (W-15)		"Oil Pond 104" (W-5)	"Weed Oil" (W-7)	"Weed Killer" (W-11)
Polymer	Number ^b										
Chlorinated polyethylene	86 (22)	562	5900	270 ^C	150	...	...	...	191	470	...
Chlorosulfonated polyethylene	6R (31)	...	...	...	...	...	...	...	310	...	...
	55 (35)	...	...	...	...	3150	...	...	320	...	...
	85 (33)	...	3600	2240	40	...	...	...	...	...	...
Elasticized polyolefin	36 (22)	68	86	10,800 ^C 8500 ^E	14	87	12 ^C	85 ^d	140	55	86
Polybutylene	98 (8)	187	440	2280	50	240	373 ^d	57 ^C	130	9	80
Polyethylene, low-density	21 (10)	655	...	...	...	220	...	...	130	51	...
Polyvinyl chloride	17 (20)	545	...	...	...	33 ^C	...	...	330	482	...
	19 (22)	285	3200	14,700 ^C	1300	165	33 ^d	59 ^C	49	62 ^C	51
	88 (20)	...	4600	235 ^C	165	...	...	...	...	...	...
	93 (11)	595 ^C	...	...	...	...	...	...	6 ^C	54 ^C	...

^aElectrical conductivity of the deionized water placed in the outer bags was approximately 5 $\mu\text{mho/cm}$. Reported values of the conductivity of the liquids in the outer bags, in some cases, may be maximum values before conclusion of test as the liquids in some of the bags were either diluted with or replaced by deionized water. The lengths of the various exposures are presented in Table 5-28.

^bMatrecon FML number and thickness in mils (in parentheses).

^cPouch failed and waste liquid mixed with the liquid in the outer bag. Reported datum is the electrical conductivity of the outer water at the last monitoring before a leak was noted. See Table 5-27 for length of exposure before leakage was noted.

^dStill in test. Reported datum is the electrical conductivity of the outer water as of February 26, 1985, after 2223 days of exposure.

^eAfter first pouch broke at a seam, a second pouch was placed in test to confirm results obtained on first pouch. Reported datum is conductivity measurement made after 1678 days of test. At that time, the liquid in the outer bag was replaced with deionized water. Conductivity at end of test (at 1725 days) was 310 $\mu\text{mho/cm}$.

TABLE 5-30. POUCH TESTS OF POLYMERIC FMLS WITH DIFFERENT WASTE LIQUIDS
 Weight Change (in Grams) of the Waste Liquid in the Pouches as Measured After Pouches were Dismantled

Polymer	Pouch Number ^a	Waste liquid									
		Acidic		Alkaline		Indus- trial "Basin F" (W-16)	"Lead Waste" (W-14)	Oily		Pest- icide "Weed Killer" (W-11)	
		"HFL" (W-10)	"HNO ₃ - HF- HOAc" (W-9)	"Stop Water" (W-4)	"Spent Caustic" (W-2)			"Slurry Oil" (W-15)	"Oil 104" (W-5)		"Weed Oil" (W-7)
Chlorinated polyethylene	86 (22)	5.9	98.7	27 ^b	22.4	...	...	...	-8.8	1.9	...
Chlorosulfonated polyethylene	6R (31)	...	...	...	...	...	...	...	-15.4	...	...
	55 (35)	...	...	...	...	5.3	...	...	-21.3	...	...
	85 (33)	...	46.6	22.2	13.0	...	...	...	...	...	...
Elasticized polyolefin	36 (22)	0.0	1.4	209.8 ^b 245.8 ^c	4.9	3.3	-0.9 ^b	-0.5 ^d	-15.2	0.0	-1.4
Polybutylene	98 (8)	0.7	0.8 ^b	18.1	7.7	5.4	-1.3 ^d	-0.2 ^b	-5.7	-0.8	-1.8
Polyethylene, low-density	21 (10)	1.3	...	...	...	11.5	...	...	-8.0	0.8	...
Polyvinyl chloride	17 (20)	4.3	...	...	...	7.5 ^b	...	...	-1.3	-0.5	...
	19 (22)	4.3	21.0	152.4 ^b	68.6	31.8	-1.2 ^d	0.5 ^d	-0.3	-0.2 ^b	-2.5
	88 (20)	...	35.8	2.5 ^b	62.4	...	...	...	...	...	...
	93 (11)	9.8 ^b	...	...	...	...	...	...	0.0 ^b	2.2 ^b	...

^aMatrecon FML number and thickness in mils (in parentheses). See Table 5-28 for exposure times.

^bPouch failed and waste liquid mixed with the liquid in the outer bag. Reported datum is weight change of the filled pouch at last monitoring before a leak was noted.

^cSecond pouch placed in test after first pouch swelled and broke at a seam.

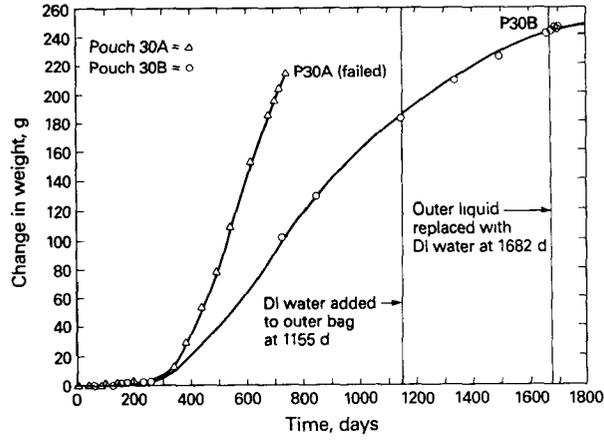
^dStill in test. Reported datum is weight change as of February 26, 1985, after 2223 days of test.

Pouches fabricated from six different FMLs (CPE 87, CSPE 85, ELPO 36, PB 98, and PVCs 19 and 88) were tested with the highly alkaline wastewater, "Slop Water" (W-4). Premature seam openings occurred in four of the pouches including the first ELPO.

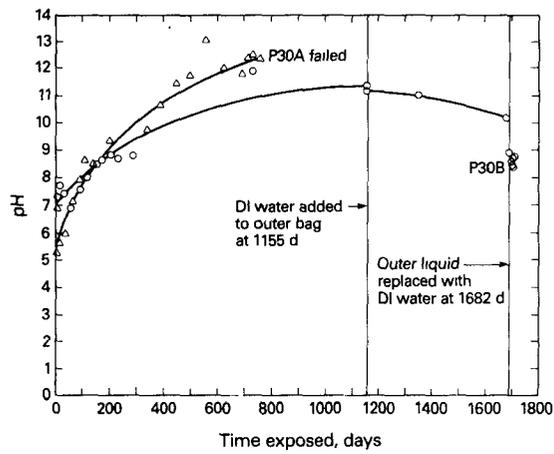
A leak in the seam of the first of two ELPO pouches (P30A) was noted at 790 days of exposure after the pouch had become bloated due to its large increase in weight. At approximately 300 days, the rate at which this pouch had changed in weight had increased, indicating a change in the permeability of the pouch walls. Because of this apparent change in permeability, a second pouch was placed in test to verify the behavior of the first pouch. The second pouch (P30B) behaved similarly; it showed no significant increase in weight until it had been in test for about 300 days, and then, even though it did not increase at as great a rate as the first pouch (P30A), it began to increase significantly in weight. Both pouches showed a similar rise in the electrical conductivity of the water outside the pouch after reaching $1000 \mu\text{mho cm}^{-1}$ at approximately 300 days of test. Again, the second pouch (P30B) did not show as steep a rate of increase in electrical conductivity as the first pouch (P30A). The results of monitoring the weight of the two pouches and the pH and electrical conductivity of the liquids in which they were immersed are presented in Figure 5-24. The second pouch (P30B) was dismantled after 1725 days of test because it had gained so much weight and had swelled to the point that bursting seemed imminent. The pouch waste was weighed, and both the pouch waste and the liquid in the outer bag were measured for pH and electrical conductivity. Measurements made on the two ELPO pouches, including those made at the time of dismantling, are presented in Table 5-31.

The highly alkaline waste liquid appeared to interact slowly with the ELPO wall. The effect became apparent during monitoring after 300 days of exposure when the rates of transmission of water into the pouch and the rate of increase in electrical conductivity of the outer water rose dramatically. After the pouches were dismantled, the pouch walls were analyzed and tested for physical properties. The results of these tests indicated that losses had occurred in the tensile strength, elongation at break, and tear resistance.

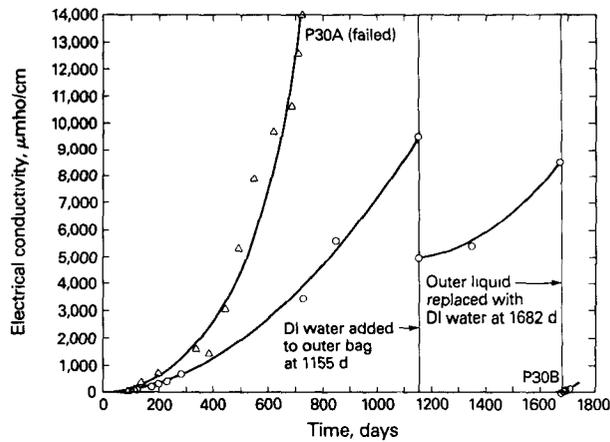
The CSPE 85 and PB 98 pouches containing the "Slop Water" wastewater reached almost seven years of exposure without failure before they were dismantled (Table 5-28). The wastewater content in both pouches increased approximately 20 g, indicating that water had permeated into the pouches (Table 5-30). The pouch walls also increased in weight: the CSPE pouch increased by 17% in weight and the PB pouch increased 3%. The outer water of both assemblies had an electrical conductivity of approximately $2200 \mu\text{mho/cm}$, as is shown in Table 5-29, indicating that the walls of both pouches allowed equal permeation of ions, probably H^+ and OH^- ions. The PB maintained its physical properties but developed a number of small blisters, approximately 1 mm in size. The CSPE softened slightly and, while it maintained its tensile strength, decreased in elongation at break, and increased in modulus. The changes in tensile and tear properties are probably a result of cross-linking of the polymer during exposure combined with absorption of water.



a. Change in weight of filled pouches.



b. pH of outer water.



c. Electrical conductivity of outer water.

Figure 5-24. Monitoring data for ELPO pouches (P30A and P30B) containing the highly alkaline waste, "Slop Water" (W-4).

TABLE 5-31. MEASUREMENTS ON THE TWO ELPO^a POUCHES
FILLED WITH "SLOP WATER" WASTE (W-4)

Parameter	Original properties	Exposed pouch	
		P30A	P30B
Exposure time, days	...	753 ^b	1725
Pouch liquid			
pH	13.1	11.9	13.2
Electrical conductivity, $\mu\text{mho/cm}$	129,000	105,000	84,000
Outer water			
pH	7.0	12.0 ^c	8.9 ^d
Electrical conductivity, $\mu\text{mho/cm}$	1.3	90,000 ^c	310 ^d
Filled pouch, original weight, g			
Final weight, g	N/A	215.13	98.45
Change in weight, g	N/A	428.72	346.94
Empty pouch, original weight, g			
Final weight, g	N/A	+213.59	+248.49
Change in weight, g	N/A	27.62	26.25
Pouch contents, change in weight, g			
Final weight, g	N/A	31.45	28.98
Change in weight, g	N/A	+3.83	+2.73
Pouch contents, change in weight, g			
Original area of pouch, cm^2	N/A	+209.76	+245.76
Final area of pouch, cm^2	N/A	486	374
Change in area, cm^2	N/A	521	383
Rates of water transmission into pouch ^e , $\text{g/m}^2\cdot\text{d}$			
Calculated by correlation from increase in pouch weight data ^f			
Initial (0 - 300 d)	N/A	0.199(10)	0.215(11)
Intermediate (300 - 1200 d)	N/A	9.005(8)	5.651(3)
Final (1200 - end)	N/A	N/A	2.900(16)
Overall (0 - end)	N/A	5.527(18)	4.125(30)
Calculated from increase in pouch liquid weight			
Overall (0 - end)	N/A	5.732	3.809
Final (300 - end) ^g	N/A	7.779	4.526
Analysis of pouch wall			
Volatiles, %	0.15	10.85	8.47
Extractables, %	5.50	2.09	2.85

^aMatrecon FML No. 36; 20-mil thickness.

^bLeak noted during monitoring of pouch at 790 days. Pouch removed from test at that time.

^cPrior to seam leak the electrical conductivity of the outer liquid was 14,000 $\mu\text{mho/cm}$ and the pH was 12.4.

^dThe outer water had a pH of 10.3 and an electrical conductivity of 8500 $\mu\text{mho/cm}$ before it was replaced with DI water on day 1682.

^eBased on original area of pouch.

^fNumber of data points given in parentheses.

^gCalculated by subtracting an increase in weight of a filled pouch at approximately 300 d from the total change in weight of the pouch contents. At 204 days, P30A had gained 2.2 g. At 287 days, P340B had gained 2.32 g.

Of the other three pouches tested with the "Slop Water" wastewater, the CPE 86 and the PVC 88 pouches began to leak at the seams after 65 days of test but were not removed from exposure until after 625 days. The PVC 19 pouch broke at a seam after 872 days of test. Before it had broken, the pouch had become bloated and had increased significantly in weight, and the liquid outside the pouch had increased significantly in electrical conductivity, probably due to migration of OH^- ions out of the pouch and H^+ into the pouch (Tables 5-29 and 5-30). Testing and analysis of the wall material showed that the FML had decreased in extractables and had increased in modulus and tensile strength. The changes in properties of the two PVC materials indicate significant loss of plasticizer after exposure to the "Slop Water" wastewater.

5.4.1.6.3 Overview of pouch test results--The results of the pouch tests that have been reported in this section and in Section 4.2.2.4.1 have been somewhat inconsistent indicating the problems with performing this test, particularly with fabricating the pouches. The test was developed both to study the permeation of constituents of waste liquids and test liquids through polymeric membranes, under conditions that simulate some of the conditions of exposure and to study one-sided exposure of FMLs to waste liquids and other test solutions. The particular constituents included:

- Water.
- Ionic constituents.
- Organic constituents, e.g. oils.

The results of testing the pouches indicate the movement of water through the pouch walls, as is shown by the increase in weight of many of the pouches. As is discussed in Section 4.2.2.4.1, PVC pouches containing LiCl solutions increased in weight in differing amounts, depending on the concentration of the LiCl in the pouch and the specific PVC FML, thus indicating the importance of the concentration gradient as a driving force for permeation through a membrane. The pouch tests with the highly acidic and highly alkaline waste liquids also showed significant transmission of water into the pouches. Transport through an FML is described in more detail in Chapter 3.

The pouch tests with solvents, also discussed in Section 4.2.2.4.1, present different problems with respect to the permeability of water. The pouches filled with acetone or xylene in DI water showed a negative transmission rate indicating the movement of acetone or xylene out of the pouches rather than any water movement into the pouches. The pouches with 50:50 acetone:water showed an outward movement of acetone when immersed in DI water and inward movement of acetone when immersed in acetone.

Taken as a whole, these results indicate that a pond lined with an FML placed in a moist, perhaps saturated, environment in which the water is relatively pure would receive water from the environment outside the pond. Such would be true even if the liner contained no holes or breaks. In the diffusion process, each constituent migrates through the FML as an independent molecular species.

In pouch tests with waste liquids that were highly acidic or highly alkaline, some increases in EC were observed in the water in the outer bags, indicating high concentrations of ions. Close inspection of the pouches after disassembly indicated some weak seams and damage to some of the FMLs at the corners, particularly in the case of fabric-reinforced FMLs; however, those pouches that were well made and had good seams yielded little increase in the EC of the water in the outer bags and thus little, if any, transmission of ions. Overall, the results of the pouch tests indicate that polymeric FMLs are probably highly resistant to ion transmission, with the possible exception of H^+ and OH^- ions. The appearance of high EC in an outer bag in a relatively short time probably indicates that liquid from inside the pouch has entered the water in the outer bag through a hole that developed at a seam or through a pinhole that developed in the pouch wall. It is recognized that the absorption of CO_2 from the air results in an increase in the EC of the water as well as a decrease in the pH of the water, and that the migration of soluble compounding ingredients out of the pouch walls or residuals from FML manufacture may also have affected EC measurements.

The pouch tests indicated that organic liquids would permeate the FMLs, although the rate varied greatly depending on the solubility of the permeating species in the FML and the difference in chemical potential of the permeating species on the two sides of the FML, as is discussed in Chapter 3. The results of pouch tests discussed in Section 4.2.2.4.1 showed that acetone and xylene permeated the walls of the pouches when the pouches were placed in DI water. The acetone permeated the walls and dissolved in the outer water; the xylene permeated but, because it is not soluble in water, rose to the surface. When the pouches with the acetone and xylene were placed in the same solvents, the movement was into the pouch where the solvent contained dissolved constituents, either organic dyes or water.

Pouch tests with waste liquids containing oils indicated that the oils permeated the walls of the pouches resulting in a film of oil being formed on the outside of the pouches. Since the oils were not soluble in water, they tended to remain on the surface of the pouches and stop further movement of oils through the pouch walls. If the oils had been soluble in the water, the concentration of the oil on the downstream surface of the FML would have been lower and migration of the oil would have continued.

The pouch test appears to be a feasible method of qualitatively assessing the permeability of FMLs over long periods of time and of assessing the durability of FMLs in contact with waste liquids or test liquids. Of particular interest were results indicating changes in the permeability of an FML after prolonged exposure, e.g. the results of the ELPO pouches tested with the "Slop Water" waste discussed in Section 5.4.1.6.2. Maintaining an FML in a moist condition appears to be an important element in assessing the long-term permeability of an FML that may slowly become affected by a waste liquid. The difficulties with the pouch test include the prolonged exposure time that may be required and the problems with fabricating hole-free pouches with seams that will maintain the integrity throughout the exposure. In addition, test results with volatile organics depend on the rate at which

volatiles are allowed to escape from the test system, i.e. from the container in which the pouch is immersed.

5.4.1.7 Permeability of FMLs to Mixtures of Organics and Aqueous Solutions--

Most leachates and waste liquids are complex dilute aqueous solutions of organic and inorganic chemical species. In order to contain these solutions, it is necessary to know the magnitude of the permeation of these species in mixtures through the FMLs. Each species has its own solubility and diffusion rate through a polymeric FML when tested individually; however, when in mixtures, it is anticipated that there may be interaction between the components of the mixture and the FML and that this interaction may affect the diffusion rates and thus the transmission of the different species. The following subsections present the results of experimental studies on the permeability of FMLs to mixtures of organics and aqueous solutions containing organics.

5.4.1.7.1 Permeability to mixtures of organics--Two studies have been performed to measure the permeation of a mixture of solvents through an FML. To simulate a mixture of waste solvents leaking from a drum onto an FML, August and Tatsky (1984) measured the transmission rates of each of six solvents from an equivolume fraction mixture through a 40-mil HDPE FML. The apparatus used by August and Tatsky consisted of two compartments separated by the FML. The upper compartment contained the solvent mixture, and the lower was partially evacuated. In this experiment, the composition of the liquid mixture was held constant. A support screen was placed under the FML in the lower compartment because of the vacuum pressure. The permeating vapors were collected in a cold trap and then analyzed by gas chromatography. The results are presented in Table 5-32. The data show the high rates of transmission for the two chlorinated solvents and the great difference in the rates among the solvents.

TABLE 5-32. PERMEATION RATES OF THE COMPONENTS OF A MIXTURE OF ORGANICS THROUGH A 40-MIL HDPE FML

Organic	Permeation rate, g m ⁻² d ⁻¹
Trichloroethylene	9.4
Tetrachloroethylene	8.1
Xylene	3.0
Isooctane	0.8
Acetone	1.4
Methanol	0.7
Total	23.4

Source: August and Tatzky, 1984, p 166.

Matrecon has performed a similar experiment in which the transmission rates of the components of a solvent mixture containing equal volumes of methanol, methyl ethyl ketone (MEK), 1,1,1-trichloroethane (TCA), toluene, and n-heptane through a 20-mil FML (ELPO 172) were maintained. This testing was performed in accordance with a procedure based on ASTM E96, Inverted Water Method (Procedure BW). Circular specimens of ELPO 172 were mechanically clamped onto the mouths of aluminum cups partially filled with the solvent mixture (see discussion of solvent vapor permeability in Section 4.2.2.4.1). The cups were stored in an upright position so that only the vapors contacted the FML specimens. The transmission rates were monitored by headspace gas chromatography. Table 5-33 lists data obtained from averaging test results from triplicate cells. The following observations were made:

- All components of the mixture diffused through the FML simultaneously, but at different rates.
- The total transmission rate and the rates for the individual solvents varied significantly as the composition of the liquid phase changed. The SVT test cups were not infinite reservoirs and the solvent loss rates declined steadily with time as the more readily transmissible components were lost.

The results of these two studies indicate that strong selective permeability causes very different permeation rates for components of mixtures.

TABLE 5-33. TRANSMISSION OF SOLVENT MIXTURES THROUGH A 20-MIL ELPO FML^a

Time, h	Weight, % of solvent remaining					
	Methanol ^b	MEK	n-Heptane	TCA	Toluene	Total ^c
0	17.6	18.0	15.2	29.8	19.3	100.0
22	≥17.3	16.6	12.6	27.0	17.2	90.8
70	≥16.8	13.8	7.9	21.8	13.2	73.7

^aMatrecon FML No. 172.

^bThe methanol loss was below the analytical detection limit of the GC column. These data are based on a limiting value, the lower detection limit.

^cThe component values do not add exactly to the "total" value; see footnote "b". Additional errors were generated by manually integrating the loss rate data using the trapezoidal method. The maximum error is 2.3%.

5.4.1.7.2 Permeability to aqueous solutions of organics--Leachates containing small amounts of organics may contact an FML. However, little is known about how the rate of permeation of an organic from an aqueous solution (i.e. a leachate) compares with the rate of permeation of the same organic in a concentrated form through the same FML. To simulate the permeation of a leachate containing organics through an FML, August and Tatzky (1984) also studied the permeation of dilute aqueous solutions of organics through a variety of FMLs using the same equipment described in the previous subsection. The results of measuring the permeation rate of a 0.05 weight percent aqueous solution of toluene through various FMLs are presented in Figure 5-25. The permeation rates of various pure organics and dilute solutions (0.1 to 0.001 weight percent) of the same organics through a 40-mil HDPE FML are compared in Figure 5-26. The data show that the permeation from a dilute solution of an organic can be substantially higher than what would be expected from the difference in concentration. For example, even though the ratio between the concentrated toluene and the dilute solution was 1000:1, the ratio between permeation rates through the HDPE was 20:1. These results indicate that significant quantities of an organic can permeate through an FML due to selective permeation, even when the organics are present in a leachate at a very low concentrations.

In a separate experiment performed by Haxo et al (1988), a three-compartment closed apparatus was used to assess the permeation of organics from dilute aqueous solutions through polymeric FMLs. The test apparatus, shown schematically in Figure 5-27, can be divided into seven zones, which are listed in Table 5-34. FML specimens separate the three compartments (Zones 2 and 5). An aqueous solution containing organics partially fills the middle compartment (Zone 4), and DI water can be placed in the bottom compartments (Zone 7). The three compartments are clamped tightly together. Thus, the organics can either volatilize into the airspace above the solution and then, permeating through the top FML specimen, enter the top compartment or the organics can permeate through the lower FML specimen and into the bottom compartment. The covers of one end of each of the top and the bottom compartments were welded to the walls to avoid potential loss of volatiles. The only potential leaks were those that might occur at the flanges between which the FML specimens that separated the three compartments were mounted. Ports with Teflon silicone rubber septums were incorporated in each of the three compartments for use in withdrawing samples for GC analysis from the aqueous and airspace zones. The two FML zones can be analyzed by GC after the apparatus is dismantled.

The three-compartment apparatus simulates the configuration of a covered landfill as follows:

- The airspace in the top compartment is like the airspace over a "cover" liner. The FML specimen between the top and middle compartments is like a "cover" liner.
- The airspace in the middle compartment simulates the headspace above a waste liquid, and the dilute solution containing organics serves as the waste liquid. The FML specimen between the middle and bottom compartments simulates the service conditions of a bottom liner.

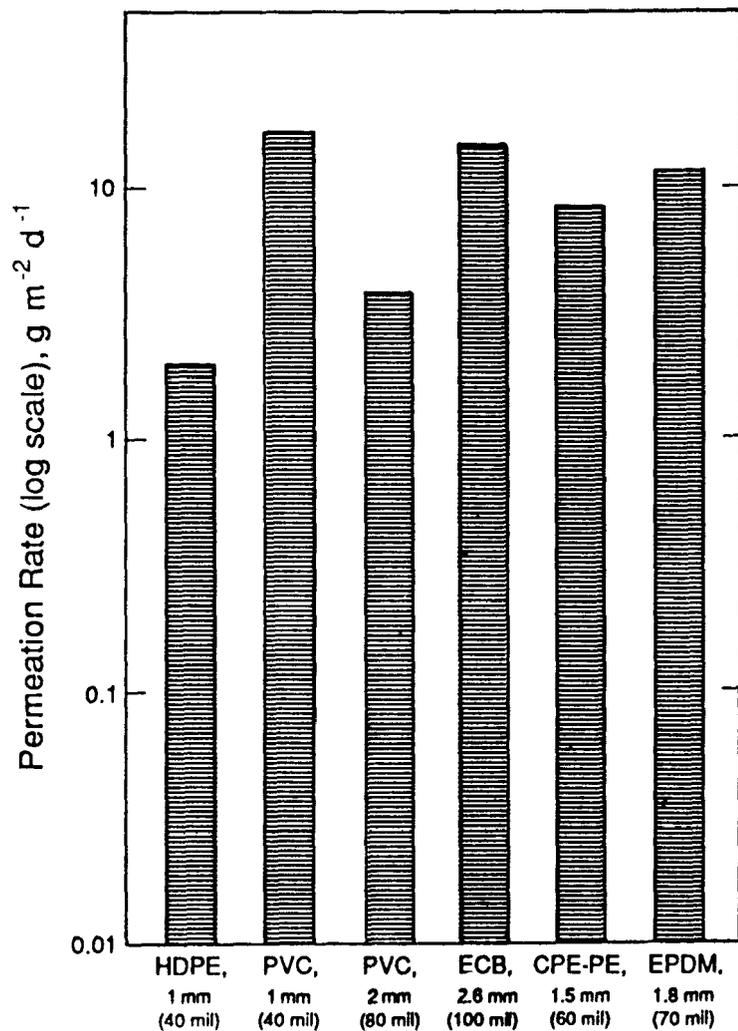


Figure 5-25. Permeation rates of 0.05 weight percent aqueous solutions of toluene through various FMLs. ECB = ethylene copolymer with bitumen. (Based on August and Tatsky, 1984, p 167).

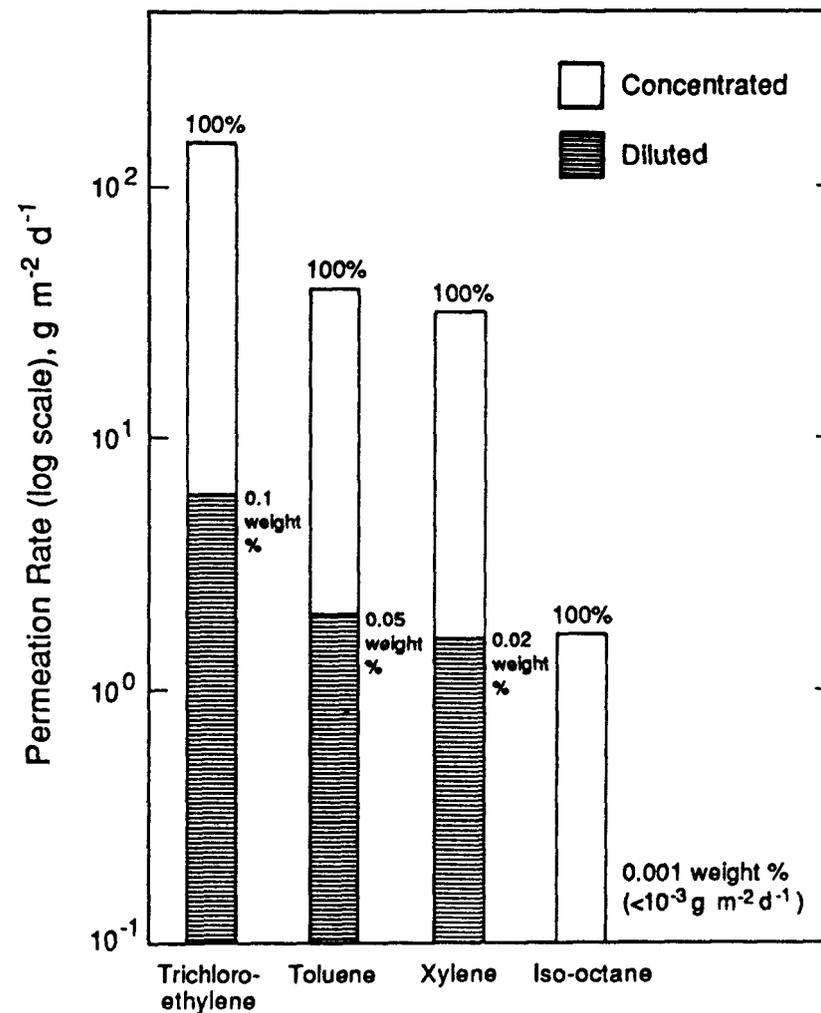


Figure 5-26. Permeation rates of concentrated and dilute solutions of various organics through a 1-mm (40-mil) HDPE FML. (Source: August and Tatsky, 1984, p 166).

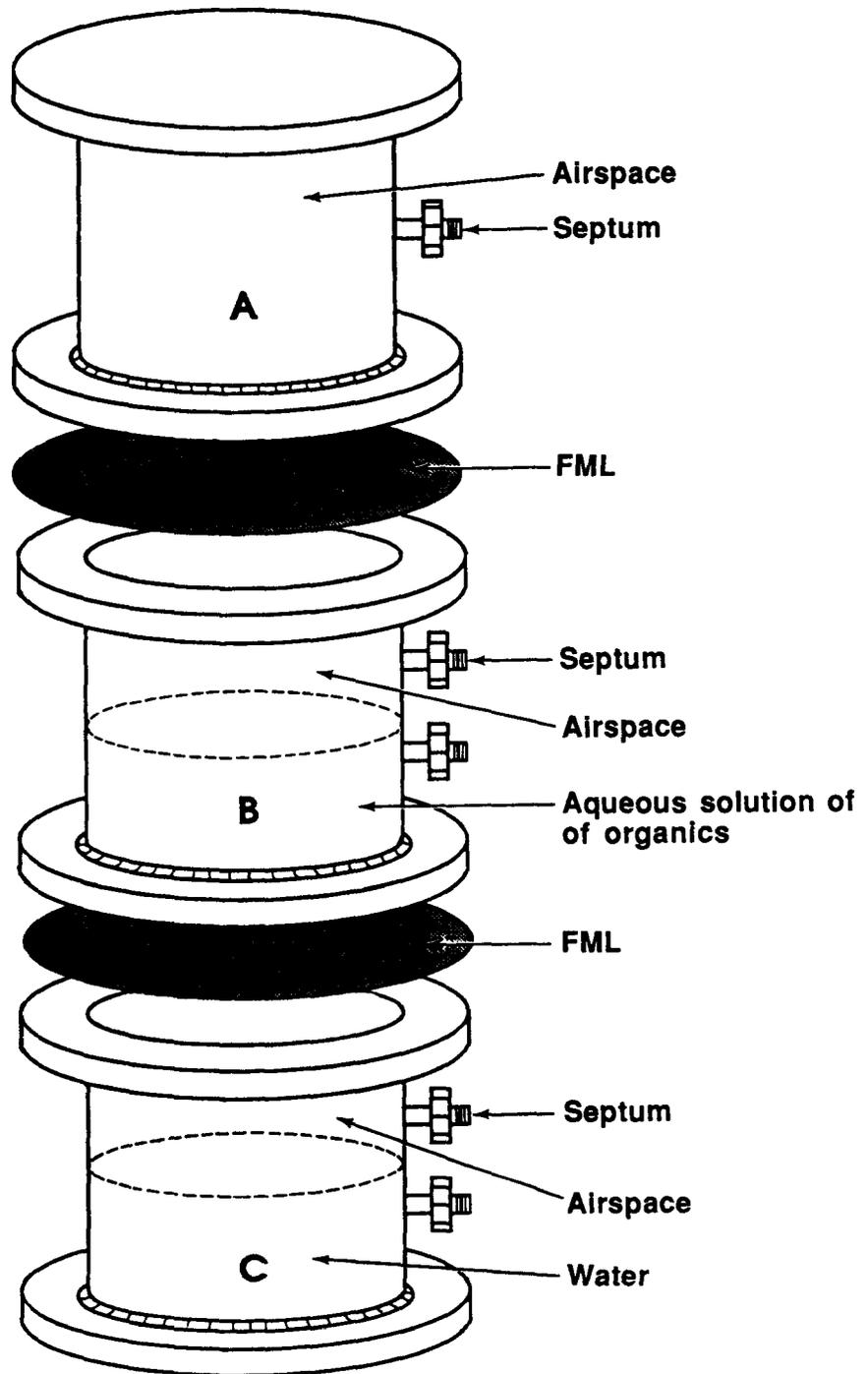


Figure 5-27. Schematic of the three-compartment test apparatus used in the study of the distribution of organics between water, air, and an FML and the permeation of organics through an FML. Inside diameter of each compartment was 4 inches. (Based on Haxo et al, 1988).

- The airspace and the deionized water in the bottom compartment simulate, respectively, pore spaces in the soil and the groundwater.

TABLE 5-34. ZONES IN THREE-COMPARTMENT TEST APPARATUS

Zone	Compartment	Description	Volume, mL
1	Top	Airspace above "cover"	806
2	Barrier between top and middle	"Cover" FML (33-mil LLDPE): Area exposed to solution	~7
3	Middle	Airspace above aqueous solution containing organics	306
4	Middle	Dilute aqueous solution containing organics	500
5	Barrier between middle and bottom	"Bottom liner" (33-mil LLDPE): Area exposed to solution	~7
6	Bottom	Airspace below "bottom liner" FML	506
7	Bottom	Deionized water	300
Total			2,432

Source: Haxo et al, 1988.

The configuration of the zones within each compartment can be modified to assess double liners and various auxiliary materials, such as covers, geotextiles, and drainage materials.

In an experiment to assess the distribution of organics between water, air, and an FML and the diffusion and the permeation of organics through an FML, a dilute aqueous solution of toluene and trichloroethylene (TCE) was placed in the middle compartment of the test apparatus. Both of these organics are commonly found in leachates and are easily identifiable and trackable by GC analysis. Information on these two organics is presented in Table 5-35. Both are identified as volatile contaminants by the Environmental Protection Agency. An LLDPE FML (Liner No. 284) was used in this experiment to separate the three compartments. Data on this FML are presented in Table 5-36.

In this experiment, seven zones were incorporated in the three compartments (Table 5-34). Zone 4 was filled with 500 mL DI water and spiked with 191 mg each of toluene and TCE to yield concentrations of 382 mg each per L of water. The five zones containing water or vapor were sampled and analyzed by GC periodically to assess the changes in concentrations in these zones.

After 256 hours, when the concentrations appeared to remain constant, the apparatus was dismantled and the FML samples were removed and analyzed by headspace GC to determine the concentrations of the organics in the FMLs. Also, analysis was performed separately on the FML in the flange area, as well as the area that contacted the vapor. The results of the analyses of samples taken at 24, 96, and 256 hours are reported in Table 5-37.

TABLE 5-35. ORGANICS USED IN THREE-COMPARTMENT APPARATUS EXPERIMENT WITH DILUTE AQUEOUS SOLUTIONS

Property	Toluene	Trichloroethylene
Purity, %	99.9	99.9
Molecular weight, %	92.13	131.40
Density at 20°C, g cm ⁻³	0.866	1.476
Specific volume, cm ³ g ⁻¹	1.155	0.677
Boiling point, °C	110.6	87.2
Vapor pressure at 25°C, mm Hg	31.96	80.30
Solubility parameters ^a :		
δ_o	8.9	9.2
δ_d	8.8	8.8
δ_p	0.7	1.5
δ_h	1.0	2.6
Solubility in water, mg L ⁻¹ ^b	515	1100

^aBarton (1983).

^bRiddick and Bunger (1970).

Source: Haxo et al, 1988.

The results show that the water in the bottom compartment (Zone 7) had absorbed organics. At the end of the test the relative concentrations of the two organics were the same in both aqueous zones, i.e. in Zones 4 and 7, demonstrating the transport of these organics through the FML and airspace to the water at the bottom. The data also show that, for each of the two organics, the concentrations in the airspaces in Zones 1, 3, and 6 were similar in value and the concentrations in the two FML specimens were essentially equal. Overall, 92.6% of the TCE and 97.7% of the toluene were accounted for in the final analyses of all zones. Part of the loss arose from sampling. The headspace GC analysis of the FML in the flange area showed no organics, which indicated that there was no leakage through the

flanges. Overall, these results show that the apparatus had come to equilibrium; they also show the high absorption of organics by the FML. At these equilibrium conditions, the coefficients of distribution between the LLDPE FML and water for TCE and toluene were 178 and 120, respectively.

TABLE 5-36. SELECTED PROPERTY VALUES OF A 33-MIL LLDPE FML (MATRECON FML NO. 284)

Property	Value
Thickness, mil	33.4
Carbon black content, %	2.5
Specific gravity of FML	0.927
Density:	
FML at 23°C, g/mL	0.924
Polyethylene (calculated by correcting for carbon black content), g/mL	0.913
Crystallinity, %	36.3
Melting point, °C	119

Source: Haxo et al, 1988, p 68.

The experiments on the distribution of organics from dilute solutions show that, even at low concentrations in an aqueous leachate, some of the organics can be highly absorbed by the polymeric FML and can permeate the liner. The amount and rate of absorption and the transport of these species through a polymeric FML is a function of such factors as relative solubility parameters of the FML and the organic, crystallinity of the FML, and molecular weight and concentration of the organic constituent. A multi-compartment apparatus, such as the one described, appears to be an appropriate and promising means of assessing the effectiveness of an FML to contain a given leachate.

5.4.2 Immersion Tests of FMLs

In rubber and plastics technology, the compatibility of polymeric products being considered for service with a particular solvent or liquid is commonly tested by immersing samples of the rubber or plastic compound in that solvent or liquid. In this type of testing the changes in weight, dimensions, and physical properties can be used to monitor the effects of immersion. It is, of course, desirable that no changes in the material occur during service; therefore, changes in dimensions and in properties can

TABLE 5-37. DISTRIBUTION OF ORGANICS IN THREE-COMPARTMENT TEST APPARATUS SEPARATED BY POLYETHYLENE FMLS

No.	Zone Description	Volume, mL	Organic	Start of test		At 24 hours		At 96 hours		At end of test, 256 hours	
				Amount, mg	Concen- tration, mg/L	Amount, mg	Concen- tration, mg/L	Amount, mg	Concen- tration, mg/L	Amount, mg	Concen- tration, mg/L
1	Airspace above "cover" FML ^b	806	TCE ^a	0	0	9.2	11.5	14.1	17.5	12.9	16.0
			Toluene	0	0	7.9	9.8	10.0	12.5	4.8	6.0
2	"Cover" poly- ethylene FML ^b	7.02	TCE	0	0	...	...	...	...	56.1	7,990
			Toluene	0	0	...	...	...	...	60.2	8,580
3	Airspace above test liquid	306	TCE	0	0	12.1	39.5	8.8	29.0	5.97	19.5
			Toluene	0	0	10.1	33.0	8.1	26.5	1.83	6.0
4	Test liquid	500	TCE	191	381	95	190	80	160	22.5	45.0
			Toluene	191	381	92	185	80	160	35.7	71.4
5	Barrier FML ^b	7.02	TCE	0	...	...	...	...	...	56.1	7,990
			Toluene	0	...	...	...	...	...	60.2	8,580
6	Airspace below FML	506	TCE	0	...	8.6	17.2	11.9	23.5	9.87	19.5
			Toluene	0	...	1.16	2.3	3.74	7.4	2.58	5.1
7	"Groundwater"	300	TCE	0	...	0.75	1.5	6.42	21.4	13.5	45.0
			Toluene	0	...	~0	~0	4.57	15.2	21.4	71.4
	Total	2,432	TCE	191	381	125.6	...	121	...	176.9	...
			Toluene	191	381	111.1	...	106.4	...	186.7	...
	Fraction ac- counted for, %		TCE	100		65		63		92.6	
			Toluene	100		58		55		97.7	

^aTrichloroethylene.

^bLinear low-density polyethylene FML (Liner No. 284).

Source: Haxo et al, 1988, p 70.

indicate a degree of incompatibility. In some applications, specific changes in properties of the material limit the serviceability of a product. For example, a fluid delivered by a rubber hose may cause excessive shrinkage which could stiffen the hose, or swelling which could restrict the flow in the hose to such an extent that the hose would no longer be serviceable.

Waste liquids can cause changes in the dimensions and the physical properties of FMLs; therefore, measuring changes in dimensions and properties after an immersion test should give an indication of the compatibility or incompatibility of an FML and a specific waste liquid. Immersion testing, in which two sides of an FML are exposed to a waste liquid, can function as an accelerated simulated-service test of an FML in that it simulates the exposure of an FML in direct contact with a waste. This type of exposure is without mechanical stress, which can be a significant factor in service conditions.

This section describes the results of immersion testing that has been performed on polymeric FMLs. Studies have been undertaken in which FML samples have been immersed in MSW leachate (Haxo et al, 1982), a range of hazardous wastes (Haxo et al, 1985b), and a series of test liquids (Haxo et al, 1988; Bellen et al, 1987; Morrison and Parkhill, 1987). These studies are discussed in the following subsections.

In general, immersion testing of polymeric products at elevated temperatures (e.g. 50°C) has been thought to be an effective way of accelerating the effects of immersion. However, this form of acceleration is effective only for specific combinations involving known processes. In other cases, the effect of the elevated temperature may cause changes in the polymeric product which do not correlate with service at a lower temperature. Some of the work reported in this section explores the usefulness of immersion at an elevated temperature in the compatibility testing of FMLs.

5.4.2.1 Immersion in MSW Leachate--

In conjunction with the simulation testing discussed in Section 5.4.1.1, samples of polymeric FMLs were immersed in MSW leachate (Haxo et al, 1982). Only a limited number of FMLs could be exposed in the simulation tests. The immersion study was undertaken to include a wider range of polymeric FMLs in the testing program and to develop a correlation between the one-sided exposure in the simulators and two-sided exposure by immersion. The availability of the leachate generated by the MSW simulators made it possible to expose the FML samples in the two exposure tests to the same waste liquid.

Twenty-eight different FMLs of 11 different polymeric types were selected for immersion testing. The FMLs selected included some that were already in exposure in the simulators as well as others that had become available either commercially or on a developmental basis. Three sets of the 28 FMLs were immersed so that specimens could be tested after 8, 19, and 31 months of immersion. No attempt was made to seal the exposed fabric ends of the fabric-reinforced FMLs that were immersed.

The immersion system allowed a blend of the leachates from the MSW simulators to flow slowly through a series of 6-gal heavy-duty HDPE tanks in which the FML specimens were hung. The size of the tanks was sufficient to allow immersion of 8 x 10-in. slab specimens. Stainless steel hooks, on which the specimens were hung, were sealed into the lids of the tank lids. Inlets and outlets were also installed in the lids to allow the flow of leachate. The lids were then welded onto the tanks. The immersion tanks used in these tests are presented schematically in Figure 5-28.

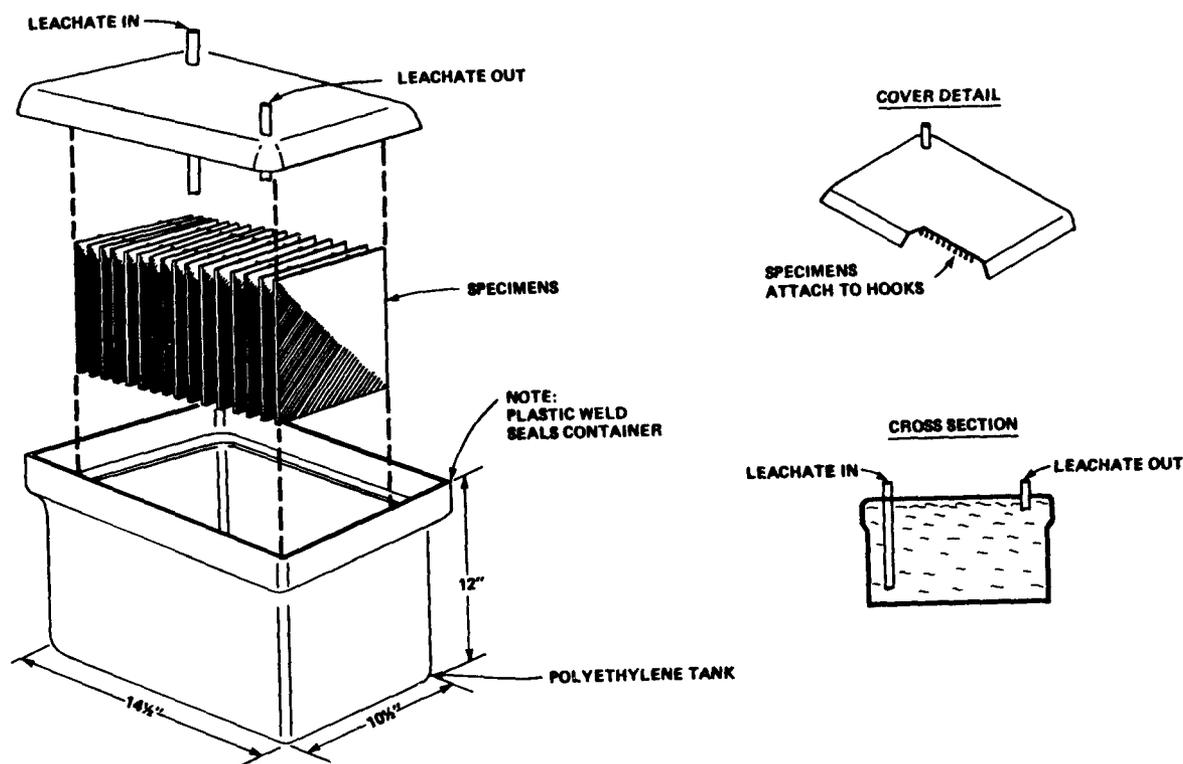


Figure 5-28. Schematic of HDPE immersion tank, showing method of holding specimens and the inlet and outlet for the MSW leachate. (Source: Haxo et al, 1982, p 80).

Initially, the flow of the leachate through the tanks was effected by gravity feed from a drum containing leachate placed above the tanks. Problems were encountered with this arrangement; solids precipitated from the leachate and plugged the system. A Masterflex pump was then installed so that leachate was delivered at the rate of 14 mL per minute through the tanks. The supply of leachate recirculated in about 12 days.

Approximately 48 gal of leachate, obtained by blending the output of the MSW simulators, was introduced into the system every four weeks and a

similar amount of the used leachate was drawn off. Samples of both the new and used leachate were tested at each addition for: pH, chemical oxygen demand (COD), total solids (TS), total volatile solids (TVS), and total volatile acids (TVA). The composition of the leachate added to the system changed little while it was used to expose the FML samples, indicating the air-tight, anaerobic character of the system. During the initial operation of the system, the analytical results (Table 5-38) were close to the calculated averages of the leachates from the simulators. In later months, however, differences developed between the two that may have been caused by biological contamination of the blended leachate.

TABLE 5-38. ANALYSIS OF LEACHATE USED IN THE IMMERSION SYSTEM^a

Property	Leachate added to system	Leachate removed from system
pH	5.27	5.27
Chemical oxygen demand, g L ⁻¹	32.6	29.0
Total volatile acids, g L ⁻¹	11.3	11.3
Total solids, %	1.70	1.80
Total volatile solids, %	0.94	1.00

^aSamples were taken on January 31, 1975.

Source: Haxo et al, 1982, p 82.

The tests performed on the FMLs before and after each of the three exposure intervals were:

- Weight of specimen.
- Dimensions of specimen.
- Tensile properties, in machine and transverse directions, three specimens per direction, ASTM D412. Testing was performed using a special dumbbell which features smaller tab ends, a shorter overall length, and a shorter narrowed test area in comparison with the ASTM D412 Die C dumbbell.
- Hardness, ASTM D2240.
- Tear strength, in machine and in transverse directions, two specimens per direction, ASTM D624, Die C.
- Puncture resistance, two specimens, FTMS 101C, Method 2065.

- Volatiles, Matrecon Test Method 1 (Appendix G).

The range of values for a selection of properties measured on all the samples from each of the eleven polymer types are shown for 8, 19, and 31 months immersion in Table 5-39. In all cases, the FMLs absorbed leachate, but the data show that swelling varies both among types of polymers and within a generic polymer type. The variations within a polymer type result from both compounding and polymer differences. In some cases, the absorption appeared to have dropped due to changes in the composition of either the leachate or the FML (due to plasticizer loss).

The effect of immersion in leachate up to 31 months appears to have a relatively mild effect on most of the FMLs as is shown for tensile strength retention versus immersion (Figures 5-29 and 30). Of the 28 FMLs in the exposure test, 11 increased in tensile, 10 decreased, and 7 remained essentially unchanged. The maximum average retention after 31 months of exposure was 135% and the lowest was 70%. The effect of immersion on the modulus (i.e. stress at 200% elongation) of the same materials is shown in Table 5-40. The PVC FMLs had a small spread in values and retained their original tensile strength as well as modulus. Overall, the polyolefins, such as polyethylene, polybutylene, and elasticized polyolefin, exhibited the lowest swelling and highest retention values.

5.4.2.2 Immersion of FMLs in Hazardous Wastes and Selected Test Liquids--

Immersion testing of a variety of polymeric FMLs in actual hazardous wastes and in selected test liquids was performed in conjunction with the simulated exposure testing discussed in Section 5.4.1.2 (Haxo et al, 1985b). As the project progressed, many new FMLs became available, including some based on polymers not being tested in the primary exposure program and some based on polymers already being tested but of significantly different composition. Only a limited number of FML-waste combinations could be tested as liners in the one-sided exposure cells; thus, immersion testing was performed to increase the number of FMLs being exposed to the hazardous wastes. In addition, some FML-waste combinations tested in the one-sided exposure cells were also tested in immersion to develop a correlation between two-sided exposure testing and exposure as a liner in the test cells. Altogether, 16 different FMLs based on 11 different polymer types were exposed to 13 wastes or test liquids.

The wastes and test liquids used in the immersion tests are listed in Table 5-41. The saturated tributyl phosphate (TBP) solution was included in the tests because of concern about the effects a solution containing a small amount of organics might have on an FML. TBP was selected, not only because of its low solubility in water, but because of its relatively low volatility and its phosphorous content which could be used as a tracer of the TBP movement.

TABLE 5-39. SUMMARY OF THE EFFECTS OF IMMERSION OF POLYMERIC FMLS IN MSW LEACHATE FOR 8, 19, AND 31 MONTHS^a

Polymer type	Number of FMLs in tests	Weight increase, %			Tensile strength, % original			Elongation, % original			Change in hardness, Duro A, points		
		8 mo.	19 mo.	31 mo. ^b	8 mo.	19 mo.	31 mo.	8 mo.	19 mo.	31 mo.	8 mo.	19 mo.	31 mo.
Butyl rubber	1	1.8	3.5	25	90-97	89-94	92	104-106	99	90-92	0	0	-1
Chlorinated polyethylene	3	8-10	16-18	25-28	80-115	81-106	78-106	64-135	76-108	71-103	-5 to 1	-8 to -2	-11 to -1
Chlorosulfonated polyethylene	3	13-19	16-27	19-32	82-124	95-132	103-138	97-107	77-94	69-86	-20 to -4	-26 to -5	-21 to -3
Elasticized polyolefin	1	0.1	1.6	8	86-94	96-107	98-106	91-92	102	96-98	0	-2	-1
Ethylene propylene rubber	5	1-21	1-12	8-24	64-107	86-93	94-113	76-138	83-146	88-138	-1 to +2	-2 to -1	-3 to +5
Neoprene	4	1-19	3-32	5-88	69-100 ^c	60-102	68-105	82-103 ^c	76-104	78-146	-11 to +5	-12 to +3	-18 to +4
Polybutylene	1	0.1	0.8	...	96-99	94-95	84-97	96-97	96	86-89	-3	-5	-3
Polyester elastomer	1	2.0	1.9	16	99-115	52-94	81-90	101-108	92-94	80-96	-4	-6	-3
Low-density polyethylene	1	0.6	0.7	3	110-180	92-149	118-161	96-181	67-192	100-168	...	...	...
Polyvinyl chloride	7	1-3	1-6	4-24	91-110	91-111	87-117	98-139	100-129	79-120	-2 to +1	-6 to +1	-6 to +3
Polyvinyl chloride + pitch	1	6	8	14	92	88-93	101-104	109-133	94-117	80-103	-2	+1	+1

^aRanges of retention values for tensile strength and elongation are lowest and highest averaged values obtained for either machine or transverse directions of all tensile specimens within the group of slab specimens of a given polymer type.

^bSome samples were inadequately cleaned, so some values are high.

^cData for fabric-reinforced neoprene FML No. 42 were not included.

Source: Haxo et al, 1982, p 84.

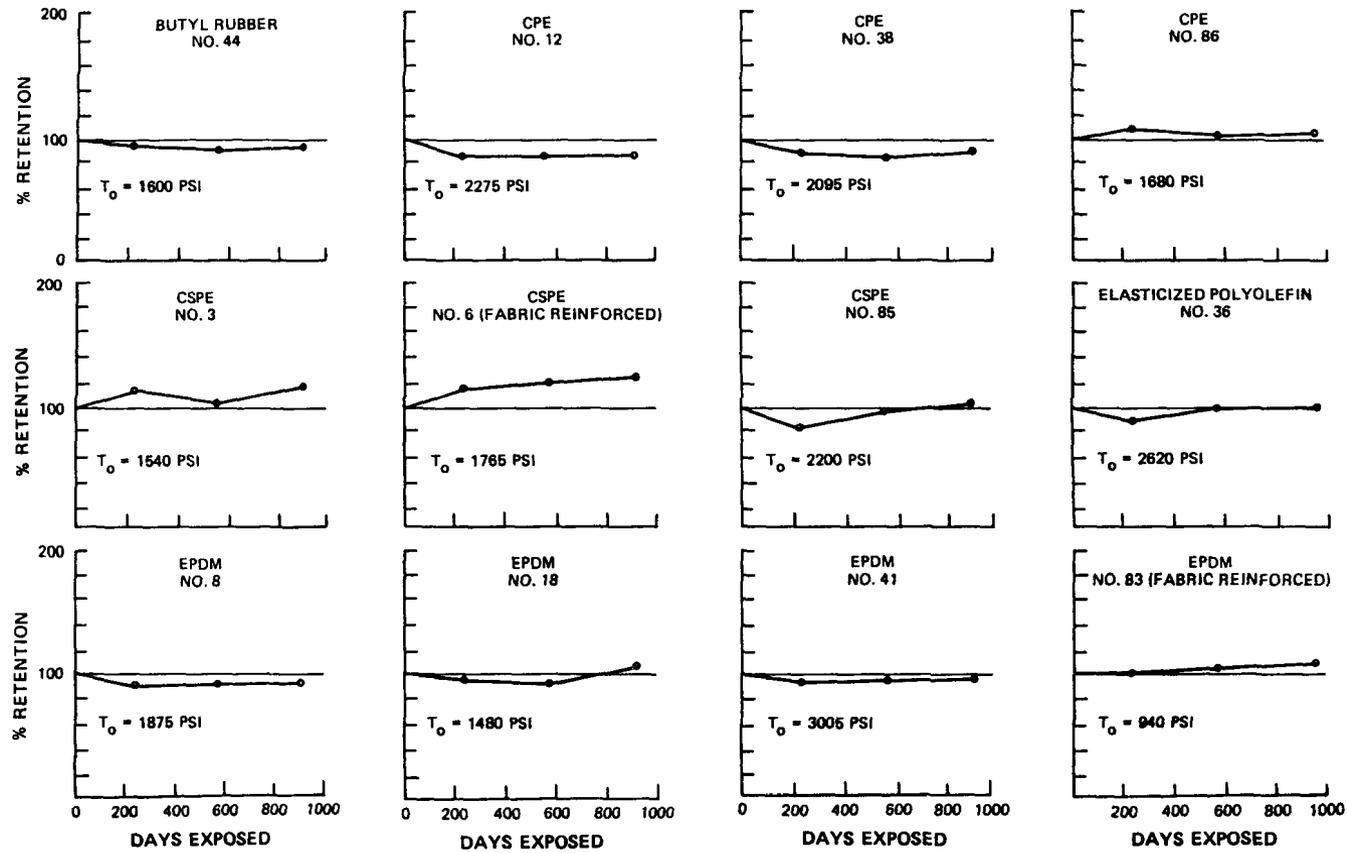


Figure 5-29. Retention of FML tensile strength as a function of immersion time in MSW leachate-- Butyl rubber, CPE, CSPE, ELPO, and EPDM FMLs. Tensile strength values are average values for machine and transverse directions; initial tensile strength for each FML is shown. Data are given for 8, 19, and 31 months. (Source: Haxo et al, 1982, p 85).

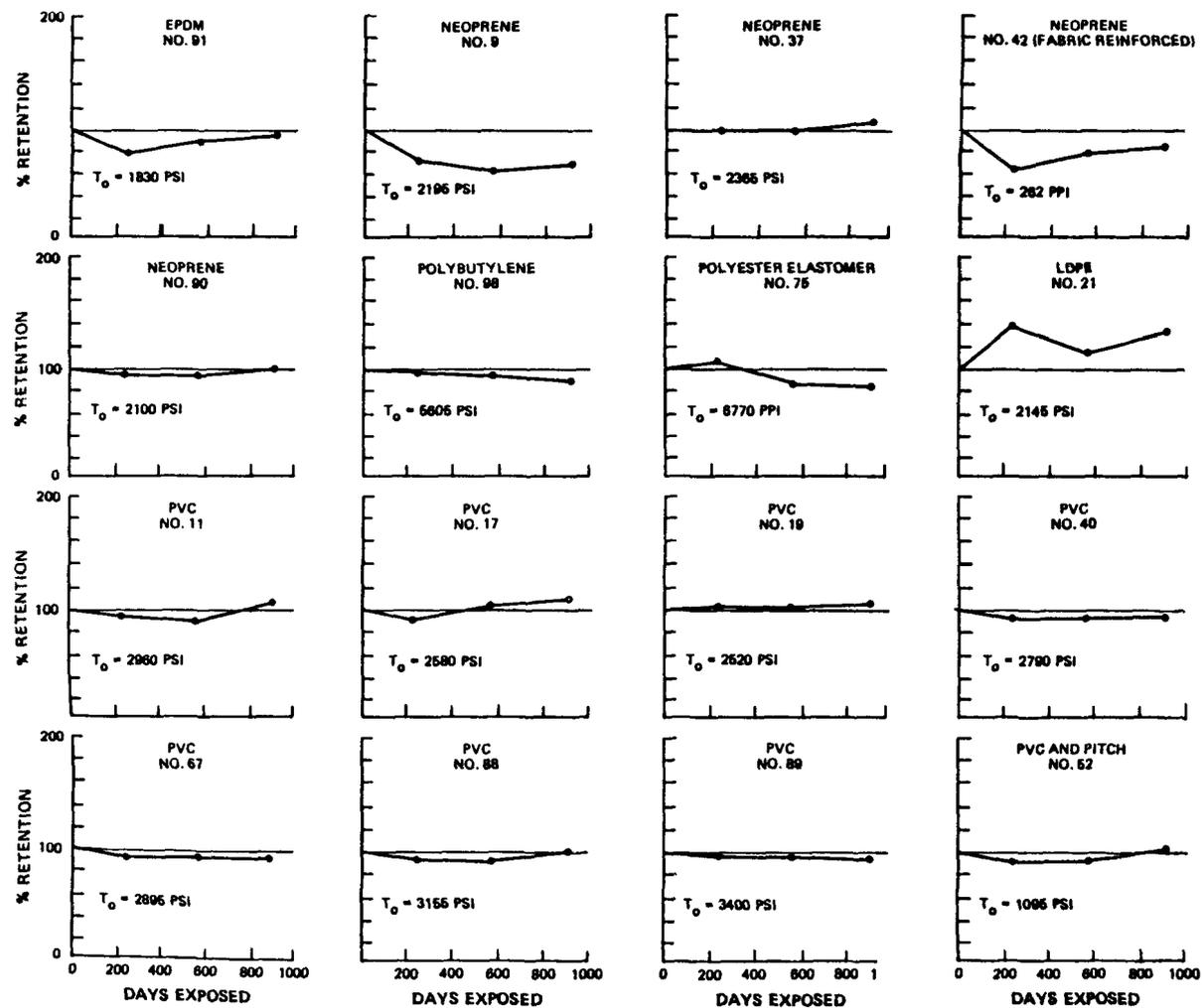


Figure 5-30. Retention of FML tensile strength as a function of immersion time in MSW leachate--EPDM, neoprene, PB, PEL, LDPE, PVC, and PVC-pitch FMLs. Tensile strength values are average values for machine and transverse directions; initial tensile strength for each FML is shown. Data are given for 8, 19, and 31 months. (Source: Haxo et al, 1982, p 85).

TABLE 5-40. RETENTION OF MODULUS^a OF POLYMERIC FMLS
ON IMMERSION IN MSW LEACHATE

Polymer	FML number ^b	S-200 of unexposed FML, psi	Retention of original value after exposure, %		
			8 mo.	19 mo.	31 mo.
Butyl rubber	44	685	86	90	98
Chlorinated polyethylene	12	1330	85	89	95
	38	1205	89	90	104
	86	810	98	106	133
Chlorosulfonated polyethylene	3	735	54	46	57
	6R	40.0 ^c	116	136	...
	85	1770	77	108	130
Elasticized polyolefin	36	1020	99	103	107
Ethylene propylene rubber	8	655	134	131	134
	18	755	111	109	117
	41	1040	100	99	105
	83R	35.8 ^c	98	98	104
	91	855	91	92	98
Neoprene	9	1235	79	77	76
	37	1635	100	100	99
	90	1340	93	101	115
Polybutylene	98	3120	101	101	106
Polyester elastomer	75	2735	102	98	100
Polyethylene	21	1260	106	102	106
Polyvinyl chloride	11	2125	87	85	98
	17	1965	80	84	94
	19	1740	89	94	112
	40	1720	91	91	104
	67	1705	92	105	117
	88	2400	79	88	101
	89	2455	96	95	105
Polyvinyl chloride + pitch ^d	52	1020	85	86	...

^aAverage of stress at 200% elongation (S-200) measured in machine and transverse directions.

^bR indicates that the FML is fabric-reinforced.

^cReported value is in ppi.

^dStress at 100% elongation value given; original and subsequent exposed specimens failed at less than 200% elongation.

Source: Haxo et al, 1982, p 86.

TABLE 5-41. WASTES AND TEST LIQUIDS IN IMMERSION TESTS

Type	Name	Matrecon waste number	pH	Electrical conductivity, $\mu\text{mho/cm}$
<u>Waste liquids^a</u>				
Acidic waste	"HNO ₃ -HF-HOAc"	W-9	1.1	155,000
	"HFL"	W-10	3.3	29,000
Alkaline waste	"Slop Water"	W-4	13.1	129,000
	"Spent Caustic"	W-2	11.3	155,000
Industrial waste	"Basin F" water	W-16	7.4	77,000
Lead waste	Lead waste blend	W-14	...	...
Oily waste	"Oil Pond 104"	W-5	...	...
	"Weed Oil"	W-7	...	...
	"Slurry Oil"	W-15	...	...
Pesticide waste	"Weed Killer" waste	W-11	3.1	3,200
<u>Test liquids</u>				
NaCl solution	5% brine	W-19	...	62,000
Deionized water	...	W-18	...	...
Trace organic	Saturated TBP ^b	W-20	...	...

^aFor detailed information on the waste liquids see Haxo et al, 1985b. Analyses of the wastes are summarized in Appendix J.

^bSaturated solution of tributyl phosphate (TBP) in DI water.

Prewighed and premeasured slabs, measuring ca 8 x 6 in. each, were immersed in the tanks of the one-sided exposure test cells (see Figure 5-15). Two slabs were immersed for each type of FML in each of the wastes so that testing could be performed after a short exposure (67 to 522 days) and a longer exposure (751 to 1456 days).

At the end of exposure, the immersed slabs were tested for changes in the following properties:

- Thickness.

- Dimensions.
- Weight.
- Volatiles.
- Extractables.
- Tensile properties.
- Modulus of elasticity (if FML was a semicrystalline thermoplastic).
- Tear resistance (if FML was unreinforced).
- Puncture resistance.
- Hardness.

Limited results from testing the exposed slabs are presented in Tables 5-42 through 5-44. Table 5-42 shows the number of days that each particular slab was immersed, Table 5-43, the changes in weight, and Table 5-44, the retention of stress at 100% elongation. Tensile testing of the unreinforced FMLs was performed in accordance with ASTM D412/D638 using a special dumbbell at a jaw separation rate of 20 ipm. This special dumbbell featured smaller tab ends, a shorter overall length, and a shorter narrowed section in comparison with the ASTM D412 Die C/ASTM D638 Type IV dumbbell. The testing of the semicrystalline FMLs after the second exposure period was performed at a jaw separation rate of 2 ipm. On most of the fabric-reinforced FMLs testing was performed in accordance with ASTM D751, Method B, using 1-in. wide strips and a 2-in. gage length.

The results of some of the immersion tests are discussed below by polymer type.

5.4.2.2.1 Chlorinated polyethylene (CPE)--Two types of CPE FMLs were immersed. One (No. 77) was an unreinforced thermoplastic FML, and the second (No. 100) was a crosslinked CPE. Liner 100 was added to assess the effect of crosslinking on the interaction of CPE with wastes.

Except for a small loss in weight of the crosslinked CPE specimens immersed in the alkaline "Slop Water" waste and in brine (5% NaCl), all of the CPE specimens increased in weight. Much of this increase in weight was through the absorption of water.

A major difference between the thermoplastic and crosslinked CPE FMLs was apparent in the dimensional changes that took place during immersion. The crosslinked CPE (No. 100) increased in dimensions approximately equally in the machine and the transverse directions whereas the thermoplastic CPE (No. 77) increased more in the transverse direction and in some cases simultaneously shrank in the machine direction and expanded in the transverse direction.

TABLE 5-42. EXPOSURE OF FML SPECIMENS IN IMMERSION TEST TO VARIOUS HAZARDOUS WASTES - NUMBER OF DAYS OF IMMERSION

Polymeric FML Polymer		Wastes ^a												
		Acidic		Alkaline		Brine	Indus- trial	"Lead Waste" ^b	Oily			Organic trace	Pest- icide	Water
		"HFL" (W-10)	"HNO ₃ - HF- HOAc" (W-9)	"Slop Water" (W-4)	"Spent Caustic" (W-2)	5% NaCl (W-19)	"Basin F" (W-16)		"Slurry Oil" (W-15)	"Oil Pond 104" (W-5)	"Weed Oil" (W-7)	Sat'd ^c TBP (W-20)	"Weed Killer" (W-11)	Deio- nized (W-18)
Butyl rubber	44	250 761	193 751	193 823	236 780	174 1456	... 1196	238 786	257 761	248 752	252 809	522 1106	242 807	174 1434
Chlorinated polyethylene	77	250 761	193 751	193 823	236 780	174 1456	... 1196	238 786	257 761	248 752	252 ...	522 1112	242 807	174 1434
	100	99 931	267 1253	99 931	99 1258	49 1345	67 1288	97 1257	99 784	97 1252	99 1279	522 1112	97 1259	49 1323
Chlorosulfonated polyethylene	6R	250 761	193 751	193 823	238 780	174 1458	... 1195	236 786	257 761	248 752	252 809	522 1119	242 807	174 1458
	55	250 761	193 751	193 823	236 780	174 1456	... 1196	238 786	257 761	248 752	252 809	522 1119	242 807	174 1434
Elasticized poly- olefin	36	250 761	193 751	193 823	238 780	174 1456	... 1196	236 786	257 761	248 752	252 809	522 1090	242 807	174 1434
Ethylene propylene rubber	83R	250 761	193 751	193 823	236 780	174 1456	... 1196	238 786	257 761	248 752	252 809	522 1076	242 807	174 1456
	91	250 761	193 751	193 823	236 780	174 1456	... 1196	238 786	257 761	248 752	252 809	522 1076	242 807	174 1434
Neoprene	90	250 761	193 751	193 823	236 780	174 1456	... 1196	238 786	257 761	248 752	252 809	522 1106	242 807	174 1434
Polyester elastomer	75	250 761	193 751	193 ...	236 780	174 1456	... 1196	238 786	257 761	248 752	252 809	522 1035	242 807	174 1434
Polyethylene: High-density	105	99 934	99 1262	99 934	99 1267	93 1360	67 1287	97 1266	99 793	97 1260	99 1288	522 1070	97 1268	93 1360
Low-density	108	99 927	99 1255	99 927	99 1266	93 1360	67 1287	97 1259	99 786	97 1253	99 1287	522 1055	97 1267	93 1322
Polypropylene	106	99 927	99 1255	99 927	99 1260	51 1322	67 1287	97 1259	99 786	97 1253	99 1287	422 1090	97 1261	51 1322
Polyvinyl chloride	11	250 761	193 751	193 823	238 780	174 1456	... 1196	236 786	257 761	248 752	252 809	522 1035	242 807	174 1434
	59	250 761	193 751	193 823	236 780	174 1456	... 1196	238 786	257 761	248 752	252 809	522 1055	242 807	174 1434
	88	250 761	193 751	193 823	236 780	174 1456	... ...	238 786	257 761	248 752	252 809	522 ^d 1070 ^d	242 807	174 1434

^aMatrecon waste serial number shown below identification. Analyses of the wastes are summarized in Appendix J.

^bBlend of three waste streams.

^cSaturated solution of tributyl phosphate (TBP) in deionized water.

^dFML No. 89.

Source: Haxo et al 1985b, p 236.

TABLE 5-43. EXPOSURE OF FML SPECIMENS IN IMMERSION TEST TO VARIOUS HAZARDOUS WASTES - PERCENT INCREASE IN WEIGHT

Polymeric FML Polymer		Percent increase in weight of samples on immersion in different wastes ^a												
		Acidic		Alkaline		Brine 5% NaCl (W-19)	Indus- trial "Basin F" (W-16)	"Lead Waste" ^b (W-14)	Oily		Organic trace Sat'd ^c TBP (W-20)	Pest- icide "Weed Killer" (W-11)	Water Deion- ized (W-18)	
		"HFL" (W-10)	"HNO ₃ - HF- HOAc" (W-9)	"Stop Water" (W-4)	"Spent Caustic" (W-2)				"Slurry Oil" (W-15)	"Oil Pond 104" (W-5)				"Weed Oil" (W-7)
Butyl rubber	44	2.74 3.71	1.39 3.77	2.04 1.81	0.37 0.74	0.87 1.4	...	20.1 28.7	32.3 31.18	97.5 104	70.8 64.2	18.1 23.1	0.76 1.57	1.34 4.4
Chlorinated polyethylene	77	9.43 12.9	9.31 19.9	1.50 1.89	0.64 1.11	2.54 1.3	...	70.9 119	59.5 d	31.6 36.9	117 ...	117 121	9.62 12.7	5.66 12.4
	100	4.2 9.24	2.0 21.2	-0.5 1.83	0.7 0.2	0.85 -1.2	0.3 1.2	23.0 29.3	11.9 115	12.4 20.9	e 118	36.2 37.5	2.8 7.3	1.45 7.5
Chlorosulfonated polyethylene	6R	6.75 8.95	10.3 10.0	3.79 7.65	3.32 4.30	5.75 4.06	...	83.0 e	51.1 105	75.10 49.5	202 368	31.5 30.1	13.07 17.26	7.99 15.8
	55	5.41 7.74	7.46 10.9	3.84 5.66	2.17 3.28	5.06 5.6	...	69.6 116	53.2 111	58.5 55.0	211 348	38.3 31.7	12.3 15.7	7.73 18.9
Elasticized poly- olefin	36	0.25 1.05	2.68 7.57	17.3 20.7	0.54 0.56	0.09 0.3	...	18.2 17.0	21.8 29.4	33.5 28.9	44.2 38.1	7.9 9.7	0.00 0.49	-0.04 0.6
Ethylene propylene rubber	83R	3.06 3.05	2.64 4.20	2.71 3.98	1.34 1.59	2.19 1.0	...	23.0 e	15.8 24.8	35.4 19.8	73.4 26.5	6.8 9.8	3.71 4.51	2.62 3.3
	91	16.7 23.9	18.3 50.9	3.13 3.34	0.23 1.30	1.19 1.0	...	29.3 34.7	35.3 34.2	80.1 84.7	79.4 76.2	5.2 5.9	8.09 20.4	1.93 3.6
Neoprene	90	9.60 12.0	10.8 17.4	0.38 2.66	0.82 1.53	3.54 ...	...	45.6 59.1	60.7 142.6	25.8 26.3	94.8 89.3	49.4 41.1	8.54 11.4	7.10 11.4
Polyester elastomer	75	0.55 2.03	4.15 6.41	e e	0.64 1.29	-0.69 1.5	...	7.57 7.40	17.1 16.6	7.90 8.47	16.3 14.7	4.7 4.6	2.39 4.15	0.00 -0.4
Polyethylene: High-density	105	0.05 0.16	0.1 0.2	0.2 0.52	0.2 0.01	0.03 0.09	-0.3 0.1	5.0 4.5	4.4 8.0	3.3 6.6	6.4 7.3	0.33 0.5	0.5 0.2	0.03 0.6
		Low-density	108	-3.3 0.08	-0.3 0.3	3.5 1.07	0.1 0.1	0.07 0.09	1.1 0.2	3.1 5.3	8.5 12.0	8.4 10.3	10.7 14.0	0.44 0.5	0.2 0.2	0.03 0.2
Polypropylene	106	0.05 -0.02	0.1 -0.01	0.1 0.08	0.2 0.1	-0.11 -0.05	0.7 0.5	6.9 5.9	0.4 1.4	0.6 6.8	1.4 9.1	0.33 -1.3	0.07 -0.1	-0.01 0.00
Polyvinyl chloride	11	10.2 18.1	16.8 22.1	-13.5 -11.1	0.09 0.43	-4.81 -6.2	...	4.36 -1.54	10.7 18.5	-7.65 -10.4	10.0 14.3	57.7 52.8	4.03 5.13	0.21 -1.6
	59	2.76 0.86	-2.82 -6.12	-6.35 -15.7	-3.00 -0.89	-4.82 -7.8	...	8.81 7.39	11.3 28.9	-1.54 -0.54	33.4 24.7	39.7 40.7	0.46 0.95	1.18 -0.5
	88	7.60 14.3	19.8 28.2	-13.5 -12.1	0.04 1.08	-1.51 -1.8	...	2.22 -5.15	7.2 14.1	-10.3 -9.9	18.1 25.2	47.6 ^f 47.5 ^f	2.89 1.62	0.65 -0.1

^aMatrecon waste serial number shown below identification. Analyses of wastes are summarized in Appendix J. Immersion times for the respective data are presented in Table 5-42.

^bBlend of three waste streams.

^cSaturated solution of tributyl phosphate (TBP) in deionized water.

^dNot measured because immersed specimen had become very "goopy" and seemed partially dissolved.

^eNot measured.

^fFML No. 89.

Source: Haxo et al, 1985b, p 238.

TABLE 5-44. EXPOSURE OF FML SPECIMENS IN IMMERSION TEST TO VARIOUS HAZARDOUS WASTES - RETENTION OF STRESS AT 100% ELONGATION

Polymeric FML Polymer		Original value ^b , psi	Retention of original property on immersion in different wastes ^a , %											Water Deion- ized (W-18)	
			Acidic		Alkaline		Brine 5% NaCl (W-19)	Indus- trial "Basin F" (W-16)	"Lead Waste" ^c (W-14)	Oily			Organic trace "Sat'd" ^d TBP (W-20)		Pest- icide "Weed Killer" ^e (W-11)
			"HFL" (W-10)	"HNO ₃ - HF- HOAc" (W-9)	"Stop Water" (W-4)	"Spent Caustic" (W-2)				"Slurry Oil" (W-15)	"Oil Pond 104" (W-5)	"Weed Oil" (W-7)			
Butyl rubber	44	308	84 93	70 88	85 89	81 91	103 89	...	59 76	66 57	44 45	36-47 ^e 38	79 60	78 89	90 89
Chlorinated polyethylene	77	900	98 117	92 129	113 130	115 126	124 152	...	37 18	44 f	44 48	8 ...	6 9	102 103	129 123
	100	618	93 79	96 45	96 110	88 119	91 121	103 85	67 44	74 49	62 77	24 28	48 55	76 136	125 108
Chlorosulfonated polyethylene	6R	938	98 126	81 68	149 180	150 171	115 g	...	98 89	90 73	49 88	7-46 ^e f	g g	109 124	142 g
	55	880	91 110	100 71	119 169	130 164	104 134	...	79 91	95 85	58 85	34 f	80 106	102 120	143 106
Elasticized polyolefin	36	923	97 105	99 93	82 93	95 109	102 114	...	80 76	70 72	62 75	55-59 ^e 54	71 87	108 116	123 104
Ethylene propylene rubber	83R	760	92 116	107 88	69 63	90 107	104 g	...	60 47	63 61	38 57	28 f	g g	98 100	118 9
	91	338	86 100	75 58	88 107	93 100	85 99	...	83 73	65 60	66 58	59-64 ^e 67	82 89	85 89	109 93
Neoprene	90	558	82 104	83 62	96 115	97 121	106 144	...	50 93	58 38	46 70	25-26 ^e 27	37 38	84 109	126 109
Polyester elastomer	75	2585	98 117	80 h	90 g	94 104	109 114	...	91 103	79 91	82 75	68-69 ^e 77	90 90	99 110	117 105
Polyethylene: High-density	105	2510 2583j	101 89 ^l	103 79 ^l	h 90 ^l	101 95 ^l	h 104 ^l	h 83 ^l	100 82 ^l	99 86 ^l	102 88 ^l	98 83 ^l	92 ^l 89 ^l	100 83 ^l	h 98 ^l
Low-density	108	1320 1210j	97 101 ^l	99 105 ^l	97 98 ^l	100 99 ^l	104 103 ^l	100 102 ^l	95 93 ^l	91 100 ^l	92 90 ^l	88 89 ^l	104 ^l 103 ^l	94 100 ^l	111 105 ^l
Polypropylene	106	k 3038j	k 101 ^l	k 98 ^l	k 98 ^l	k 106 ^l	k 105 ^l	k 102 ^l	k 95 ^l	k 108 ^l	k 100 ^l	k 97 ^l	109 ^l 107 ^l	k 99 ^l	k 108 ^l
Polyvinyl chloride	11	1420	83 95	84 93	196 206	103 110	116 139	...	82 95	89 91	168 186	48-70 ^e 46	15 18	99 106	111 108
	59	995	99 124	199 252	161 239	103 123	136 185	...	89 106	114 87	118 145	32-35 ^e 45	27 28	118 130	113 116
	88	1735	70 83	68 70	183 m	86 99	96 125	...	83 95	99 122	145 172	37-41 ^e 45	23 ^l 25 ^l	83 99	100 104

^aMatrecon waste serial number shown below identification. Analyses of wastes are summarized in Appendix J. Immersion times for the respective data are given in Table 5-42.
^bAverage of values in machine and transverse directions of specimens tested in accordance with ASTM D412 or D638 at 20 in. per minute unless otherwise noted.
^cBlend of three waste streams.
^dSaturated solution of tributyl phosphate (TBP) in deionized water.
^eWaste stratified into an aqueous and an oily phase. Reported value ranges indicate the different effects of the two phases.
^fNot measured because of condition of immersed specimen.
^gNot measured.
^hImmersion sample failed at less than 100% elongation.
ⁱRetention of values obtained for specimens tested at 2 in. per minute.
^jAverage of values in machine and transverse directions of specimens tested at 2 in. per minute.
^kUnexposed material failed at less than 100% elongation when tested at 20 in. per minute.
^lFML No. 89. Original value = 1688 psi.
^mTransverse direction failed at 80% elongation.
 Source: Haxo et al, 1985b, p 241.

As was anticipated, the crosslinked CPE increased less in weight on immersion in the wastes than did the thermoplastic uncrosslinked FML. However, the effects of swelling did not necessarily carry over into the physical properties (Table 5-44). In the case of the samples immersed in the nonoily wastes, both the crosslinked and the thermoplastic sheetings tended to increase in modulus (stress at 100% elongation), i.e. to stiffen, with the exception of the crosslinked CPE immersed in the acidic wastes. The thermoplastic CPE tended to stiffen more than the crosslinked CPE. Of the samples immersed in the oily wastes, even though both FMLs lost in modulus, the retention of S-100 was significantly less for the thermoplastic CPE than for the crosslinked. The thermoplastic CPE lost severely on exposure to the "Slurry Oil" waste, the lead waste, the "Weed Oil" waste, and the trace organic solution. The "Weed Oil" waste appeared to have completely dissolved the thermoplastic CPE specimen. The retention of elongation at break was generally less than 100% and was about equal for the thermoplastic and crosslinked compounds.

The thermoplastic FML (CPE 77) increased significantly in weight in the saturated TBP solution. This increase in weight is the net of the water and TBP that were absorbed minus the plasticizer in the original compound that might have been lost to the solution. To determine how much of the original plasticizer migrated into the solution, the extractables obtained after the the volatiles were removed from the sample were analyzed for total TBP content. The amount of plasticizer remaining in the exposed FML was calculated. Table 5-45 presents the results, which indicate that most of the plasticizer (i.e. the extractables) in the original compound had remained in the FML.

5.4.2.2.2 Chlorosulfonated polyethylene (CSPE)--Both of the CSPE FMLs tested in immersion were "potable" grade CSPE compounds. Overall, the two FMLs responded very similarly to the wastes, even though one was fabric reinforced and the other was not. All of the immersed specimens swelled and increased in weight. The samples immersed in the oily wastes increased the most. These increases ranged from 30% to more than 350%. In the predominantly aqueous wastes, the weight increases and the amount of water absorbed as indicated by the volatiles were less significant. Furthermore, the weight increases of the samples immersed in deionized water were greater than those immersed in wastes and liquids containing high salt concentrations, e.g. the "Spent Caustic" waste. The extractables increased only among those specimens immersed in the oily wastes, indicating absorption of these wastes. The specimens immersed in aqueous wastes had approximately the same extractables as the unexposed sheeting. This indicates that the loss of plasticizer to the waste was low.

The "Weed Oil" waste was by far the most aggressive toward the CSPE FMLs resulting in significant losses in modulus (Table 5-44). Losses in modulus were much less in the other oils and not to the extent that might be anticipated from the swelling. These CSPE FMLs appear to have crosslinked during the immersion.

TABLE 5-45. ANALYSES OF CPE AND PVC FMLS
EXPOSED IN SATURATED TBP^a SOLUTION

Parameter	CPE	PVC
Matrecon FML number	77	59
Extractables of unexposed liner, % by weight of the original liner	9.13	35.9,37.4
Exposure time, days	1112	1055
Extractables after exposure, % exposed FML (db ^c):		
TBP ^a , % exposed FML (db ^c)	26.1	51.7
TBP ^a , % exposed FML (db ^c)	19.8	23.3
Extractables, non-TBP, % exposed FML (db ^c)	6.3	28.4
Calculated extractables remaining in original compound after exposure ^d , %	7.9	37.0

^aTributyl phosphate.

^bAnalyses of extract by gas chromatography.

^cdb = dry basis, i.e. devolatilized basis.

^dNon-TBP extractables divided by sum of non-extracted FML and non-TBP extractables.

Source: Haxo et al, 1985b, p 152.

With respect to the nonoily wastes, exposure resulted in increases in weight ranging from approximately 2.2 to 20%, major increases in modulus and in some cases decreases in elongation at break, such as in the "Slop Water" waste. The changes in modulus and elongation at break reflect the crosslinking reaction that took place during the immersion.

5.4.2.2.3 Ethylene propylene rubber (EPDM)--One of the EPDMs was a crosslinked FML (EPDM 91), and the second was a fabric-reinforced (8 x 8, polyester) thermoplastic FML (EPDM 83R). The response of these FMLs to the wastes and test liquids was generally different though in some, e.g. in deionized water, the two responded similarly.

Contrary to what would normally be expected, the thermoplastic EPDM (No. 83R) absorbed less waste and retained its properties better than the crosslinked EPDM (No. 91). Even in the case of the oily wastes, the absorption was generally less.

In the case of the nonoily wastes, the crosslinked EPDM increased significantly more in weight in the acidic wastes and in the "Weed Killer" waste. This appears to reflect the sensitivity to moisture on the part of this FML.

The volatiles contents determined after immersion indicated that, in most cases, the weight increases were due to water absorption, particularly in the crosslinked specimens immersed in the acidic wastes. The extractables data indicated that little if any of the plasticizer in the original compounds was lost to the wastes. The only specimens that increased in extractables were those that had been immersed in the oily wastes.

The effects of the immersion on stress at 100% elongation generally reflected the amount of weight increase, particularly for those specimens immersed in the oily wastes and the crosslinked EPDM immersed in the "HNO₃-HF-HOAc" acidic waste.

The effects of the immersion on elongation at ultimate break were highly variable with retentions varying from 47 to 154%. The elongation of the thermoplastic, fabric-reinforced sheeting increased in all cases, whereas most of the crosslinked specimens immersed in the oily wastes lost in elongation.

5.4.2.2.4 Polyester elastomer (PEL)--An experimental PEL (No. 75) was tested. The specimens increased in weight on immersion in all but possibly two of the wastes. These losses were minor and may have been within experimental error. The PEL specimens gained weight principally in the hydrocarbon oily wastes; the gain in weight in the solution containing tributyl phosphate was not as great. The specimens immersed in the acidic "HNO₃-HF-HOAc" waste gained weight significantly; in addition, they lost severely in elongation as had the same sheeting in the one-sided exposure cells. This deterioration was the result of the hydrolysis of the polyester polymer. The retention in stress at 100% elongation of the PEL film tended to decrease with an increase in weight. Except for the loss in elongation in the acidic waste, which was drastic, the retention of elongation was good.

5.4.2.2.5 Polyethylene (PE)--Neither the HDPE nor the LDPE sheetings immersed in this study were marketed as FMLs, and both were nonpigmented. Both sheetings exhibited comparatively low values for weight increases in all wastes. However, as with the other polymeric FMLs, the weight increases, though low, were the greatest in the specimens exposed in the oily hydrocarbon wastes. The LDPE increased in weight more than the HDPE in these wastes. The saturated TBP solution caused only a slight increase in weight. The weight increases in all the other wastes were less than 0.6% except for the LDPE exposed to the "Slop Water" waste.

Note: As indicated above, the sample of HDPE (No. 105) investigated in the immersion test was not marketed as an FML, nor was the grade of HDPE used in that sheeting known to have been used in the manufacture of FMLs. We later

found by differential scanning calorimetry that it was considerably more crystalline than grades of polyethylenes used in lining materials, had a higher density, and a considerably higher modulus of elasticity than the modulus of the HDPE used in FMLs that are now available. We also found that the HDPE (No. 105) showed indications of inadequate resistance to environmental stress-cracking compared with the HDPE currently used in FMLs. In a stress-cracking test, the HDPE sheeting (No. 105) was tested in accordance with ASTM D1693 but at a thickness of 30 mils, which is below the required thickness for this test. It sustained some early breaks (216 h) at 100°C, whereas currently-available HDPE FMLs tested at thicknesses of 80 and 100 mils did not fail in 1,000 hours at 100°C. At the present state of knowledge of HDPE FML performance, specific correlations between environmental stress-cracking resistance under different conditions and field service of FMLs have not been established.

5.4.2.2.6 Polyvinyl chloride (PVC)--Three different PVC FMLs (Numbers 11, 59, and 88) were immersed, representing PVC FMLs from three different suppliers.

These three PVC FMLs differed considerably among themselves and in their responses to the different wastes. The changes in weight during immersion ranged from significant loss, i.e. 15.7%, to substantial gains, i.e. 57.7%, depending on the waste liquid and the immersion time. All three sheetings lost weight in the "Slop Water," the brine, and "Oil Pond 104" waste. In water they all initially increased in weight and then lost weight. In other wastes, some gained and others lost weight. All increased in volatiles content which reflects the absorption of water from the wastes. Analysis of the extractables after removal of the volatile constituents indicated that in several cases there was substantial loss in the original plasticizer, such as was the case with the specimens immersed in the "Slop Water." In some cases, the extractables content increased due to the absorption of nonvolatile organics, e.g. hydrocarbon oils. Analysis of the extractables of the sample of PVC 59 immersed in the saturated TBP solution and which had increased significantly in weight showed that the original plasticizer had not been extracted by the immersion.

The effects on the dimensions of the immersed specimen varied greatly but generally correlated with the weight changes, i.e. if the specimen increased in weight, the dimensions increased, and if the specimen lost weight, it decreased in length and width. In the case of shrinkage, a confined FML would come under tension, possibly causing a hole which could become larger with increased shrinkage.

The effects on tensile properties appeared to correlate negatively with the weight changes. Those specimens that lost weight all became stiffer as is shown by the retention of stress at 100% elongation (Table 5-44); those that increased in weight generally became softer. The effects of weight loss

also showed up in the retention of elongation for those FMLs which lost a substantial amount of plasticizer and which not only became stiff, but lost in elongation at break.

Overall, the PVC FMLs varied considerably in their response to different wastes. Certain wastes, such as the highly alkaline wastes, were particularly aggressive toward the PVC; certain oils can cause loss of plasticizer and excessive stiffening and loss of elongation. Concurrent with these losses, a PVC FML can shrink and develop tension in the sheets.

5.4.2.3 Immersion in Test Liquids--

Immersion of samples of FMLs in test liquids of known composition can be used to make a preliminary test of the compatibility of an FML and a waste liquid that contains the constituents of the test liquid. This type of immersion test has also been used to determine the solubility parameters of FMLs and to develop criteria for assessing the chemical compatibility of FMLs. Nevertheless, in terms of FML-waste compatibility, the results of such tests are limited because of lack of knowledge about the interaction between a combination of liquids and an FML.

In the following subsections, data resulting from immersion tests with liquids of known compositions are presented.

5.4.2.3.1 Equilibrium swelling of FMLs and FML-related compositions in test liquids--As part of a study to determine the solubility parameters of FMLs, Haxo et al (1988) determined the equilibrium "volume" swelling of 28 FML-related polymeric compositions in 30 organics and DI water. These 28 polymeric materials included thermoplastic, crosslinked, and semicrystalline compositions of which 22 were commercial FMLs or sheetings and six were laboratory-prepared compositions. This group of 28 compositions included variations in polymers and compounds, including differences in polymer type, level of crystallinity, crosslink density, filler level, and amount and type of plasticizer. The results of determining the solubility parameters are presented in Section 4.2.2.4.3. The polymer compositions used in the swelling tests are listed in Table 5-46. Detailed data on the composition and properties of the materials used in this study are presented in Appendix F. The 30 organics which were used in the study and which are listed in Table 5-47, represent a wide range of solubility parameters, as is shown in Table 5-48.

To determine the equilibrium swelling of each polymeric material in the test liquids, the weight of an immersed sample was monitored until a maximum value (i.e. equilibrium) was reached. A sample consisted of three FML specimens, which were placed in a 20 mL disposable scintillation vial for each combination. The inside of the vial cap was lined with Teflon-coated aluminum foil to prevent the loss of organics. The 20 mL vial was satisfactory for most combinations of polymeric compositions and organics; however, for those combinations in which excessive swelling took place, the specimens were transferred to 70 mL vials. In all vials, the specimens were hung so they did not touch each other.

TABLE 5-46. POLYMERIC COMPOSITIONS IN SWELLING TESTS TO DETERMINE EQUILIBRIUM SWELLING

Polymer	Matrecon identification number ^a	Type of polymer ^b	Property		
			Extractables, %	Extraction organic ^c	Specific gravity
Chlorinated polyethylene	195	TP/AM	14.85	n-heptane	1.260
	335R	TP/AM	4.48	n-heptane	1.313
	378R	TP/AM	7.94	n-heptane	1.333
Chlorosulfonated polyethylene	169R	TP/AM	11.29	acetone	1.297
	174R	TP/AM	7.15	acetone	1.364
	DOY-3 ^d	TP/AM	<1.0 ^e	...	1.147
	DOZ-2 ^d	TP/AM	<1.0 ^e	...	1.401
	DPO ^d	TP/AM	<1.0 ^e	...	1.193
	DPP ^d	TP/AM	<1.0 ^e	...	1.143
Epichlorohydrin rubber	178	XL/AM	7.63	MEK	1.458
Ethylene propylene rubber	232	XL/AM	22.78	MEK	1.166
Ethylene vinyl acetate	308A	TP/AM	0.75	ethanol	0.951
Neoprene	168	XL/AM	11.23	acetone	1.500
Nitrile rubber	DPN ^d	XL/AM	<1.0 ^e	...	1.024
Polyester elastomer	316	TP/CX/AM	1.09	n-heptane	1.149
	323	TP/CX/AM	≤0.6	n-heptane	1.253
Polybutylene	221A	CX	3.68	MEK	0.907
Polyethylene: Low-density Linear low-density High-density	309A	CX	1.85	MEK	0.938
	284	CX	0.65	MEK	0.929
	184	CX	0.73	MEK	0.951
	263	CX	≤0.6	MEK	0.953
	305	CX	0.98	MEK	0.954
HDPE/EPDM-alloy	181	CX	2.09	MEK	0.949
Polyurethane	351	TP/AM	1.50	n-heptane	1.118
Polyvinyl chloride	153	TP/AM	34.57	2:1 CCl ₄ : CH ₃ OH ^f	1.263
	DPQC ^c	TP/AM	40.12	2:1 CCl ₄ : CH ₃ OH ^f	1.226
Elasticized polyvinyl chloride	176R	TP/AM	9.13	CH ₃ OH	1.219
Polyvinyl chloride, oil-resistant	144	TP/AM	30.97	2:1 CCl ₄ : CH ₃ OH ^f	1.356

^aR = fabric reinforced.

^bTP = thermoplastic; AM = amorphous; XL = crosslinked; CX = semicrystalline.

^cMEK = Methyl ethyl ketone.

^dLaboratory-prepared compound (see Appendix F, Tables F-11 and F-12).

^eCalculated from compound formulation.

^fBy volume.

Source: Haxo et al, 1988, p 26.

TABLE 5-47. ORGANICS USED IN THE EQUILIBRIUM SWELLING TESTS BY TYPE OR CLASS

Class of organic	Specific organic
Alkanes	n-Octane Isooctane Cyclohexane
Aromatic hydrocarbons	Xylenes (mixture of o-, m-, and p-) Tetrahydronaphthalene "Tetralin®"
Alcohols	Methanol 2-Ethyl-1-hexanol n-Propanol Cyclohexanol Benzyl alcohol Furfuryl alcohol Ethylene glycol
Chlorinated hydrocarbons	Tetrachloroethylene Trichloroethylene
Esters	Di(ethylhexyl) phthalate Diethyl phthalate Isoamyl acetate Ethyl acetate Diethyl carbonate Butyrolactone Propylene carbonate
Ketones	Acetone Methyl ethyl ketone Cyclohexanone Methyl isobutyl ketone
Nitrogen compounds	Nitroethane N,N-Dimethylacetamide Quinoline 2-Pyrrolidone
Phenols	m-Cresol

Source: Haxo et al, 1988, p 24.

TABLE 5-48. PROPERTIES OF THE ORGANICS USED IN FML EQUILIBRIUM SWELLING AND SOLUBILITY PARAMETER STUDY

Name	δ^a , cal ^{1/2} cm ^{-3/2}				Organic, no., and code ^b				Property			
					No.	R _d	R _p	R _h	MPC, °C	BPC, °C	Density ^c , g/cm ³	Solubility in water ^d at 25°C, mg/L
	o	d	p	h								
n-Octane	7.6	7.6	0	0	1	1	1	1	-57	125	0.703	0.66
Isoamyl acetate	8.4	7.5	1.5	3.4	2	1	1	2	-78	142	0.876	20,000
2-Ethyl-1-hexanol	9.9	7.8	1.6	5.8	3	1	1	3	-76	183	0.833	700 (20°C)
Methyl isobutyl ketone	8.3	7.5	3.0	2.0	4	1	2	1	-80	114	0.801	17,000
Ethyl acetate	8.9	7.7	2.6	3.5	5	1	2	2	-84	77	0.902	80,800
n-Propanol	12.0	7.8	3.3	8.5	6	1	2	3	-127	97	0.804	Miscible
Nitroethane	11.1	7.8	7.6	2.2	7	1	3	1	-90	112	1.045	46,800
Methyl ethyl ketone	9.3	7.8	4.4	2.5	8	1	3	2	-87	80	0.805	240,000
Methanol	14.5	7.4	6.0	10.9	9	1	3	3	-98	65	0.791	Miscible
Cyclohexane	8.2	8.2	0.0	0.1	10	2	1	1	6.5	81	0.779	55
Diethyl carbonate	8.8	8.1	1.5	3.0	11	2	1	2	-43	126	0.975	Insoluble
Cyclohexanol	10.9	8.5	2.0	6.6	12	2	1	3	22	160	0.963	37,500 (26.5°C)
Di(ethylhexyl) phthalate	8.9	8.1	3.4	1.5	13	2	2	1	-50	384	0.981	0.4 ^e
Cyclohexanone	9.6	8.7	3.1	2.5	14	2	2	2	-47	155	0.947	23,000
Furfuryl alcohol	11.9	8.5	3.7	7.4	15	2	2	3	-29	170	1.135	Miscible
Diethyl phthalate	10.0	8.6	4.7	2.2	16	2	3	1	-3	298	1.118	0.09 ^e
N,N-Dimethylacetamide	11.1	8.2	5.6	5.0	17	2	3	2	-20	165	0.937	Miscible
Ethylene glycol	16.1	8.3	5.4	12.7	18	2	3	3	-13	196	1.113	Miscible
Tetralin	9.8	9.6	1.0	1.4	19	3	1	1	-35	207	0.973	Insoluble
Trichloroethylene	9.3	8.8	1.5	2.6	20	3	1	2	-87	87	1.462	1,100
m-Cresol	11.1	8.8	2.5	6.3	21	3	1	3	10	203	1.034	25,100 (40°C)
Tetrachloroethylene	9.9	9.3	3.2	1.4	22	3	2	1	-22	121	1.623	2,870 (20°C)
Quinoline	10.8	9.5	3.4	3.7	23	3	2	2	-15	237	1.095	6,090 (20°C)
Benzyl alcohol	11.6	9.0	3.1	6.7	24	3	2	3	-15	205	1.045	800 (20°C)
Propylene carbonate	13.3	9.8	8.8	2.0	25	3	3	1	-55	240	1.189	Moderate
Butyrolactone	12.9	9.3	8.1	3.6	26	3	3	2	-45	204	1.12	Miscible
2-Pyrrolidone	13.9	9.5	8.5	5.5	27	3	3	3	25	245	1.12	Miscible
Water	23.4	7.6	7.8	20.7	28	1	3	3	0	100	1.00	...
Isooctane	7.0	7.0	0	0	29	1	1	1	-107	99	0.692	2.4
Xylenes (o, m, and p)	8.8	8.7	0.5	1.5	30	2	1	1	-48-+13	138-144	0.868	190
Acetone	9.8	7.6	5.1	3.4	31	1	3	2	-95	56	0.791	Miscible

^aBarton (1975). δ_o = Hildebrand solubility parameter; δ_d = dispersive solubility parameter; δ_p = polarity solubility parameter; and δ_h = hydrogen-bonding solubility parameter.

^bEach code was made up of three digits representing the range values assigned to an organic after the ordering of organics by each component solubility parameter as presented in Section 5. R_d is the range value for the dispersive solubility parameter; R_p the range value for the polarity solubility parameter; and R_h the range value for the hydrogen-bonding solubility parameter. Each selected test organic was assigned a unique number.

^cLange (1967); MP is the melting point and BP is the boiling point of the organic.

^dRiddick and Bunger (1970).

^eEPA (1982).

The specimens, which measured 0.5 x 1.5 in., were cut from slabs or sheetings with a die used for cutting out ESC specimens (ASTM D1693). However, the specimens were treated as a unit, not individually, and were weighed as a set before and after immersion. Before immersion, the weight of the sets of specimens ranged from 0.5 to 5 g with most weighing under 2 grams.

The specimens were weighed before immersion and after 2 days, 1 week, and 2 weeks. Additional weighings were taken approximately once a week if the specimens had not reached equilibrium after the second week of exposure. Once equilibrium swelling had been reached, the equilibrium swelling based on volume was calculated from the equilibrium swelling based on change in weight. The volume increase was calculated by correcting for the density of the respective organics used to swell the FML specimens. No adjustment was made for the initial density of the specimen; neither was any adjustment made for loss of plasticizer or any other material that may have been extracted from the original specimens. Adjustment for loss of extracted components would have required extraction tests of specimens after they had been dried out.

Results of determining the equilibrium "volume" swelling of the polymeric specimens are presented in the following tables:

- Table 5-49. Equilibrium Volume Swelling of the CPE and CSPE Specimens Immersed in 30 Organics and in Water.
- Table 5-50. Equilibrium Volume Swelling of the ECO, EPDM, EVA, CR, Nitrile Rubber (NBR), PEL, and PB Specimens Immersed in 30 Organics and in Water.
- Table 5-51. Equilibrium Volume Swelling of the LDPE, LLDPE, HDPE, HDPE-A, PU, PVC, PVC-E, and PVC-OR Specimens Immersed in 30 Organics and in Water.

Crystallinity of the base polymer appears to be the dominant factor in reducing the swelling of an FML or an FML-related composition in all of the organics and to override both the solubility parameters and crosslinking. Among compositions based on amorphous polymers, the proximity of the component solubility parameters to those of the organics could be used in most cases to indicate the swelling and the probability of changes in properties. Nevertheless, empirically derived data are still necessary for untested combinations of organics and FMLs.

5.4.2.3.2 Immersion testing of FMLs to develop chemical compatibility requirements--As there were no established or accepted benchmarks for FML performance based on immersion tests, Bellen et al (1987) conducted a test program to generate data on the chemical resistance of commercial FMLs. It was anticipated that the data would be useful in assessing the results of compatibility tests, such as those performed in accordance with EPA Method

TABLE 5-49. EQUILIBRIUM VOLUME SWELLING OF THE CPE AND CSPE SPECIMENS^a IMMERSSED IN 30 ORGANICS AND IN WATER

Liquid	Hildebrand solubility parameter (°)	FML-polymer/ID number/extractables, %								
		CPE 195 14.85 ^b	CPE 335R 4.48	CPE 378R 7.94	CSPE 169R 11.29	CSPE 174R 7.15 ^c	CSPE DOY-3 <1.0 ^d	CSPE DOZ-2 <1.0 ^d	CSPE DPO <1.0 ^d	CSPE DPP <1.0 ^d
Isooctane (Ref. Fuel A)	7.0	4.24	10.1	5.83	1.50	8.71	22.8	11.5	17.8	21.1
n-Octane	7.6	6.08	12.5	6.40	1.77	12.9	31.7	14.5	24.3	28.2
Cyclohexane	8.2	26.6	51.0	16.8	119.5	99.7	137.4	D ^e	192.6	273.4
Methyl isobutyl ketone	8.3	D ^e	188.5	D ^e	38.4	40.8	95.5	63.8	93.1	118.6
Isoamyl acetate	8.4	D ^e	200.0	D ^e	42.1	45.4	105.5	89.3	102.9	135.8
o-Xylene	8.8	41.2	D ^e	53.0	577.2	153.2	291.5	D ^e	448.2	751.2
Diethyl carbonate	8.8	87.1	72.5	27.0	8.61	13.2	30.2	20.0	26.7	33.1
Dioctyl phthalate	8.9	361.9	218.1	141.7	32.0	29.2	73.7	52.4	65.1	100.4
Ethyl acetate	8.9	D ^e	137.5	107.4	10.7	16.5	36.5	24.8	32.3	39.6
Methyl ethyl ketone	9.3	D ^e	137.9	282.0	20.4	26.8	58.4	36.3	53.0	67.6
Trichloroethylene	9.3	D ^e	D ^e	62.7	435.0	D ^e	325.6	D ^e	508.9	820.8
Cyclohexanone	9.6	D ^e	251.3	121.4	139.4	101.5	190.1	205.9	240.8	359.0
Acetone	9.8	102.9	56.3	85.0	7.56	13.3	24.5	17.1	21.7	28.2
Tetralin	9.8	D ^e	D ^e	D ^e	353.5	180.9	279.5	D ^e	523.1	765.7
Tetrachloroethylene	9.9	122.6	D ^e	45.2	468.3	160.8	263.1	D ^e	446.1	718.4
2-ethyl-1-hexanol	9.9	4.57	3.96	8.58	1.52	3.12	3.30	1.46	2.35	3.45
Diethyl phthalate	10.0	191.4	125.2	72.7	9.57	14.0	21.4	15.8	18.5	24.2
Quinoline	10.8	D ^e	D ^e	D ^e	96.8	79.8	159.1	202.7	161.6	234.7
Cyclohexanol	10.9	2.13	2.96	7.91	2.40	5.65	9.24	1.78	3.01	4.46
N,N-dimethylacetamide	11.1	D ^e	17.3	62.0	17.8	20.9	51.5	30.1	33.2	38.6
m-Cresol	11.1	67.9	48.5	23.1	14.8	19.6	42.8	30.6	22.9	27.3
Nitroethane	11.1	58.8	38.2	38.5	3.97	7.64	15.3	11.9	11.7	14.4
Benzyl alcohol	11.6	35.2	27.4	9.56	6.87	8.79	37.3	11.4	8.22	9.95
Furfuryl alcohol	11.9	17.6	6.00	1.66	3.82	5.39	20.9	4.37	2.98	3.74
1-Propanol	12.0	2.13	5.42	9.12	2.03	3.13	13.9	2.25	2.01	3.30
Butyrolactone	12.9	93.8	46.9	90.2	4.38	7.31	11.9	8.85	7.66	10.2
Propylene-1,2-carbonate	13.3	23.0	9.08	13.6	1.37	5.63	1.24	1.25	1.94	2.72
2-Pyrrolidone	13.9	111.6	38.8	107.1	12.2	11.2	24.8	8.92	6.38	12.6
Methanol	14.5	3.56	9.27	3.91	7.61	4.58	49.9	8.90	9.54	15.4
Ethylene glycol	16.1	2.21	3.64	5.33	2.06	3.22	2.32	0.57	1.47	3.53
Water	23.4	3.99	6.14	8.91	6.50	4.44	15.4	3.00	6.02	5.33

^aCPE 195, CPE 335R, CPE 378R, CSPE 169R, and CSPE 174 are commercially manufactured FMLs; further data for these materials are presented in Appendix F, Table F-7. CSPE compounds labeled DOY-3, DOZ-2, DPO, and DPP are laboratory prepared compounds; information on these compounds is presented in Appendix F, Tables F-11 and F-12.

^bExtractables determined in accordance with Matrecon Test Method 2 (see Appendix E) using n-heptane as the solvent.

^cExtractables determined in accordance with Matrecon Test Method 2 (see Appendix E) using acetone as the solvent.

^dCalculated from compound formulation.

^eD = dissolved or disintegrated.

Source: Haxo et al, 1988, p 125.

TABLE 5-50. EQUILIBRIUM VOLUME SWELLING OF THE ECO, EPDM, EVA, CR, NITRILE RUBBER (NBR), PEL, AND PB SPECIMENS^a IMMERSSED IN 30 ORGANICS AND IN WATER

Liquid	Hildebrand solubility parameter (δ_0)	FML-polymer/ID number/extractables, %							
		ECO 178 7.63	EPDM 232 22.78	EVA 308A 0.75	CR 168 11.23 ^b	NBR DPN <1.0 ^c	PEL 316 1.09 ^d	PEL 323 ≤0.6	PB 221A 3.68
Isooctane (Ref. Fuel A)	7.0	0.53	68.6	28.3	0.96	9.84	7.25	0.86	25.0
n-Octane	7.6	0.98	86.8	34.1	0.61	10.9	8.27	2.88	26.3
Cyclohexane	8.2	6.35	125.9	97.4	30.8	30.7	19.0	4.46	61.6
Methyl isobutyl ketone	8.3	67.4	5.20	3.67	56.1	425.7	38.3	10.5	9.63
Isoamyl acetate	8.4	71.3	5.70	27.6	66.0	246.6	41.3	10.5	12.9
o-Xylene	8.8	64.3	103.1	125.6	109.0	256.9	105.5	17.1	28.9
Diethyl carbonate	8.8	66.6	5.08	15.5	25.9	199.0	40.3	11.0	6.44
Dioctyl phthalate	8.9	25.1	4.16	12.6	73.4	191.6	18.0	0.72	2.50
Ethyl acetate	8.9	87.6	4.96	17.8	33.7	317.1	44.3	11.6	7.30
Methyl ethyl ketone	9.3	88.7	8.33	18.8	39.4	496.8	52.3	12.9	6.53
Trichloroethylene	9.3	102.6	135.4	249.0	123.1	516.4	De	25.1	42.5
Cyclohexanone	9.6	121.4	3.00	28.4	111.9	701.2	123.5	15.8	9.56
Acetone	9.8	75.0	0.88	14.5	10.1	354.0	33.5	11.2	21.7
Tetralin	9.8	154.2	68.6	82.2	180.9	546.8	280.3	24.7	3.26
Tetrachloroethylene	9.9	22.4	146.0	181.8	105.4	90.0	70.9	14.5	17.5
2-ethyl-1-hexanol	9.9	5.01	4.83	15.2	5.27	36.1	16.7	1.51	1.46
Diethyl phthalate	10.0	97.5	0.50	6.28	33.9	475.8	38.0	3.22	0.80
Quinoline	10.8	127.0	4.92	26.2	97.7	672.1	274.0	21.6	5.22
Cyclohexanol	10.9	7.32	7.46	9.19	2.32	35.0	16.7	2.40	2.07
N,N-dimethylacetamide	11.1	127.0	3.93	7.32	60.3	611.5	60.7	16.5	1.97
m-Cresol	11.1	183.8	2.72	55.5	27.2	De	De	De	1.60
Nitroethane	11.1	99.5	0.70	9.33	3.08	439.2	56.1	13.7	2.47
Benzyl alcohol	11.6	123.4	0.38	11.4	13.2	473.7	194.3	17.1	0.85
Furfuryl alcohol	11.9	120.5	0.24	4.54	1.99	251.4	174.6	15.3	0.23
1-Propanol	12.0	4.97	6.40	7.41	3.84	26.9	14.8	7.28	1.15
Butyrolactone	12.9	108.9	0.00	2.69	3.11	362.5	22.5	9.73	0.52
Propylene-1,2-carbonate	13.3	80.3	0.80	1.06	0.11	131.2	8.30	3.30	0.95
2-Pyrrolidone	13.9	100.0	1.29	1.97	14.9	151.8	14.6	4.67	0.61
Methanol	14.5	13.7	1.59	5.89	12.7	19.5	14.7	4.72	0.98
Ethylene glycol	16.1	9.30	0.49	1.55	1.76	9.48	2.42	1.67	0.69
Water	23.4	23.6	1.18	0.66	6.55	9.15	2.62	2.13	1.53

^aNitrile rubber (NBR) compound labeled "DPN" is a laboratory-prepared compound; information on this compound is presented in Appendix F, Tables F-11 and F-12. All of the other materials are commercially manufactured FMLs; further data for these materials are presented in Appendix F, Tables F-7 and F-8.

^bExtractables determined in accordance with Matrecon Test Method 2 (see Appendix E) using n-heptane as the solvent.

^cExtractables determined in accordance with Matrecon Test Method 2 (see Appendix E) using acetone as the solvent.

^dCalculated from compound formulation.

^eD = dissolved or disintegrated.

Source: Haxo et al, 1988, p 126.

TABLE 5-51. EQUILIBRIUM VOLUME SWELLING OF THE LDPE, LLDPE, HDPE, HDPE-A, PU, PVC, PVC-E, AND PVC-OR SPECIMENS^a IMMERSED IN 30 ORGANICS AND IN WATER

Liquid	Hildebrand solubility parameter (o)	FML-polymer/ID number/extractables, %										
		LDPE 309A 185 ^a	LLDPE 284 0.65 ^b	HDPE 184 0.73 ^b	HDPE 263 ≤0.6 ^b	HDPE 305 0.98 ^b	HDPE-A 181 2.09 ^b	PU 351 1.50 ^c	PVC 153 34.57 ^d	PVC DPQ 40.12 ^d	PVC-E 176R 9.13 ^e	PVC-OR 144 30.97 ^d
Isooctane (Ref. Fuel A)	7.0	10.1	11.4	7.06	4.36	7.89	15.9	4.76	21.7	22.1	3.25	1.83
n-Octane	7.6	13.1	14.2	8.49	7.68	9.68	18.6	6.79	19.9	20.3	2.70	1.79
Cyclohexane	8.2	23.1	24.5	11.8	11.2	12.8	34.7	19.8	19.9	16.4	14.2	4.94
Methyl isobutyl ketone	8.3	3.67	4.49	3.62	2.27	4.23	4.36	95.8	Df	Df	Df	Df
Isoamyl acetate	8.4	6.52	6.18	4.24	2.75	6.34	7.72	63.4	245.4	Df	Df	230.6
o-Xylene	8.8	19.9	20.4	12.6	11.6	14.3	28.8	71.7	7.92	17.3	84.0	11.1
Diethyl carbonate	8.8	4.56	2.61	2.37	2.15	2.69	2.96	56.5	11.8	23.8	42.6	10.2
Diethyl phthalate	8.9	2.71	0.92	0.46	0.64	0.49	3.12	24.3	176.4	143.7	55.6	193.7
Ethyl acetate	8.9	3.01	3.04	2.63	2.61	2.61	3.27	85.1	147.5	Df	Df	150.8
Methyl ethyl ketone	9.3	2.72	4.06	2.53	2.17	2.55	3.42	214.9	Df	Df	Df	Df
Trichloroethylene	9.3	19.9	21.5	10.5	10.9	11.8	32.1	129.3	17.0	27.6	109.4	22.5
Cyclohexanone	9.6	5.04	4.36	3.03	1.40	4.88	5.40	Df	Df	Df	Df	Df
Acetone	9.8	3.23	1.98	2.42	1.23	1.64	1.41	92.9	171.9	Df	Df	177.0
Tetran	9.8	11.5	12.3	7.67	6.80	1.88	16.9	233.3	111.0	Df	Df	124.4
Tetrachloroethylene	9.9	25.0	25.5	13.7	13.7	13.5	41.4	53.4	2.64	0.19	64.1	16.5
2-ethyl-1-hexanol	9.9	4.21	1.59	0.52	0.32	1.06	1.44	42.3	12.8	3.02	8.34	6.08
Diethyl phthalate	10.0	0.81	1.36	0.89	0.45	1.37	1.35	80.3	86.58	124.3	56.3	93.9
Quinoline	10.8	3.67	4.06	3.30	1.79	4.22	5.33	Df	Df	Df	Df	Df
Cyclohexanol	10.9	2.07	1.71	0.86	0.40	1.21	1.81	51.8	11.2	0.37	9.61	2.11
N,N-dimethylacetamide	11.1	2.44	3.93	1.67	0.52	2.47	2.02	Df	Df	Df	Df	Df
m-Cresol	11.1	2.17	1.59	2.72	0.79	2.39	1.18	Df	7.65	0.68	93.1	7.32
Nitroethane	11.1	1.12	0.94	1.17	0.60	0.90	1.89	50.4	44.3	81.8	Df	40.3
Benzyl alcohol	11.6	0.76	0.44	0.94	0.17	0.91	0.61	Df	11.8	9.53	52.2	1.68
Furfuryl alcohol	11.9	0.20	0.16	0.22	0.70	0.39	0.06	735.8	13.1	11.3	23.1	6.22
1-Propanol	12.0	1.01	1.05	0.77	0.68	1.15	1.34	41.0	19.0	19.4	5.04	5.44
Butyrolactone	12.9	0.26	0.66	0.37	0.16	0.71	0.19	180.4	Df	Df	53.4	178.6
Propylene-1,2-carbonate	13.3	0.52	0.75	0.28	0.24	0.24	0.9	13.0	11.9	27.8	16.1	15.5
2-Pyrrolidone	13.9	0.79	0.79	0.86	0.16	0.90	0.54	Df	277.7	Df	42.9	258.0
Methanol	14.5	3.46	1.74	1.40	1.09	2.60	2.86	34.4	17.7	11.7	2.98	17.6
Ethylene glycol	16.1	0.56	0.41	0.41	0.24	0.39	0.43	6.95	3.43	4.89	3.12	4.32
Water	23.4	4.61	1.54	0.62	0.23	1.51	1.60	1.66	1.58	4.17	2.32	2.65

^aThe PVC compound labeled "DPQ" is a laboratory-prepared compound; information on this compound is presented in Appendix F, Tables F-11 and F-12. All of the other materials are commercially manufactured FMLs. Further data for these materials are presented in Appendix F, Tables F-9 and F-10.

^bExtractables determined in accordance with Matrecon Test Method 2 (see Appendix E) using methyl ethyl ketone as the solvent.

^cExtractables determined in accordance with Matrecon Test Method 2 (see Appendix E) using n-heptane as the solvent.

^dExtractables determined in accordance with Matrecon Test Method 2 (see Appendix E) using 2:1 mixture of CCl₄ and CH₃OH as the solvent.

^eExtractables determined in accordance with Matrecon Test Method 2 (see Appendix E) using CH₃OH as the solvent.

Df = dissolved or disintegrated.

Source: Haxo et al, 1988, p 127.

9090, and could be used to develop general criteria to assess the chemical compatibility of a specific FML proposed for use in lining specific waste storage and disposal facilities.

In this program, 6 commercial FMLs were immersed in 20 different chemical solutions or liquids, including acids and bases, polar and nonpolar organics, organic and inorganic solutions, and concentration variations. The FMLs were immersed at 23° and 50°C in the solutions for 1, 7, 14, 28, and 56 days (a short-term test) and for four-month increments up to 2 years (a long-term test). The immersed samples were observed for changes in appearance, weight, dimensions, and tensile and tear properties. The six FMLs that were selected for the test program are listed in Table 5-52. They represent a range of different polymer types, including variations in chemical composition, polarity, crystallinity, and crosslink density. All six of the FMLs were unreinforced; five were 30 mils in nominal thickness and the sixth, an ECO FML, was 60 mils in thickness.

TABLE 5-52. UNREINFORCED FMLS SELECTED FOR CHEMICAL RESISTANCE TESTING

Polymer	Type of compound ^a	Nominal thickness, mils	Polarity
CPE	TP	30	Polar
CSPE-LW ^b	TP	30	Polar
Epichlorhydrin (ECO)	XL	60	Polar
EPDM	XL	30	Nonpolar
HDPE	CX	30	Nonpolar
PVC	TP	30	Polar

^aTP = thermoplastic; XL = crosslinked; CX = semicrystalline.

^bLow water absorption CSPE, i.e. industrial grade.

Source: Bellen et al, 1987, p 29.

The 20 chemical liquids used in the study are listed in Table 5-53. Four of the chemicals, all organics, were each used at three concentrations and the NaCl was used at two concentrations to give information on the effect of concentration.

The FML samples were immersed in chemical solutions in glass jars. Glass was chosen because of its resistance to the wide range of chemicals being tested, its transparency (so that the condition of the samples could be inspected), and the relatively low cost of the jars. For the long-term immersions, in which the samples were observed for changes in weight and dimensions at four-month intervals, 1-qt canning jars were used. A screw-on cap lined with PE was used to control evaporative loss from the jars. Three 1 x 3-in. preweighed and premeasured FML specimens were placed in the canning jars. For the shorter immersions (up to 56 days), 2-gal apothecary jars were used. Three slabs were immersed in each jar: two were approximately 8 x 8.5

in. in size, and the third measured 1 x 3 inches. The larger slabs were for the property tests, and the third was used to determine weight and dimensional changes. For the shorter immersions, one jar per FML immersion period solution combination was used. The apothecary jars were sealed with rope caulking between the glass lid and the jar. Jars containing solutions of volatile chemicals were also taped with a stretchable heat and moisture-resistant transparent tape to reduce evaporative loss. The sealing methods were reasonably effective in controlling the loss of volatiles, i.e. MEK and DCE, as the concentration changes of the organic solutions during the tests were relatively small.

TABLE 5-53. CHEMICAL LIQUIDS SELECTED FOR FML IMMERSION TESTS^a

Name	Formula	Chemical type	Concentrations, % wt:wt ^b
Water	H ₂ O	Control	100
Hydrochloric acid	HCl	Acid	10
Sodium hydroxide	NaOH	Base	10
Sodium chloride	NaCl	Salt	10, sat'd (ca 35)
Potassium dichromate	K ₂ Cr ₂ O ₇	Oxidizer	10
Phenol	C ₆ H ₅ OH	Phenol	1,4, sat'd (ca 8)
Furfural	C ₄ H ₃ OCHO	Aldehyde	1,4, sat'd (ca 8)
Methyl ethyl ketone ^d	CH ₃ COC ₂ H ₅	Ketone	3,13, sat'd (ca 26)
1,2-Dichloroethane	Cl(CH ₂) ₂ Cl	Chlorinated-hydrocarbon	0.1,0.5, sat'd (ca 0.8)
ASTM #2 oil	...	Oil	100 ^e , sat'd (water with oil stirred in)

^aAll chemicals were technical grade quality or better, per ASTM D543.

^bPart per 100 parts of water.

^cBoth the water for water immersion tests and the water used for the organic chemical solutions were lightly buffered in order to provide pH control and ionic strength. Sodium bicarbonate and calcium chloride were used to a level of 100 mg L⁻¹ hardness as CaCO₃ and to provide a pH of 8.3±0.5.

^dAn 8% solution of methyl ethyl ketone was used in place of the saturated solution for testing the CPE.

^eNeat ASTM #2 oil.

Source: Bellen et al, 1987, p 41.

All immersions were conducted with an FML surface-to-volume ratio of approximately 40 mL in.⁻² of FML surface area. The surface to volume ratio was specified for consistency and to assure that the amount of solvent present in solution would not be limiting. Chemical solutions were mixed in the immersion jars. Those solutions containing the volatile chemicals were prepared on the same day that the FML samples were placed in immersion; those solutions containing the nonvolatile chemicals were prepared on the same day or the day before the FML samples were immersed.

Immersion jars were placed in controlled temperature chambers. Jars were set on open wire shelving to allow air circulation for temperature control. The temperature of jars of water in the chambers placed on top and bottom shelves were measured twice daily ($\pm 2^\circ\text{C}$ tolerance each).

The tests used to measure the physical properties of the different FMLs and the number of specimens in each test are listed in Table 5-54. Physical properties of the exposed FML samples were measured after each exposure period of the short-term test and at the conclusion of the long-term immersion test. Weight and dimensions were measured after each time period in the short-term test and after every four months in the long-term test.

Complete results are presented in the final report of Bellen et al (1987), in which data and discussions are organized by particular FML. No effort was made to compare material responses because each type of FML has unique properties and unique responses to immersion.

The authors observed five basic types of response to chemical immersion:

- Changes in physical properties and weight.
- Swelling by changes in dimensions.
- Swelling and softening with loss of strength.
- Shrinking and stiffening with loss of elongation.
- Combination of swelling and shrinking depending on immersion conditions.

The response of FMLs to increased immersion temperature indicated that higher temperatures (at least up to 50°C) can be used to accelerate the material response for some FMLs, but not others. With caution, the effects of temperature could be distinguished from a chemical response.

When the response was minor or the response time very fast, the difference in results between the 23°C exposure and the 50°C exposure was often small. In these cases, the higher exposure temperature did not significantly accelerate the response, but neither did it change the response. This indicates that the higher temperature neither affected the FML nor accelerated

TABLE 5-54. TESTING OF SAMPLES IN IMMERSION TESTS

Test	Type of FML compound		
	Crosslinked	Thermoplastic	Semicrystalline
<u>Measurements on immersion specimens</u>			
Thickness	Dead weight gage ^a	Dead weight gage ^a	Dead weight gage ^a
Length and width	Calipers ^a	Calipers ^a	Calipers ^a
Weight	Analytical balance ^a	Analytical balance ^a	Analytical balance ^a
<u>Physical properties</u>			
Tensile properties:			
Method	ASTM D412	ASTM D882	ASTM D638
Type of specimen	Die C	1 x 4-in. strips	Type IV
Number of test specimens	5 each direction	5 each direction	5 each direction
Values reported	Breaking factor (ppi)	Breaking factor (ppi)	Breaking factor (ppi)
	Elongation at break (in.)	Elongation at break (in.)	Yield strength (ppi)
		Stress at 100% elongation (ppi)	Elongation at break (in.)
			Elongation at yield (in.)
			Modulus of elasticity (psi)
Tear resistance:			
Method	ASTM D624	ASTM D624	ASTM D1004
Type of specimen	Die C	Die C	... ^b
Number of specimens	5 each direction	5 each direction	5 each direction

^aBellen et al, 1987, pp 205-13. Three specimens tested for long-term tests; one tested for short-term tests.

^bASTM D1004 test specimen is the same as the ASTM D624 Die C.

Source: Bellen et al, 1987, p 58.

the exposure. Some data indicated that the magnitude of the response did not increase with temperature, but the rate at which the response stabilized did increase. For such FMLs, elevating the temperature would effectively accelerate immersion testing. For other FML-chemical combinations, the magnitude of response was affected by temperature. The authors concluded that using elevated temperatures for predicting chemical resistance is generally not a good practice unless an FML's response to heat stress is known.

All of the FMLs were immersed in three different concentrations of four organics. Differences in concentration affected the FML responses. As an example, the effect of furfural concentration on PVC weight change, breaking strength, and stress at 100% elongation (S-100) modulus is presented in Figure 5-31. This example shows the importance of knowing concentration levels in evaluating compatibility or possibly for predicting acceptable chemical concentrations in waste streams based on allowable levels of property change when properties level off at constant values.

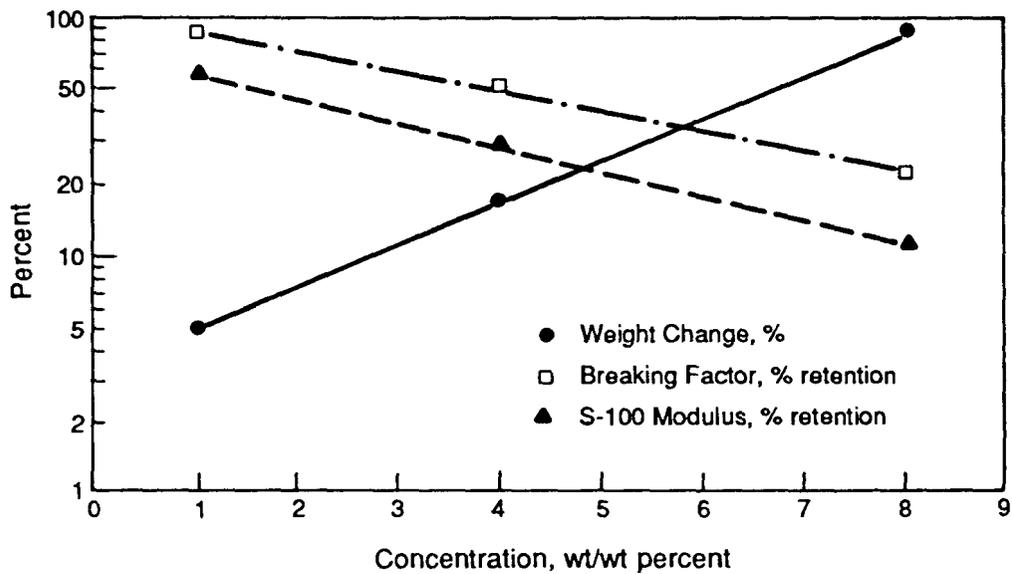


Figure 5-31. Relationship of changes in physical properties to furfural concentration at 23°C for PVC. (Source: Bellen et al, 1987, p 96).

Bellen et al (1987) proposed a mathematical curve fitting method for evaluating immersion data as a function of time. The method assumes the liner approaches a limit of physical property change asymptotically. The method can be used to predict the ultimate end point of physical property change and sampling time intervals for continued immersion testing in the specific chemical solution or liquid.

Some of the general conclusions of this study of FMLs in simple chemical solutions or liquids are:

- Immersing an FML in the waste it is intended to contain and determining changes in physical and analytical properties is essential for determining chemical compatibility of the FML with the specific waste.
- In general, the magnitude of an FML's response to an aqueous solution containing an organic solvent is a function of its concentration. However, solutions containing low concentrations of some chemicals can have a more significant effect on those solutions containing higher concentrations of other chemicals. These results indicate that immersing an FML in the major constituents of a given waste is not satisfactory for determining chemical compatibility between that waste and the given FML.
- In evaluating the chemical compatibility between an FML and a given waste, the ability of the FML to come to an equilibrium in the chemical environment as well as the magnitude of changes in properties needs to be considered.
- For some FML/waste combinations, increasing the immersion temperature can be used to accelerate testing. However, for others, increasing the temperature to 50°C produced a different rather than an accelerated response. Since not all FMLs are suitable for service at 50°C, immersing some FMLs at elevated temperatures may be too aggressive to simulate anticipated use. In addition, the ability of an FML to resist degradation needs to be considered when evaluating chemical resistance.
- A change in weight during immersion generally indicates changes in the properties of an FML.
- Water alone can significantly affect the properties of an FML, particularly in conjunction with an elevated temperature. The effect of immersion in water alone should be determined in evaluating the chemical resistance of an FML.
- Chemical compatibility tables (e.g. those developed by resin and FML manufacturers) should only be used to screen FMLs to find possible incompatible combinations. The limitations of compatibility tables are that materials are usually tested with simple solutions or neat solvents and only rated qualitatively (e.g. good, fair, or poor) and that the test conditions used to determine resistance are not always described. Exposure testing with the specific waste to be contained is necessary before compatibility can be determined.
- Generalization of any compatibility criteria and the results of testing an FML after immersion must be done with caution. Even though

FMLs of similar composition can be expected to respond similarly, the degree of the response (i.e the amount of property change) may change with different formulation and manufacturing techniques.

5.4.2.3.3 Immersion testing of seams--As part of a research program to evaluate FML seams exposed to simulated service conditions, Morrison and Parkhill (1987) investigated the effects of immersion in a range of test solutions on samples of FML factory and field seams prepared by the method appropriate to the specific FML. A total of 37 combinations of FMLs and seaming methods were immersed in nine solutions, including six chemical solutions, two brines, and tap water. The FMLs included:

- 30-mil CPE (unreinforced), 4 seam samples.
- 36-mil CPE (fabric-reinforced), 4 seam samples.
- 30-mil CSPE (fabric-reinforced), 2 seam samples.
- 36-mil CSPE (fabric-reinforced), 11 seam samples.
- 38-mil ethylene interpolymmer alloy (EIA) (fabric-reinforced), 2 seam samples.
- 30-mil EPDM (fabric-reinforced), 2 seam samples.
- 30-mil LLDPE (unreinforced), 2 seam samples.
- 30-mil HDPE (unreinforced), 1 seam sample.
- 80-mil HDPE (unreinforced), 3 seam samples.
- 30-mil PVC (unreinforced), 5 seam samples.
- 30-mil PVC/CPE (unreinforced), 1 seam sample.

The specific seaming procedures used in preparing the samples evaluated in the test program are indicated in Table 5-55. Test slabs from some of the seam samples were also immersed and tested for changes in weight and thickness. The immersion media were:

<u>Chemical</u>	<u>Concentration^a, %</u>	<u>Type</u>
Phenol	10	Organic acid
Hydrochloric acid	10	Inorganic acid
Sodium hydroxide	10	Inorganic base
Methyl ethyl ketone	10	Ketone
Furfural	5	Aldehyde
Methylene chloride	100 ^b	Halogenated hydrocarbon
NaCl at 23°C	36.1 (saturated)	Brine
NaCl at 50°C	37.0 (saturated)	Brine
Water	100	Tap water (Denver, CO)

^aParts per 100 parts of water, by weight.

^bNeat methylene chloride.

TABLE 5-55. SEAMING PROCEDURES USED TO PREPARE SAMPLES^a FOR IMMERSION IN TEST SOLUTIONS

Polymer	FML		Thermal						Miscellaneous				
	Type of compound	Fabric ^b	Hot air (THA) ^c	Dielectric (TDI) ^c	Hot wedge (THW) ^c	Dual hot wedge (TDW) ^c	Extrusion weld		Solvent		Vulcanized cap strip (VZ) ^c	With gum tape and cement (GTC) ^c	Adhesive (AD) ^c
							Flillet (EFW) ^c	Lap (ELW) ^c	Neat (SA) ^c	Bodied (BSA) ^c			
CPE	TP	U	...	12	...	...	...	...	11,28,29	...	...	...	...
		R	1,2	...	...	...	...	...	18	17	...	...	...
CSPE	TP	R	3,4,5,6	8	...	...	...	...	23,24	7,19	...	...	21
EIA	TP	R	9,26	...	...	...	...	...	25	20,22	...	...	...
EPDM	XL	R	...	...	...	...	...	...	...	...	10	27	...
HDPE	CX	U	...	...	...	33	30,31	32	...	...	...	...	...
LLDPE	CX	U	...	...	13,34	...	...	...	...	...	...	...	...
PVC	TP	U	...	15	...	...	...	...	14,35,36,37	...	...	...	...
PVC/CPE	TP	U	...	16	...	...	...	...	...	...	...	...	...

^aNumbers reported in table are seam sample identification numbers.

^bU = unreinforced; R = fabric-reinforced.

^cAuthors' code for identifying seaming procedure used in preparing samples.

Source: Morrison and Parkhill, 1987.

Methylene chloride is only slightly soluble in water (2.0 parts per 100 parts water at 20°C); therefore, neat solvent was used to avoid the problem of phase separation. Pure chemicals or aqueous chemical solutions were selected for testing rather than simulated or actual wastes from waste sites, to simplify verification of testing procedures. The use of one- or two-component chemical solutions also simplified interpretation of the data.

The tests that were performed on the seams fabricated from the different FMLs by the different methods or on small coupons of the individual FMLs included:

- Weight change to 52 weeks.
- Thickness change to 52 weeks.
- Shear strength.
- Peel strength.
- Dead weight load test.

The changes in weight of the FML samples immersed in the various test liquids for 52 weeks are presented in Table 5-56.

Some of the significant effects of immersion in these liquids were:

- All of the FML samples that were thermoplastic dissolved or disintegrated in the methylene chloride. The one FML that was cross-linked (EPDM) and the six semicrystalline FML samples swelled.
- Weights of several samples went through a maximum, indicating swelling; went through a minimum, indicating extraction; then began swelling again. An example of this is the behavior of PVC samples in furfural which is presented in Figure 5-32.
- The aqueous organics at the concentrations used in this test program resulted in considerable changes in the weight of the thermoplastics, either because of swelling or extraction.
- Several of the samples did not reach an equilibrium by the end of 52 weeks, as is shown in Figure 5-32. These results indicate that with aqueous solutions, such as waste liquids, exposure periods longer than the 120 days used in EPA Method 9090 (EPA, 1986) are necessary to determine the effects of immersion.

The results of the peel and shear tests of the immersed seams are summarized in Table 5-57. These results indicate that some organics have a severe effect on the FMLs and their seams; also, they indicate the aggressiveness of the NaOH solution.

TABLE 5-56. CHANGE IN WEIGHT OF FMLS EXPOSED TO VARIOUS TEST LIQUIDS FOR 52 WEEKS^a

Polymer	Sample ^c	Type of compound ^d	Nominal thickness, mil	Tap water	Change, percent by weight							
					Saturated NaCl ^b		10% Phenol	10% HCl	10% NaOH	10% MEK	100% CH ₂ Cl ₂	5% Furfural
					23°C	50°C						
CPE	L	TP	30	10.19	1.41	1.10	25.61	1.41	-2.07	29.89	-100.00	67.60
	M	TP	30	9.78	1.27	1.99	25.88	1.24	-2.22	38.63	-100.00	80.00
	A(R)	TP	36	22.10	2.37	3.09	37.11	9.47	8.25	18.25	-100.00	47.81
	B(R)	TP	36	9.27	1.20	0.48	6.10	-0.22	-5.37	12.72	-100.00	24.92
CSPE	C(R)	TP	30	4.06	0.65	1.74	14.53	0.60	1.20	4.60	-100.00	14.99
	D(R)	TP	36	8.10	2.23	4.45	16.54	2.90	2.25	16.01	-100.00	23.89
	E(R)	TP	36	5.81	3.00	4.46	17.54	2.68	2.15	7.25	-100.00	18.09
	F(R)	TP	36	6.77	1.27	3.29	38.04	6.04	3.60	10.19	-100.00	38.55
	G(R)	TP	36	4.92	2.46	2.96	16.64	9.15	14.05	6.30	-100.00	17.43
	H(R)	TP	36	5.12	2.46	2.73	16.68	3.68	14.59	6.47	-100.00	17.76
	I(R)	TP	36	11.72	2.96	4.15	19.03	20.15	11.94	14.82	-100.00	22.01
EIA	J(R)	TP	38	4.03	1.81	2.38	-100.00	7.12	-5.22	5.77	-100.00	32.30
EPDM	K(R)	XL	30	3.55	1.55	2.94	8.61	3.76	1.29	4.74	4.03	11.80
HDPE	N	CX	30	-0.01	-0.01	0.14	-0.48	-0.28	0.32	0.39	6.74	0.83
	O	CX	80	0.05	0.06	0.13	0.12	-0.29	0.19	0.55	4.07	0.59
	P	CX	80	0.01	0.01	...	-0.01	-0.31	0.12	0.18	3.17	0.34
	Q	CX	80	0.06	0.02	0.00	-0.41	-0.26	0.14	0.28	4.78	0.51
LLDPE	R	CX	30	0.00	0.07	0.27	-0.50	-0.79	0.21	0.63	7.52	0.72
PVC	S	TP	30	1.57	-0.97	-0.54	-16.38	6.41	-18.11	2.91	-100.00	5.55
	T	TP	30	2.42	-0.81	-0.57	-15.90	3.69	-19.65	5.51	-100.00	13.12
	U	TP	30	1.53	-0.18	-0.50	-12.78	7.04	-14.97	11.37	-100.00	15.35

^aAll solutions are aqueous; exposure was at room temperature (23°C), except where otherwise indicated.

A "5%" or "10%" solution means 5 or 10 g of solvent per 100 g H₂O, respectively. Methylene chloride was neat.

^bSaturated solution at 23°C is 26.5% by weight (36.1 g per 100 g H₂O); saturated solution at 50°C is 27.0% by weight (37.0 g per 100 g H₂O).

^cIdentification code; R = fabric reinforced.

^dTP = thermoplastic; XL = crosslinked; CX = semicrystalline thermoplastic.

Source: Morrison and Parkhill, 1987, pp 81-85.

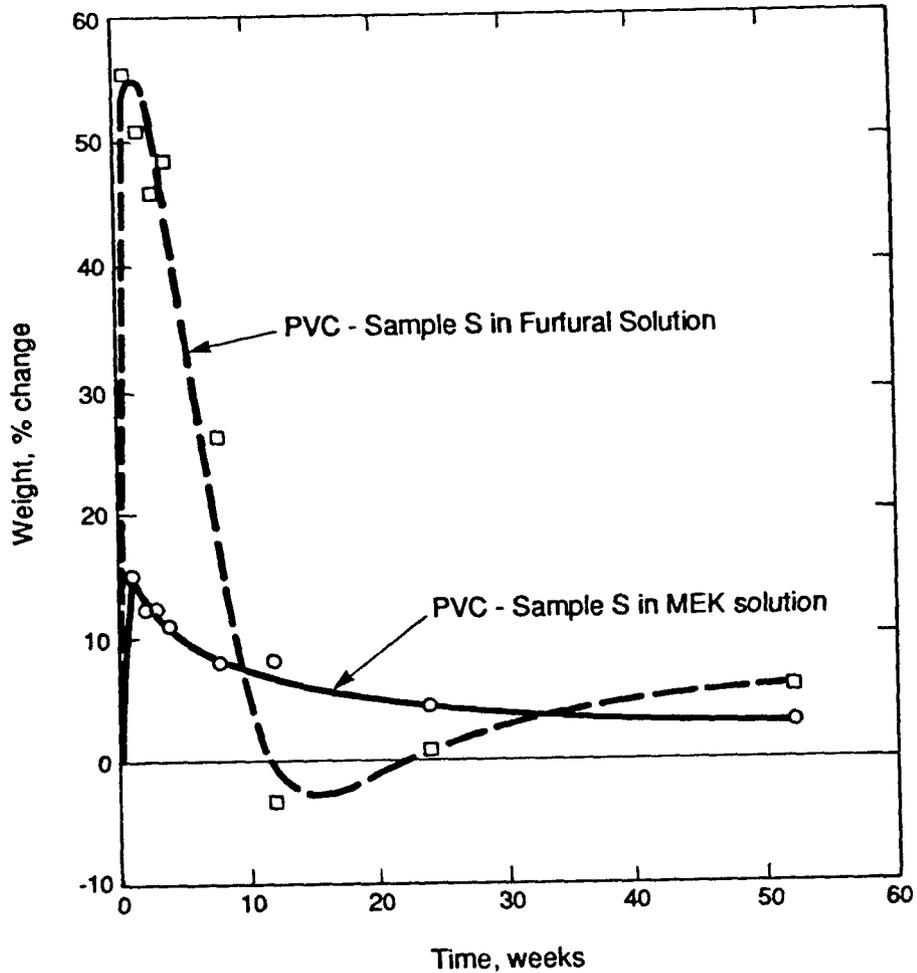


Figure 5-32. Change in weight of a PVC immersed in furfural and MEK aqueous solutions as a function of time. (Source: Morrison and Parkhill, 1987, p 84).

5.4.3 Compatibility Testing of FMLs

The compatibility of a candidate FML with the waste to be contained is an essential consideration in making the final choice of an FML for use as a liner in a waste storage or disposal facility. In view of the vast variety, complexity, and uncertainty of the compositions of the waste liquids and leachates that must be contained, a test was needed to assess the compatibility of a candidate liner with the specific waste liquid to be contained. A method was suggested in the 1983 edition of the EPA Technical Resource Document, "Lining of Waste Impoundment and Disposal Facilities" (Matrecon, 1983). Later in 1983, the EPA proposed a test method for determining the compatibility of wastes and FMLs. This method, which was noticed in the Federal Register (EPA, 1984), has been revised extensively and was recently published in SW-846 as Method 9090 (EPA, 1986). The current version of Method 9090 is presented in Appendix L.

TABLE 5-57. PERFORMANCE OF FML SEAM SAMPLES EXPOSED TO VARIOUS TEST LIQUIDS^a

Polymer	Sampled ^d	Nominal thickness, mil	Seam sample ^e	Type of seam ^f	Tap water	Test liquid ^b								
						Saturated NaCl ^c		10% Phenol	10% HCl	10% NaOH	10% MEK	100% CH ₂ Cl ₂	5% Furfural	
						23°C	50°C							
CPE	L	30	11	SA	S	S	S	U	S	U	U	U	U	
	L	30	28	SA	U	S	S	U	S	U	U	U	U	
	M	30	12	TDI	U	S	S	U	S	U	U	U	U	
	M	30	29	SA	U	S	S	U	S	U	U	U	U	
	A(R)	36	1	THA	U	U	U	U	U	U	U	U	U	
	A(R)	36	17	BSA	U	U	U	U	U	U	U	U	U	
	B(R)	36	2	THA	S	S	S	U	U	U	U	U	U	
	B(R)	36	18	SA	S	S	U	U	U	U	U	U	U	
CSPE	C(R)	30	3	THA	S	S	S	U	S	U	S	U	S	
	C(R)	30	19	BSA	S	S	Q	S	S	U	S	U	U	
	D(R)	36	4	THA	U	U	U	U	S	U	U	U	U	
	D(R)	36	20	BSA	U	U	U	U	S	U	U	U	U	
	E(R)	36	5	THA	S	S	Q	U	Q	U	U	U	U	
	E(R)	36	21	AD	S	S	S	U	Q	U	S	U	S	
	F(R)	36	6	THA	U	U	S	U	U	U	U	U	U	
	F(R)	36	22	BSA	S	S	S	U	S	U	S	U	U	
	G(R)	36	7	BSA	S	S	Q	U	S	U	S	U	S	
	G(R)	36	23	SA	S	S	S	U	S	U	S	U	U	
	H(R)	36	8	TDI	S	S	S	U	S	U	S	U	U	
	H(R)	36	24	SA	S	S	S	U	S	U	S	U	Q	
I(R)	36	25	SA	S	S	Q	U	U	U	S	U	S		
EIA	J(R)	38	9	THA	S	S	S	U	S	U	U	U	U	
	J(R)	38	26	THA	S	S	S	U	S	U	U	U	U	
EPDM	K(R)	40	10	VZ	S	S	S	S	S	U	S	S	S	
	K(R)	40	27	GTC	U	U	S	U	U	U	U	Q	U	
HDPE	N	30	30	EFW	S	S	S	S	S	S	S	S	S	
	O	80	31	EFW	S	S	S	S	S	S	S	S	S	
	P	80	32	ELW	S	S	S	S	S	S	S	S	S	
	Q	80	33	TDW	S	S	S	S	S	S	S	S	S	
LLDPE	R	30	13	THW	S	S	S	S	S	S	S	S	S	
	R	30	34	THW	Q	Q	Q	Q	Q	Q	Q	Q	U	
PVC	S	30	14	SA	S	S	S	U	S	U	U	U	U	
	S	30	35	SA	S	S	S	U	S	U	U	U	U	
	T	30	15	TDI	S	S	S	U	S	U	U	U	U	
	T	30	36	SA	S	S	S	U	S	U	U	U	U	
	U	30	37	SA	S	S	S	U	S	U	U	U	U	
PVC-CPE	...	30	16	TDI	U	U	U	U	U	U	U	U	U	

^aSummary of the results of testing samples after 3, 6, and 12 months of exposure. U = unsatisfactory; Q = questionable; S = satisfactory. Performance was considered unsatisfactory if there was more than a 20% loss in either shear or peel strength after exposure.

^bAll solutions are aqueous; exposure was at room temperature (23°C), except where otherwise indicated. A "5%" or "10%" solution means 5 or 10 g of solvent per 100 g H₂O, respectively. Methylene chloride was neat.

^cSaturated solution at 23°C is 26.5% by weight (36.1 g per 100 g H₂O); saturated solution at 50°C is 27.0% by weight (37.0 g per 100 g H₂O).

^dIdentification for FML as tested in immersion. R = fabric-reinforced.

^eIdentification for FML and seaming system.

^fAD = adhesive; BSA = bodied solvent adhesive; EFW = extrusion fillet weld; ELW = extrusion lap weld; GTC = gum tape and cement; SA = solvent adhesive; TDI = thermal--dielectric; TDW = thermal--hot dual wedge; THA = thermal--hot air; THW = thermal--hot wedge; VZ = vulcanized plus 0.75-in. cap strip.

Source: Morrison and Parkhill, 1987, pp 10-15.

Method 9090 attempts to simulate some of the conditions that an FML may encounter in service and to determine the effects on an FML of contact with a waste liquid. In this exposure test, samples in slab form are immersed for up to four months at 23° and 50°C in a representative sample of a waste liquid or leachate. A number of physical and analytical tests are performed on the unexposed FML for baseline data and on samples after exposure to the waste liquid for 30, 60, 90, and 120 days. Consequently, the test procedure is complex and involves many steps including selecting representative samples of both the waste to be contained and an FML for testing, exposing the FML samples to the waste under highly controlled conditions, physical testing and analysis of unexposed and exposed FML samples, and interpreting the final results.

Developing a reliable compatibility test requires determining and assessing those factors that can affect test results and result in errors. Ideally, a test should be relatively simple and yield results that are accurate and precise. A factor of particular importance in this test is the control of the composition of the sample of waste liquid and the effect that lack of adequate control may have on an FML in the test. It is recognized that a single representative sample of waste liquid must be used to conduct the test and that the composition of this sample may not reflect the actual composition of the waste liquid as a function of time.

Of particular concern is the effect of trace organics on FML-waste compatibility. Haxo et al (1985b) reported the results of immersing FML samples in a dilute (<0.1%) but saturated solution of tributyl phosphate (see Section 5.4.2.2). Even at this low concentration, samples of CPE, CSPE, neoprene, and PVC FMLs gained significant amounts of weight. These results indicate that an FML can absorb large quantities of an organic from a leachate containing only a trace concentration. The effect this tendency to absorb trace concentrations has on FML permeability has been studied by August and Tatsky (1984) and Haxo et al (1988). The results of these studies indicate that an organic in a dilute aqueous solution will partition or distribute itself between the water in which it is in solution and an FML until equilibrium is reached and that the organic will permeate the FML at a much higher rate than would be expected from knowledge of the permeation rate of the neat organic and its concentration in the dilute solution (see Section 5.4.1.6.2).

In actual service in a waste containment unit the liquid that may contact a liner is generally a dilute solution of water and various dissolved constituents, some of which are inorganic and others organic; the latter can be either volatile or nonvolatile, or both. The concentrations of the constituents will probably be low and more or less constant, or will change only slowly with time. In performing laboratory testing of an FML to assess its compatibility with a waste liquid, it is desirable to simulate as much as possible the conditions that exist in service. Inasmuch as the amount of organics that is absorbed by an FML affects its properties, the concentrations of the organics in the solution to which it is exposed should remain essentially constant.

It is not known what effect minor variations in waste composition would have on the test results. Using synthetic hazardous waste leachates is one method that has been suggested for verifying the compatibility of an FML in cases where no actual leachate is available. To develop a synthetic leachate, thorough analyses have been performed on actual hazardous waste leachates to determine their composition, and particularly to identify the organic constituents that are present (Bramlett et al, 1987; McNabb et al, 1987), as is discussed in Section 2.2.4. The results of these analyses indicate the wide range of organic constituents present in the leachates and the difficulty in identifying them. Because so little is known about the interaction between FMLs and unidentified trace organics, using a synthetic leachate to verify compatibility of an FML and a leachate leaves many questions unresolved.

In addition, even during the course of testing, changes that would not reflect the actual composition in service can occur in the composition of the representative waste liquid sample. In the case of solutions containing volatile organics, the organics could be absorbed by the FML or could escape from the test tanks. In either case, a lower concentration of organics in the test liquid would result.

Because of the limited duration of exposure, it is also desirable to refine the test to be able to project longer exposure times and, possibly, service life. Tests of properties that would reflect the long-term performance, serviceability, and durability of an FML in service more accurately than those tests presently in Method 9090 should also be investigated and, if possible, incorporated into the method.

The results of immersion tests performed by Bellen et al (1987) and Morrison and Parkhill (1987) showed that some FML samples, particularly some of those that were immersed in aqueous solutions of organics, did not reach equilibrium swelling after 52 weeks of exposure. These results indicate that the 120-day maximum exposure time in Method 9090 may not be a sufficient length of time for tests with aqueous solutions.

The EPA is in the process of developing expert systems to use in evaluating FML-waste compatibility data generated in a Method 9090 liner compatibility test (Rossman and Haxo, 1985). These systems are applicable to PVC, HDPE, and CSPE FMLs. One such system is the Flexible Liner Evaluation Expert (FLEX) computer program, which is available in draft form from the EPA (see Section 7.5.3.2.1.2).

The following subsections present results of research performed by Haxo et al (1988) on compatibility testing with particular reference to EPA Method 9090. The objective of this research was to establish the magnitude of some of the factors that can affect Method 9090 test results and to develop information that will aid in the interpretation of the test results. As presently written, Method 9090 is designed to assess the changes in selected properties that take place in samples of an FML that have been immersed in a specific waste liquid. At the present state of knowledge, there is a lack of information about FMLs in service with respect to the type and degree of

changes in properties obtained in EPA Method 9090 tests which would indicate that a given FML is acceptable for use as a liner for the long-term containment of the waste liquid or leachate used in the test. However, results from the test can be used to demonstrate that a specific combination of an FML and a waste liquid is incompatible and that the FML should not be used as a liner to contain that particular waste.

5.4.3.1 Compatibility Testing Performed with Actual and Synthetic Leachates Containing Organics--

Haxo et al (1988) monitored the level of organics in the test solutions and in the FML specimens in two EPA Method 9090 tests that were performed with actual and synthetic leachates. In particular, they studied:

- Changes in the composition of the waste liquid during an exposure due to absorption of organics by the FML specimens.
- The loss of volatile constituents from aqueous waste liquids during exposure, and the level of control required to prevent the volatiles from escaping from the exposure tanks.
- The effect of temperature on the level of control required to maintain concentration levels of the waste constituents during exposure.
- Whether replacement of waste liquids during testing is a feasible means of maintaining concentration levels of the waste constituents during exposure.

The overall approach in performing this research was:

- To basically follow EPA Method 9090, as noticed in the Federal Register of October 1984. Additional tests that appeared to be appropriate for this study were also included.
- To use exposure tanks that do not absorb or permeate volatile or nonvolatile organics. No. 316 stainless steel was selected for fabricating the tanks; Teflon gaskets were used in sealing the covers to the test tanks to prevent loss of volatiles.
- To follow the compositions of the waste liquids by GC analysis and to analyze the exposed FMLs for volatile organics by headspace GC and for nonvolatiles by extraction and GC analyses of the extract.
- To conduct several simple tests to determine whether volatiles had been lost in the various steps of the compatibility test, i.e. whether volatiles had been lost from the waste liquid or from FML samples that had absorbed volatile organics.
- To spike actual leachates and water with volatile and nonvolatile organics typically found in the actual waste liquids and track their movement by GC analyses.

At present, EPA Method 9090 does not indicate the materials out of which the exposure tanks should be fabricated. It does indicate that the tanks should be equipped so that there is no evaporation of any of the solutions and suggests that they should be equipped with a reflux condenser. Because of the chemical resistance of polyethylene and polypropylene, tanks made of these materials have been used. Both materials appear to be satisfactory for testing the compatibility of FMLs with leachates that only contain dissolved inorganics. However, in tests with waste liquids or leachates that contain volatile or nonvolatile organics, the walls of the tank can compete with the FML under test for the organics present. Furthermore, the walls are permeable to the organics. Competition between the tank walls and an FML for organics is particularly a problem when an FML material similar in composition to the tank walls is being tested, e.g. when the FML and the tanks are both polyethylenes. To avoid this competition, a steel exposure tank that incorporates a Teflon gasket between the cover and the top of the tank was designed and fabricated.

A schematic of the tank used in the compatibility testing performed in this study is presented in Figure 5-33. The tank has the following features:

- The tank, stirrer, and sample rack are constructed of 316 stainless steel.
- The volume of leachate or exposure liquid held by a tank is 5.2 gallons (19,682 mL).
- A Teflon gasket is installed between the tank lid and the flange around the top of the tank. The gasket is used to prevent loss of volatiles; Teflon was selected to minimize absorption of leachate constituents by the gasket.
- A stirrer can be operated continuously to prevent stratification within the waste liquid.
- Each tank can be operated at 23° or 50°C. Temperature is monitored with a mercury thermometer, as well as with a thermocouple sensor monitored by a data logger. The data logger also serves as a secondary temperature control system that will turn off the heating system should the temperature rise beyond pre-set limits.
- The tank is heated by heaters attached to the outside of the tank in an area near the stirrer.
- Two short standpipes are secured in the lid of each tank and used for filling the tank to its capacity, thus minimizing the possibility that volatiles will leave the leachate to enter a headspace.
- Each lid is equipped with a septum through which sampling or spiking of leachate can be performed.

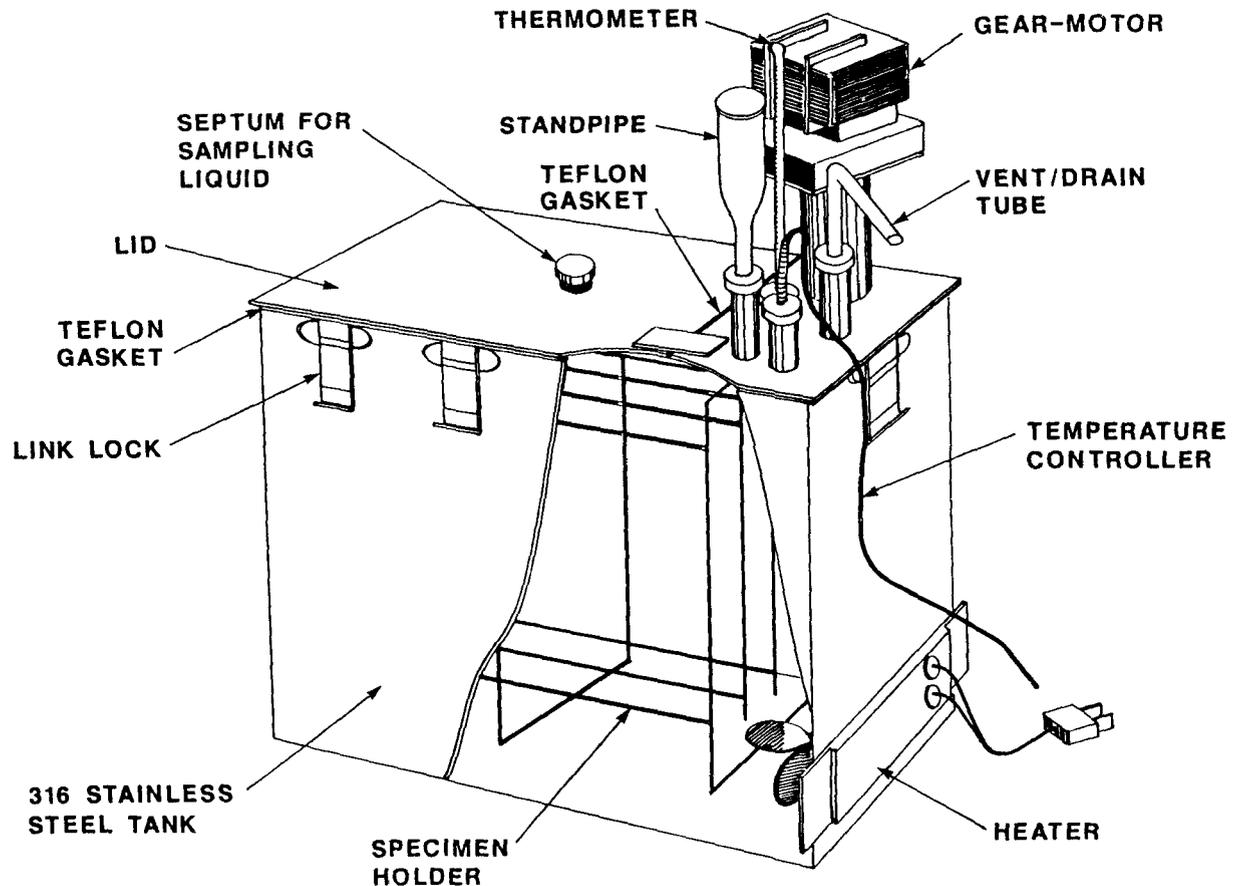


Figure 5-33. Schematic of the exposure tank used in the FML compatibility studies with spiked leachate and water. (Source: Haxo et al, 1988, p 78).

5.4.3.1.1. Compatibility test of an HDPE FML performed with an actual leachate spiked with selected organics--A short-term exploratory compatibility test was performed on a polyethylene FML with a leachate that had been obtained from a hazardous waste landfill and was spiked with a group of volatile organics. Spiking a leachate with constituents that are or may be in a leachate was considered to be a means of accelerating a compatibility test since it would increase the severity of the exposure conditions. In the context of the research project, it was also desirable to introduce known species of organics which could be absorbed by the FML from dilute aqueous solutions and tracked relatively easily by GC. The availability of a waste that contained volatiles provided the opportunity of running a short-term test to assess the effects of the volatiles and to observe possible loss of volatiles during testing. The organics used to spike the leachate included the following:

- Trichloroethylene.
- 1,1,1-Trichloroethane.
- Benzene.

- Toluene.
- o-Xylene.
- m-Xylene.
- p-Xylene.

The concentrations of the organics in the FML were monitored by headspace gas chromatography (HSGC), which is described in Section 4.2.2.5.1 (p 4-94).

The results of this experiment showed the importance of maintaining the volatiles content in the exposure tanks. Even with excessive amounts of the organics, the volatiles were lost from the tanks. Increases in the weight of the slabs and in their volatiles content after three weeks of exposure to the spiked leachate indicated significant absorption of the volatile components of the spiked leachate. These increases were accompanied by significant changes in some physical properties. For example, there were significant losses in tensile at yield, tensile strength, modulus, puncture resistance, and hardness. When the slab was returned to the tank and allowed to continue in exposure after the 27th day, the volatiles content dropped substantially and the properties returned closely to baseline values. This return to baseline values indicates that most of the property changes that occurred in the early part of the test were due to swelling. It should be noted that the Teflon gasket, which, in the procedure performed by Matrecon, is normally replaced at the end of each test interval, was not replaced in this test as it appeared to be in good condition at the end of 20 days of exposure.

It was concluded that at each time interval when the tanks are opened to recover the samples for testing, the leachate should be replaced with fresh liquid that has been kept in sealed drums. Furthermore, the gasket should be changed, and the sealing surfaces of the cover and the metal container should be checked carefully.

5.4.3.1.2 Compatibility test of an HDPE FML performed with DI water spiked with organics--A second EPA Method 9090-type test was performed on an HDPE FML using spiked DI water to form a synthetic leachate that contained 11 different organics, both volatile and nonvolatile (Haxo et al 1988). The organics that were selected included the seven of the volatile organics used in the compatibility test described in the previous subsection. Two additional volatile organics were included in the spiking solution, i.e. acetone and methyl ethyl ketone (MEK), as were two nonvolatile organics that are used as plasticizers for PVC and other polymers, i.e. tri-n-butyl phosphate (TBP) and di(ethylhexyl) phthalate (DEHP). Because TBP and DEHP have a higher molecular weight, they would be absorbed more slowly by the HDPE. The concentrations of the volatile constituents were monitored by HSCG, and the concentrations of the nonvolatile organics by GC analysis of the extract.

The objectives of this experiment were:

- To perform an EPA 9090-type liner compatibility test with a test liquid consisting of DI water with a "spike" that contained 11

organics which included seven used in the earlier EPA 9090-type test performed for this project.

- To assess the effect of temperature on exposure, i.e. 23° and 50°C.
- To determine the changes in concentration on the organics in the liquid using GC and to compare the results with the amounts of the organics absorbed by the HDPE samples. These amounts would be determined by headspace GC of the FML samples.

The test data on the volatiles and weight changes indicated that there were significant losses in volatiles from the test system as the test proceeded. These losses were reflected by the relatively insignificant changes in the physical properties at the end of the immersion. The GC analyses showed that the concentrations of all of the volatile organics dropped, both in the exposed FMLs (after initially absorbing a relatively high concentration) and in the water, indicating a relationship between the concentration of the organics in the water and in the FML. The results of the HSGC analyses of the FML samples are presented in Table 5-58. The increase in extractables indicated that the two plasticizers incorporated in the original test liquid were gradually absorbed by the FML samples, which was confirmed by the GC analyses of the extracts (Table 5-58). Whereas the results of the previous Method 9090 test performed for this project indicated that an increase in volatiles content can affect the physical properties of an HDPE FML, the results of this test indicated that an increase in extractables did not appear to affect the physical properties of the exposed HDPE samples. The net results indicate the importance of the effects of volatile organics on the properties of a polymeric FML.

It is concluded from the results of this experiment that tight control of volatiles in an EPA Method 9090 test is essential, and that the concentration of all constituents in a leachate used in a compatibility test must be maintained at original levels.

The data also indicated that "synthetic leachates" require more development in order to be used in liner-waste compatibility testing. It appears that addition of a spiking of a few volatile organics to water to yield a "leachate" is not sufficient and that a broader background of organics is needed. It should be noted that, in the test using spiked leachate, the volatile organics in the spike plus organics in the original leachate had greater effects on the properties of an FML than did essentially the same volatile organics alone when added in the spike.

The loss of volatiles at the higher exposure temperature resulted in higher retention of properties than at the lower exposure temperature, probably a result of the evaporation of volatile organics. These results indicate problems in performing a Method 9090 test at 50°C and higher.

TABLE 5-58. GC ANALYSIS OF THE EXPOSED FML SAMPLES

Exposure temperature, tank number, and time	Volatiles in FML by Headspace gas chromatography, mg g ⁻¹									GC of extractables, mg g ⁻¹		
	Acetone (197 ^a)	MEK (201 ^a)	1,1,1-TCA (326 ^a)	Benzene (231 ^a)	TCE (406 ^a)	Toluene (338 ^a)	m- and p-Xylenes (191 ^a)	o-Xylene (103 ^a)	Total	TBP (251 ^a)	DEHP (250 ^a)	Total
<u>Tank I (23°C)</u>												
34 days	0	0	1.42	0.46	1.58	2.63	1.86	1.17	8.72	0.32	0.11	0.43
69 days	0	0	0.45	0.18	0.98	1.75	4.17	1.53	9.06	5.62	0.41	6.03
105 days	0	0	0.25	0.04	0.21	0.34	1.85	0.82	3.51	6.44	0.63	7.07
139 days	0	0	0	0	0	0.02	0.19	0.04	0.25	...	...	...
<u>Tank III (23°C)</u>												
34 days	0	0	0.68	0.30	1.26	2.25	1.33	0.80	6.62	0.08	0.08	0.16
69 days	0	0	0.18	0.05	0.30	0.81	3.00	1.03	5.37	0.52	0.14	0.66
105 days	0	0	0.08	0.01	0.07	0.16	1.26	0.53	2.11	5.29	0.32	5.61
139 days	0	0	0.02	0.00	0.01	0.05	0.08	0.00	0.16	...	...	...
<u>Tank II (50°C)</u>												
34 days	0	0	0.1	0.02	0.16	0.66	0.78	0.57	2.29	1.61	0.31	1.92
69 days	0	0	0.01	0	0.08	0.05	1.06	0.46	1.66	3.34	0.42	3.76
105 days	0	0	0	0	0	0	0.17	0.14	0.31	9.47	0.64	10.11
139 days	0	0	0	0	0	0	0	0	0	...	...	...
<u>Tank IV (50°C)</u>												
34 days	0	0	0.10	0.11	0.40	0.96	1.29	0.83	3.69	1.53	0.26	1.79
69 days	0	0	0	0.01	1.01	0.03	0.82	0.37	2.40	5.31	0.42	5.73
105 days	0	0	0	0	0	0	0.10	0.11	0.21	7.57	0.52	8.09
139 days	0	0	0	0	0	0	0	0	0	...	...	...

^aTotal concentration in mg L⁻¹ of the organics injected in the water in two portions. Value assumes complete dissolution in the water.

Source: Haxo et al, 1988, p 96.

5.4.3.2 Evaporation of Volatile Organics from Water Solutions and Exposed FMLs--

In testing an exposed FML and insofar as the amount of organics that is absorbed by an FML affects its properties, the concentrations of the organics in the FML must remain essentially the same as they were when the FML was in exposure. As the volatile components can evaporate relatively easily, FML samples that are being recovered and tested should be protected from loss of volatiles. A loss of volatiles can result in values for many properties different from values for the properties of the FML as it existed at the time it was removed from service.

The effects of exposing an FML to a service environment can be of one or more of three basic types:

- Degradation of the polymer itself, either by reduction in molecular weight or by crosslinking, either of which could cause drastic changes in properties.
- Extraction of plasticizers or other compounding ingredients in the FML. This can result in a variety of effects including hardening and loss of antioxidants and other antidegradants which could result in faster rates of degradation of the polymer.
- Swelling of the FML due to absorption of organics and water. In this case, exposure may result in loss of physical properties and increases in permeability. The evaporation of volatile absorbed constituents may result in recovery of many of the baseline values of the FML; consequently, the effects of the exposure, which would be observed at the time a sample is removed from service, are lost. It would be ideal if the testing of an FML specimen could be performed while it is immersed in a waste stream as is sometimes done in the testing of the compatibility of rubbers and plastic compositions with various solvents, oils, and other fluids.

It is the third type of effect which is of particular concern in testing FMLs that have been in contact with waste liquids that contain minor amounts of organics. To demonstrate some of the effects resulting from the evaporation of volatiles, either from the test tank in which the FMLs are being exposed in an EPA Method 9090-type test or from the loss of volatiles after removal from immersion, several experiments were performed by Haxo et al (1988); these are described in the following subsections.

5.4.3.2.1 Evaporation of volatile organics from aqueous solutions--The evaporation of several volatile organics from dilute aqueous solutions was measured. These measurements were made by preparing 200 mL solutions of various types of organics in concentrations ranging from 200 to 10,000 mg L⁻¹ in 400 mL beakers. The beakers were left uncovered and the organics were allowed to evaporate. The concentrations of the organics remaining in the beaker were monitored by GC analysis. The results showed a pronounced loss

from the solutions for all of the organics, particularly the aromatic hydrocarbons toluene and xylene. Selected results are presented in Figures 5-34 and 5-35. The comparative rates of loss are illustrated in Table 5-59, in which the times to one-half of the initial concentrations are presented.

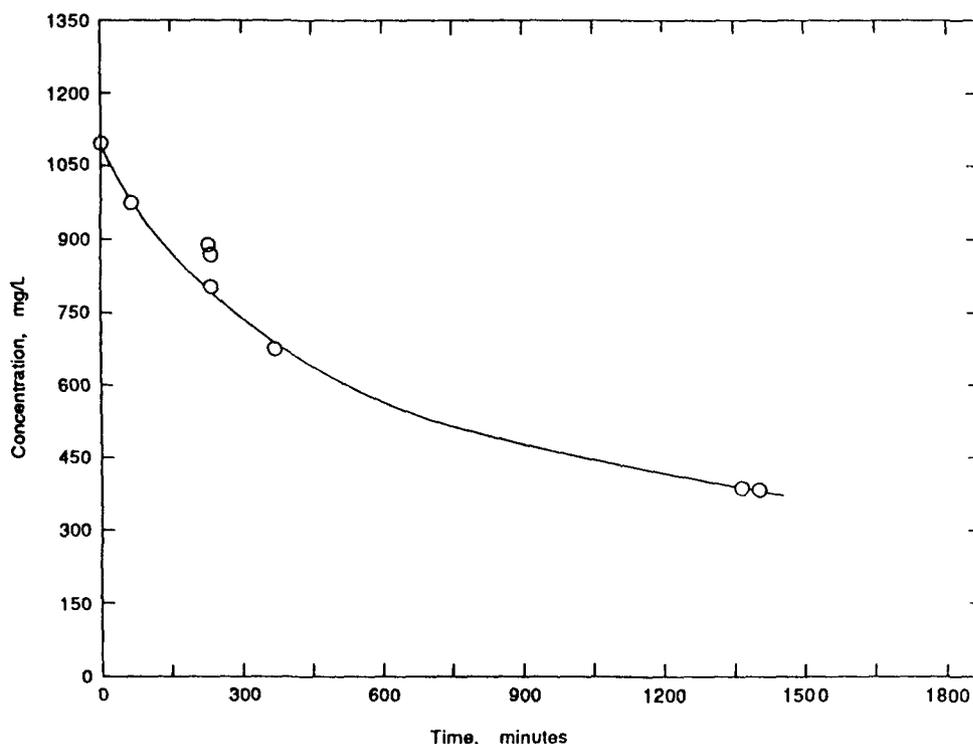


Figure 5-34. Reduction in concentration of TCE in a dilute aqueous solution of initial concentration of 1100 mg L^{-1} by evaporation from an open beaker at room temperature. 200 mL of solution was in a 400 mL beaker. (Source: Haxo et al, 1988, p 104).

These results indicate the need when conducting compatibility tests to take precautions to prevent the loss of volatiles from the time a waste liquid is received for test through the four months of exposure. These data also indicate the need to prevent loss of the volatiles from the time the waste liquid is collected through shipping and testing. The results confirm the data that were obtained in the two EPA Method 9090-type tests which are described above.

5.4.3.2.2 Evaporation of organics from saturated FML specimens--The loss of volatiles from exposed FML samples was demonstrated in a series of tests with HDPE and various organics. Typical results are shown in Figure 5-36 for toluene, TCE, and a mixture of organics that were absorbed by small samples of a 100-mil HDPE FML. Again, there was rapid evaporation of the volatile constituents when a sample was withdrawn from the organic. The

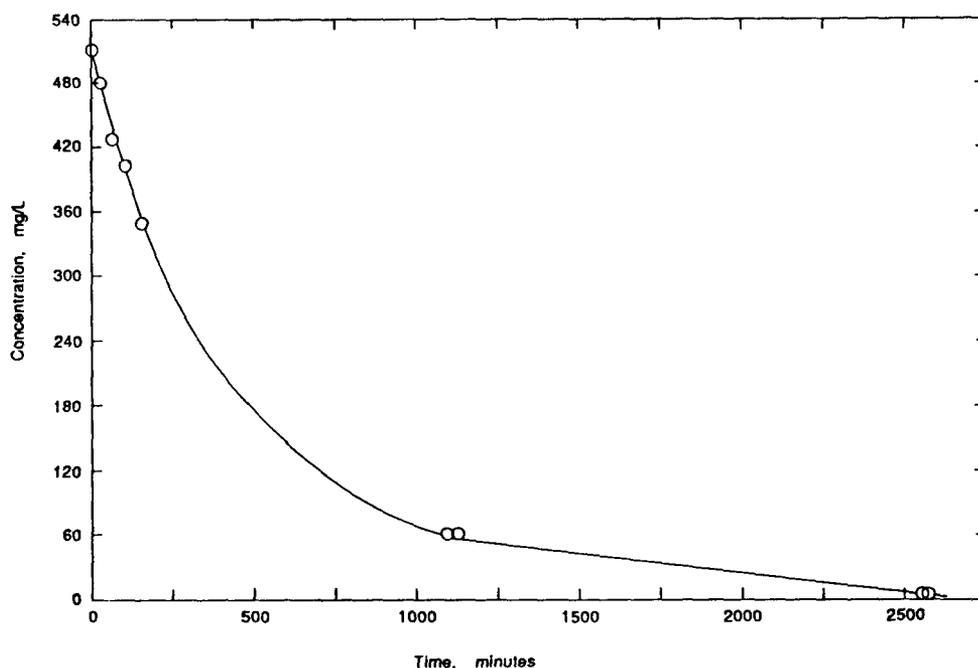


Figure 5-35. Reduction in concentration of toluene in a dilute aqueous solution of initial concentration of 520 mg L⁻¹ by evaporation from an open beaker at room temperature. 200 mL of solution was in a 400 mL beaker. (Source: Haxo et al, 1987b, p 105).

TABLE 5-59. EVAPORATION OF VOLATILE ORGANICS FROM AQUEOUS SOLUTIONS

Organic	Initial concentration, mg L ⁻¹	Time to one-half initial concentration, min.
Acetone	10,000	384
Trichloroethylene	1,100	650
Toluene	520	310
m-Xylene	195	138

Source: Haxo et al, 1988, p 106.

evaporation of a volatile organic from an FML exposed to volatiles is generally not as rapid as the evaporation from an aqueous solution; however, in performing a compatibility test, even though the time is relatively short between removal of an FML sample from the waste and testing, these data demonstrate the need for protecting the samples once they are withdrawn from a waste liquid containing volatile organics. It is recognized that the rate

of evaporation of a volatile organic or water from an FML sample is affected by the type of organic, the test temperature, air movement, and sample size, thickness, and shape. It should be pointed out that even during physical testing, such as tensile testing, the specimens lose volatiles. This loss may be a factor due to the duration of the test and the increased surface and reduced thickness of the specimen during the actual physical testing.

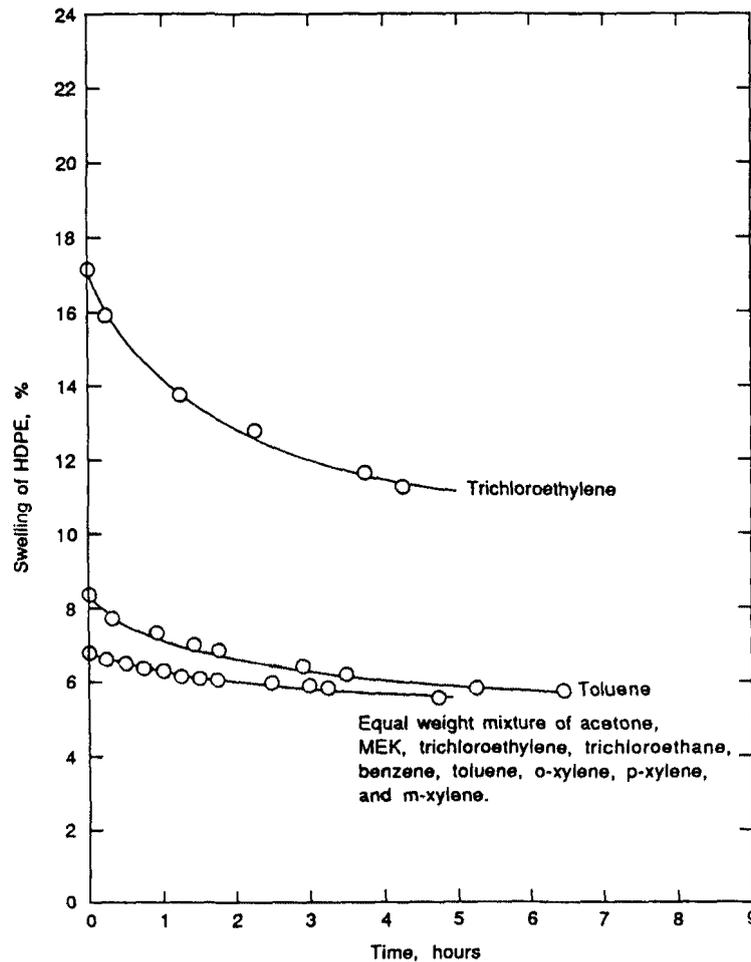


Figure 5-36. Loss of organics from HDPE FML samples saturated with different organics. (Source: Haxo et al, 1988, p 106).

5.5 EFFECTS OF MECHANICAL STRESS

To function within an engineered system, FMLs and other components of a liner system must be able to maintain their integrity after exposure to mechanical stresses. Short-term mechanical stresses can include stresses during installation such as those caused by placement of the soil cover and dropped tools, stresses caused by thermal shrinkage, and stresses related to the weight of the materials placed on top of the liner system. Long-term

mechanical stresses are most often the result of the weight of the materials on top of the liner system or differential settlement of the subgrade.

Various attempts have been made to simulate the effects of mechanical stresses on FMLs and ancillary components of a liner system. The following subjects are discussed in this section:

- The ability of an FML to conform to a subgrade.
- The leakage rates through holes in FMLs.
- The effect of compressive stresses on the hydraulic transmissivity of geonets and geotextiles.

5.5.1 Large-Scale Hydrostatic Testing Over a Subgrade

Various testing devices have been developed that simulate the in-service behavior of an FML under hydrostatic pressure to evaluate the ability of an FML to conform to irregularities in a subgrade, which is an important feature in the design of a facility. Irregularities such as cracks, rocks, and voids can cause localized settlement of the subgrade and result in puncture of the FML. Various types of test subgrades have been used in an exploratory fashion to simulate the following situations:

- Bursting over interstitial spaces in a subgrade.
- Puncture over protrusions in an uneven subgrade.
- Bursting related to settlement of the subgrade.
- Bursting related to damage caused by placing a load on a soil or gravel cover material that has been placed on an FML.

Using geotextiles to protect an FML has also been investigated.

As an example of a typical testing device, a schematic of the testing device vessel developed by the Bureau of Reclamation is presented in Figure 5-37 (Frobel, 1981 and 1983). In this device, hydrostatic head and loading rates were simulated by a compressed air-on-water pressurization system. The compressed air-on-water system was preferred over a water pressure system to improve pressure control and to increase the range of operating pressures, i.e. to increase the maximum hydrostatic head. Maximum design pressure was 1034 kPa (150 psi) which is equivalent to approximately 105 m (350 ft) of head. Actual maximum pressure was limited by line pressure. The vessel top and bottom sections were fabricated from 500-mm (20-in.) outside-diameter pipe. Each vessel provided approximately 0.2 m² (300 in.²) of surface area for FML testing. To provide versatility in removing and installing test subgrades, the vessels were designed to accommodate interchangeable subgrade pans. The pressurization of the vessels was controlled and monitored during testing by a computer.

Morrison and Starbuck (1984) reported the results of testing unaged samples of 20-, 30-, and 45-mil PVC at the Bureau of Reclamation over three subgrades:

- Four Plexiglass pyramids placed in sand. These pyramids, similar to those developed by Rigo (1977), were used to attempt a reproducible puncture-type subgrade configuration. The pyramids have equilateral bases measuring 100 mm (4 in.) on a side and a height of 70 mm (2.75 inches). The tops of the pyramids are truncated 1 mm (0.04 in.) below the apex. The pyramids were surrounded with sand, the depth of which could be varied to give different pyramid heights.
- Five plastic pipes of varying diameters simulating interstitial voids. The diameters of the pipe ranged from 25 mm (1 in.) to 75 mm (3 inches). The open end of the pipes were level with a sandy subgrade.

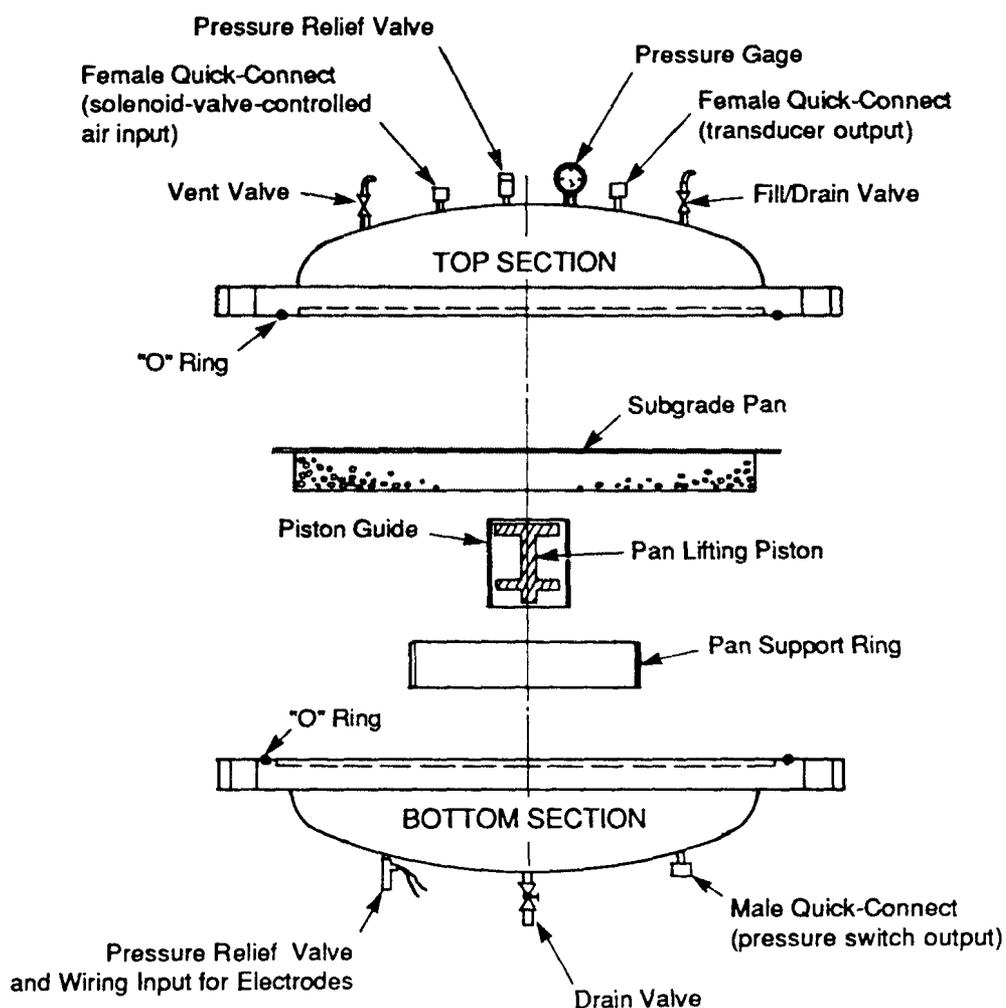


Figure 5-37. Detailed section through a hydrostatic testing vessel. (Based on Frobel, 1981, p 10).

The air pressure in these tests was raised incrementally 6.9 kPa (1 psi) every 30 minutes. Water temperature was maintained between 21.1°C (70°F) and 23.3°C (74°F). Test results are summarized in Table 5-60. These results indicated that of the three subgrades used, the one simulating interstitial voids was the most severe.

TABLE 5-60. HYDROSTATIC RESISTANCE OF THREE PVC FMLS OVER THREE DIFFERENT SUBGRADES^a

PVC thickness		Test subgrade ^b	Time to failure, min.	Maximum pressure		Remarks
mm	mils			kPa	lb/in. ²	
0.51	20	Cylinders	570	137.9	20.0	Failed on 75-mm (3-in.) cylinder
0.76	30	Cylinders	995	234.4	34.0	Failed on 75-mm cylinder
1.14	45	Cylinders	1189	286.1	41.5	Failed on 75-mm cylinder
0.51	20	Pyramids	...	503.3	73.0	No failure at maximum line pressure
0.76	30	Pyramids	...	875.6	127.0	No failure at maximum setting on pressure booster
1.14	45	Pyramids	...	875.6	127.0	No failure at maximum setting on pressure booster
0.51	20	Gravel	...	503.3	73.0	No failure at maximum line pressure
0.76	30	Gravel	2710	675.7	98.0	One pinhole
1.14	45	Gravel	...	834.3	121.0	No failure at maximum setting on pressure booster

^aWater temperature for all tests was maintained between 21.1°C (70°F) to 23.3°C (74°F).

^bCylinders: five plastic pipes with diameters of 25 mm (1 in.), 38 mm (1.5 in.), 50 mm (2 in.), 60 mm (2.37 in.), and 75 mm (3 in.); pyramids: four plastic pyramids with equilateral bases of 100 mm (4 in.) on a side and a height of 70 mm (2.75 inches). The pyramids were buried in sand so that they only had an effective height of 25 mm (1 inch); gravel: 9 to 19-mm (0.375 to 0.75-in.) size aggregate.

Source: Morrison and Starbuck, 1984, p 36.

Frobel et al (1987) tested three thicknesses of LLDPE with and without geotextiles and three thicknesses of HDPE in a testing device similar to the Bureau of Reclamation device over varying heights of test pyramids embedded in sand. The test pressure was raised 6.9 kPa (1 psi) every 30 min. of test until failure occurred. The results of these tests, which are presented in Table 5-61, indicate the effectiveness of using a geotextile to reduce the susceptibility of an FML to puncture.

Fayoux (1984) performed hydrostatic tests of a series of FMLs in a similar testing device using a subgrade consisting of a bed of crushed 20-40 mm quartzite stones. In these tests the pressure was increased incrementally 100 kPa (14.5 psi) after each minute of test. Fayoux observed that in general the thinner FMLs (e.g. 20-mil PVC) failed in areas where there was a lack of support (i.e. in the spaces between the stones) whereas the thicker, more rigid FMLs (all bitumens or polymer-modified bitumens) tended to span these spaces and fail where the stones were pointed or had sharp edges.

Steffen (1984) performed limited exploratory testing to determine the effect of uneven subgrade settlement on the deformation and bursting strength of FMLs. The testing device used was similar to those discussed except that pressurization was performed by air alone and a means for allowing the subgrade materials to be drawn off was incorporated in the bottom of the testing device. Steffen noted an uneven distribution of stresses across the cross section of the deformation area.

Fayoux (1984) also tried to determine what effect the action of two stones which are positioned on either side of an FML and which are under static stress would have on an FML's integrity. This type of action can occur when an FML is covered by granular materials. The important factors in such a study include:

- Particle size and shape of subgrade material.
- Particle size and shape of cover material.
- Whether the FML is protected by a geotextile.
- The type and thickness of the FML.
- The stress applied from above to the cover material.

To perform these tests, an FML sample was placed in the base of a hydrostatic tester and then covered with the cover material. The cover material was pressed into the FML sample at a specific rate up to a predetermined load and for a predetermined time. When the load was removed, the cover material was taken off the sample, and the sample still in its base was tested for hydrostatic puncture. Limited results suggested that a 30-mil PVC FML was susceptible to puncture by fine limestone gravel (0-10 mm) which had been loaded onto the FML at 300 kPa (43.5 psi) even when a geotextile was placed on one side of the FML. Other results suggested the effectiveness of using a geotextile to reduce an FML's susceptibility to puncture.

TABLE 5-61. HYDROSTATIC PUNCTURE RESISTANCE TESTING OF HDPE FMLS AND LLDPE FMLS WITH AND WITHOUT GEOTEXTILES OVER VARYING PYRAMID PROTRUSIONS

Polymer	FML system Thickness, mil Geotextile		Pyramid height					
			0.5 in.		1.0 in.		1.5 in.	
			Fail pressure, kPa ^a	Fail time, min.	Fail pressure, kPa	Fail time, min.	Fail pressure, kPa	Fail time, min.
LLDPE	20	None	4.1	<2	2.4	<2	1.6	<2
LLDPE	20	6 oz yd ⁻²	21.4	95	6.9	28	6.9	12
LLDPE	20	12 oz yd ⁻²	213.9	930	20.7	94	13.8	34
LLDPE	30	None	6.9	15	6.9	12	4.8	<2
LLDPE	30	6 oz yd ⁻²	69.0	308	27.6	142	27.6	130
LLDPE	30	12 oz yd ⁻²	345.0	1515	55.6	240	41.4	190
LLDPE	40	None	19.9	63	6.9	15	13.8	63
LLDPE	40	6 oz yd ⁻²	158.7	763	27.6	145	22.1	92
LLDPE	40	12 oz yd ⁻²	441.4	1930	62.1	270	62.1	280
HDPE	60	None	17.3	75	6.9	20	6.9	<2
HDPE	80	None	26.6	116	13.8	38	6.9	12
HDPE	100	None	40.6	176	13.8	52	6.9	28

^a1 psi = 6.9 kPa.

Source: Frobel et al, 1987, p 574.

5.5.2 Holes in FMLs

In order to function properly, an FML liner must be installed and placed into service free of flaws and holes through which liquid might flow. The liner must be liquid-tight so that only gases and vapors permeate on a molecular basis. The goal of improved design, materials, construction techniques, and quality control/quality assurance is to cause the incidence of holes in installed FMLs to approach zero and, at the same time, to build in enough redundancy and backup in the design to prevent leakage out of the containment unit if holes do occur. It is recognized that leaks in lined facilities have occurred due to imperfect planning design, that punctures and tears occur during construction and liner installation, and that there may be failures resulting from uneven subsidence or other failure of the supporting soil during service.

Because there was a lack of knowledge on leakage rates through flaws in FMLs, a study was undertaken to evaluate the rate at which liquids leak through flaws in the FML component of composite FML-soil liners (Brown et al, 1987). The flow of water through flaws of various sizes and shapes was measured using specially constructed permeameters filled with gravel or soil of known hydraulic conductivity. The variables that were studied included:

- Flaw size and shape.
- FML type and thickness.
- The presence or absence of a geotextile between the compacted soil and the FML.
- The hydraulic conductivity of the soil base on which the FML was placed.
- The liquid head.
- The liquid characteristics.

The soils were compacted in 60-cm diameter permeameters and overlain with the FMLs to be tested. Round holes, slits, or seam flaws of different sizes were incorporated in the FML samples.

A 15-cm layer of gravel was placed over the FML to provide ballast, and a head chamber was used to apply as much as 100 cm of head on the FML. Tests were also conducted with a permeameter that was modified to apply overburden pressure, which is shown schematically in Figure 5-38, and a permeameter that had a pressure vessel bolted to it so that the permeameter could approximate a 10-m hydraulic head. Three different soil bases were used. A gravel subbase was used to determine the flow rate allowed by the flaw without a limiting subbase. Two soil bases having nominal conductivities of $1 \times 10^{-4} \text{ cm s}^{-1}$ and $1 \times 10^{-6} \text{ cm s}^{-1}$ were used to determine the effect of the hydraulic conductivity of the base on flow rate. Tap water was the permeating liquid in most of the tests; however, limited testing was also performed with a simulated MSW leachate and xylene waste. A mathematical model was developed to simulate the flow rates through the permeameters and was modified to allow calculation of leak rates under field conditions.

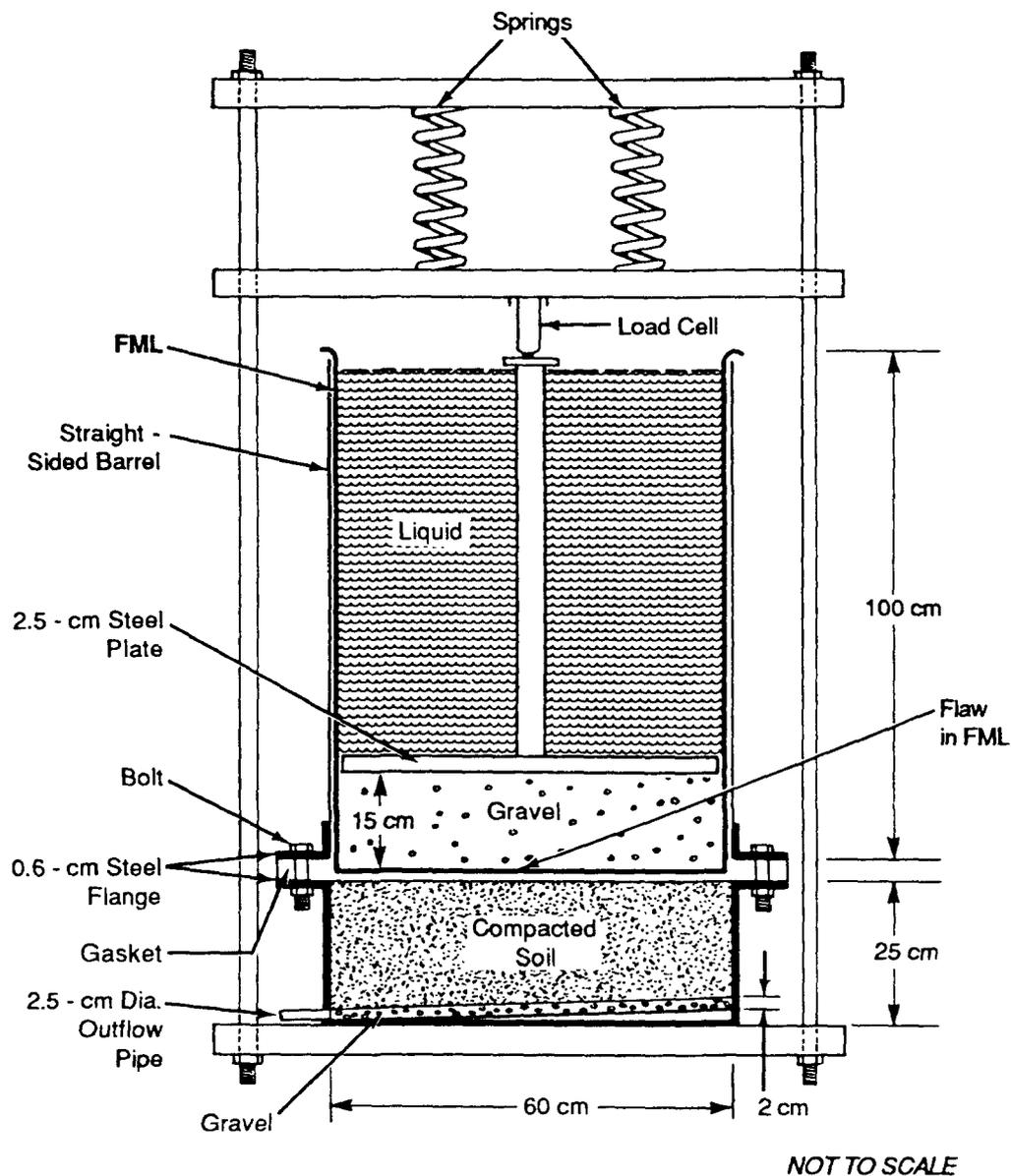


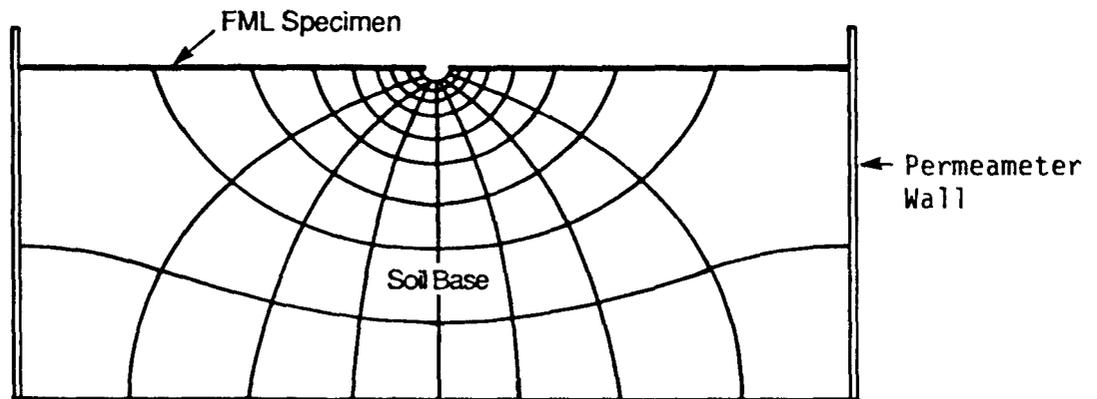
Figure 5-38. Schematic diagram of a permeameter modified to apply overburden pressure (not to scale). A 15 x 15-cm square of 0.3-cm mesh screen was placed over the flaw to prevent gravel from blocking flow. (Source: Brown et al, 1987, p 15).

The flow of liquids through flaws in FMLs was found to be primarily dependent on the size and shape of the flaw, the liquid head, and the hydraulic conductivity ability of the soil base. Flow rate was nearly independent of the FML thickness, liquid properties, and the presence or absence of an underlying geotextile.

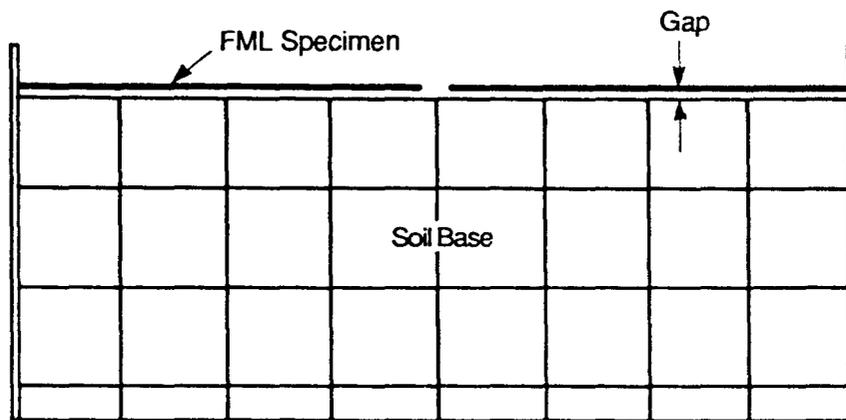
Variability in flow rates through seam flaws and slits was much greater than that through round holes due to the variable cross-sectional areas that

could result, depending on how much one side of the slit or the seam was displaced relative to the other. The results indicated that the average leak rates through the slit and seam flaws over a gravel base increased over twelve-fold when the flaw length was increased from 5 to 15 cm.

One observation made during the study was that the liquid passing through the hole spread laterally between the FML and the top of the compacted soil. Under these flow conditions, the liquid will infiltrate into the soil over a much larger area resulting in a higher leak rate. Figure 5-39 presents the two extremes of the flow patterns beneath a hole in an FML, one in which there is no lateral flow beneath the hole, and the second in which there is lateral flow in the gap between the liner and the soil. In estimating leakage rates, it would be too conservative to assume that a seal has been formed between the FML and the soil without a gap through which lateral flow can occur. Thus, width was included in the mathematical model.



(a) Flow pattern in which there is no lateral flow between an FML and the soil base.



(b) Flow pattern in which there is complete lateral flow between an FML and the soil base.

Figure 5-39. Flow patterns under the extreme conditions below a hole in an FML. (Source: Brown et al, 1987, p 31).

For soil bases, the head loss across the system may be divided into the head loss as the liquid enters the hole, the head loss across the hole in the FML, the head loss as the liquid flows laterally between the FML and the soil, and the head loss through the soil. The amount of head loss caused by the liquid flowing laterally between the FML and the soil depends on the width of the gap between these two media. The gap widths for the 10^{-4} and 10^{-6} soils were estimated from the permeameter data to be 0.015 and 0.002 cm respectively. Thus, less permeable soils containing greater amounts of clay form a better seal with the FML and restrict lateral flow of liquids. Gap widths and resultant flow rates were also decreased by overburden pressure from simulated layers of waste.

The results of the tests with the pressurized system indicated that soil can erode just below a flaw in an FML, particularly when the liquid head is large (e.g. in a lagoon) and when the base conductivity is greater than 10^{-6} cm s⁻¹. This evidence of erosion caused by water flowing through flaws in FMLs under elevated head is a serious concern, since erosion of the soil base may result in stretching and the eventual rupture of the FML. However, a geotextile placed below an FML can result in lateral flow of the liquid and protect the soil from erosion. The mathematical model was adapted to predict the conditions necessary for erosion to begin. It is recognized that the model does not strictly represent an FML-soil liner in which the compacted soil has a hydraulic conductivity $\leq 1 \times 10^{-7}$ cm s⁻¹, but it illustrates the protection that a geotextile affords a soil below an FML with a flaw.

5.5.3 In-Service Drainage Capability of Geotextiles and Geonets

Transmissivity is the property most often used to measure the in-plane drainage capability of a synthetic drainage medium. ASTM D35 Committee on Geotextiles, Geomembranes, and Related Products has developed a standardized parallel flow test to measure hydraulic transmissivity (ASTM D4716). In this type of test, a testing device provides a longitudinal flow path so that the stream lines of flow through the drainage medium being tested are generally parallel. A schematic of a parallel flow hydraulic transmissivity testing device is presented in Figure 5-40. This type of device can be used to test geonets, geocomposites, and geotextiles. An important factor in the in-service drainage capability of a synthetic drainage medium is the normal stress acting on the medium. The ASTM method determines hydraulic transmissivity under specified constant hydraulic head conditions and under varying compressive stresses.

In a parallel flow testing device, and assuming laminar flow, hydraulic transmissivity can be calculated as follows:

$$\theta = \frac{qL}{\Delta hW}$$

where

$$\theta = \text{transmissivity (ft}^2 \text{ min.}^{-1}\text{)}$$

q = flow rate ($\text{ft}^3 \text{ min.}^{-1}$)

L = length (ft)

Δh = hydraulic head difference forcing flow (ft), and

W = width (ft).

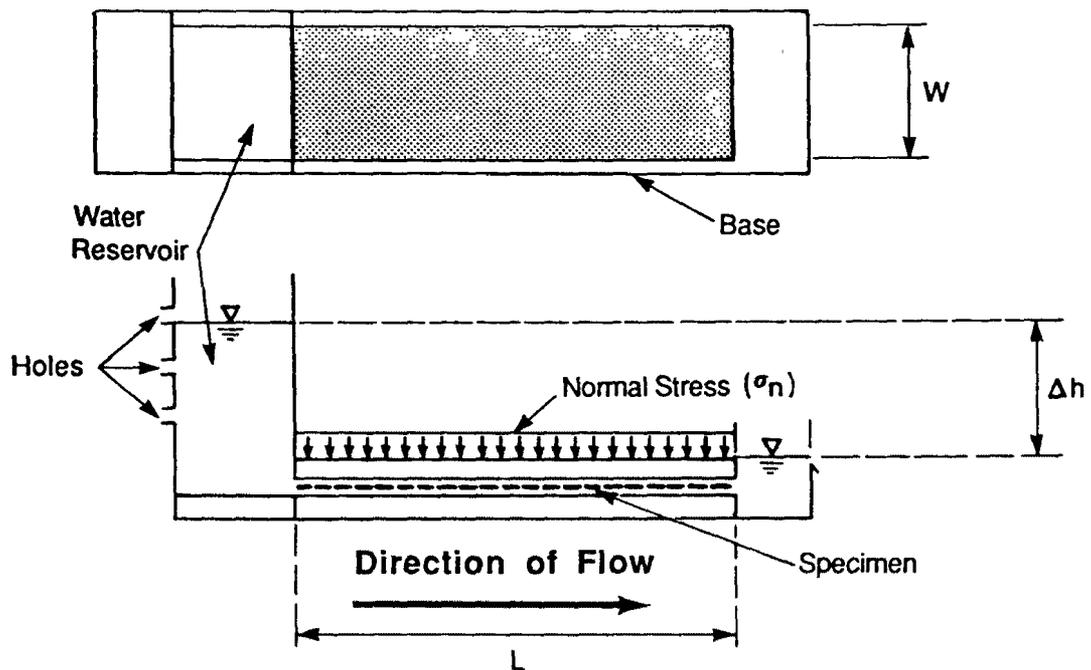


Figure 5-40. Hydraulic transmissivity testing device. Note the holes in the water reservoir for controlling hydraulic head. (Source: Carroll, 1987, p 19).

The derivation of this formula from Darcy's law is discussed in Section 4.2.5.3 (p 4-150). Thus, it can be seen that transmissivity is the rate of flow (or discharge) per unit width per unit hydraulic gradient ($\Delta h/L$).

This section presents limited results of testing geotextiles and geonets for hydraulic transmissivity.

5.5.3.1 Hydraulic Transmissivity of Geotextiles--

The range of drainage through geotextiles has been evaluated by Gerry and Raymond (1983). The resulting typical values for transmissivity are presented in Table 5-62. These results indicate that only the nonwoven-needed geotextiles have appreciable in-plane flow capability and thus are preferable in applications where in-plane flow is important. Koerner and

Bove (1983) tested a number of commercially available nonwoven-needled geotextiles. The results of these tests are summarized in Figure 5-41. Koerner and Bove (1983) made the following observations:

- All fabrics show an exponentially decreasing trend due to initial compression of these lofty fabrics at low stresses.
- All fabrics show a nearly constant transmissivity value at stresses higher than approximately 19 kPa (400 psf) where the fiber structure is sufficiently dense to support the applied stress.
- This constant, and residual, value is in the range of 0.40 to 1.4 x 10⁻⁶ m³/s·m (0.003 to 0.010 ft³/min·ft).
- There is considerable crossover of trends in the data from the various geotextiles that were tested.
- There is, however, a general trend that the heavier and/or thicker geotextiles have the highest transmissivity.

TABLE 5-62. TYPICAL VALUES OF DRAINAGE CAPABILITY (IN-PLANE FLOW) OF GEOTEXTILES^a

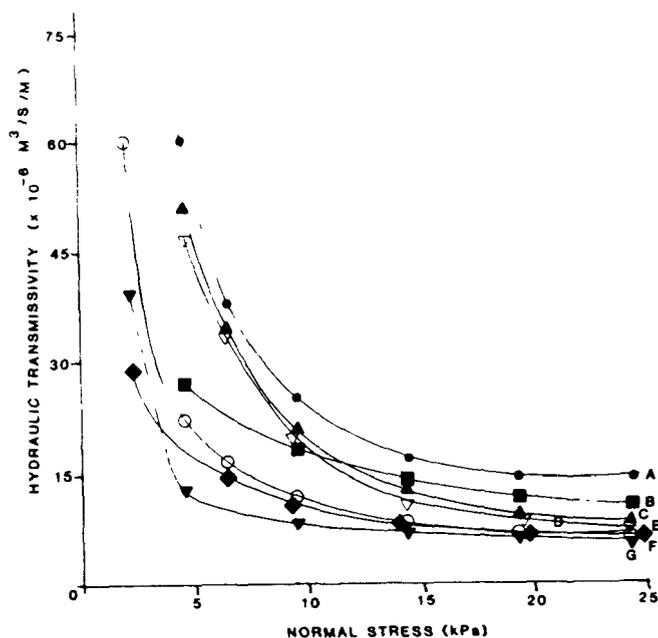
Type of geotextile	Transmissivity		Permeability coefficient	
	m ³ /s·m	ft ³ /min·ft	cm/s	ft/min
Nonwoven-heat set	3.0 x 10 ⁻⁹	2.0 x 10 ⁻⁶	0.0006	0.0012
Woven-slit film	1.2 x 10 ⁻⁸	8.1 x 10 ⁻⁶	0.002	0.0039
Woven-monofilament	3.0 x 10 ⁻⁸	2.0 x 10 ⁻⁶	0.004	0.0079
Nonwoven-needled	2.0 x 10 ⁻⁶	1.3 x 10 ⁻³	0.04	0.079

^aValues taken at applied normal pressure of 40 kPa (830 psf).

Source: Gerry and Raymond, 1983.

5.5.3.2 Hydraulic Transmissivity of Geonets Under Different Boundary Conditions--

Limited results of testing a solid rib and a foamed rib geonet using rigid plates above and below the nets are presented in Section 4.2.5.3. The results of exploratory research on the effect of intrusion by FMLs into geonets were also discussed. This subsection presents data from transmissivity tests in which geonets were compressed between different types of surfaces to



Geotextile	Mass Per Unit Area		Nominal Thickness		Polymer	
	oz/yd ²	g/cm ²	Mils	mm	Type	Filament
A	16	540	210	5.3	PET	continuous
B	18	600	190	4.7	PET	staple
C	18	600	150	3.8	PP	continuous
D	16	540	160	4.1	PP	continuous
E	12	400	110	2.8	PP	continuous
F	14	470	130	3.3	PP	staple
G	16	540	110	2.8	PET	continuous

FIG. 2—Transmissivity response versus applied normal stress for various needled nonwoven geotextiles, after Koerner and Bove [5].

Figure 5-41. Transmissivity response versus applied normal stress for various needled nonwoven geotextiles. (Source: Koerner and Bove, 1983, p 37).

simulate various in-service conditions (Williams et al, 1984; Koerner, 1988). The variables in these tests included:

- Type of geonet.
- Number of layers of geonet.
- Type of surface and support of surface contrasting top and bottom of geonet.
- Hydraulic gradient.
- Compressive stress.

In the tests reported by Williams et al (1984), three types of geonets were tested. One geonet was tested in a single, double, and triple layer configuration. Testing was performed with various boundary conditions so that the geonet was contacted by either a steel plate or a clay covered by a geotextile or a 20-mil PVC FML. Complete results are presented in Figure 5-42.

Williams et al (1988) observed the following:

- The hydraulic transmissivities of the tested geonets tended to decrease with increasing hydraulic gradient (which indicates transient or turbulent flow) and with increasing normal stresses.
- The effect of normal stress varied with the type of geonet (Tests 1, 4, and 5).
- Under the steel-plate-facing-steel-plate test conditions (Tests 1, 2, and 3), the hydraulic transmissivities of multiple layers of geonets were approximately additive.
- The geotextiles in contact with geonets reduced the hydraulic transmissivity of the nets due to intrusion of the geotextile into the channels of the net. The needle-punched geotextile intruded more than the heat-bonded geotextile (Tests 8 and 9).
- The 20-mil PVC in contact with a geonet reduced the hydraulic transmissivity of the geonet (Test 10).

Koerner (1988) measured the hydraulic transmissivity of a 0.25-in. thick geonet under two different boundary conditions. The first profile simulated the service conditions of a geonet in an FML-only top liner design, and the second profile simulated the service conditions of a geonet in a design containing an FML-soil composite liner as the top liner. These tests were performed (1) to determine whether the clay particles would extrude through the geotextile voids and (2) to determine whether the intrusion of the geotextile into the geonet via the overlying clay would significantly affect the drainage capacity of the geonet. The FML used in these tests was a 60-mil HDPE, and the geotextile was a needlepunched, nonwoven polyester, continuous filament fabric of 16 oz yd⁻² mass per unit area. The load was applied for 15 minutes, and flow was measured over the subsequent 15 minutes. The results of these tests are presented graphically in Figure 5-43. These results show the effect of hydraulic gradient and applied normal pressure on flow rate. In addition, flow rates through the HDPE-geonet-geotextile-clay cross section were 20-40% less than the flow rates through the HDPE-geonet-HDPE cross section, indicating that intrusion of the geotextile into the geonet did occur. The flow response curves and the cleanliness of the geonet test specimens after disassembly indicated, however, that flow was not blocked by extrusion of the clay through the geotextile voids.

It should be noted that these results are based on short-term tests using water to measure flow rates. The effect of creep on the flow rates of

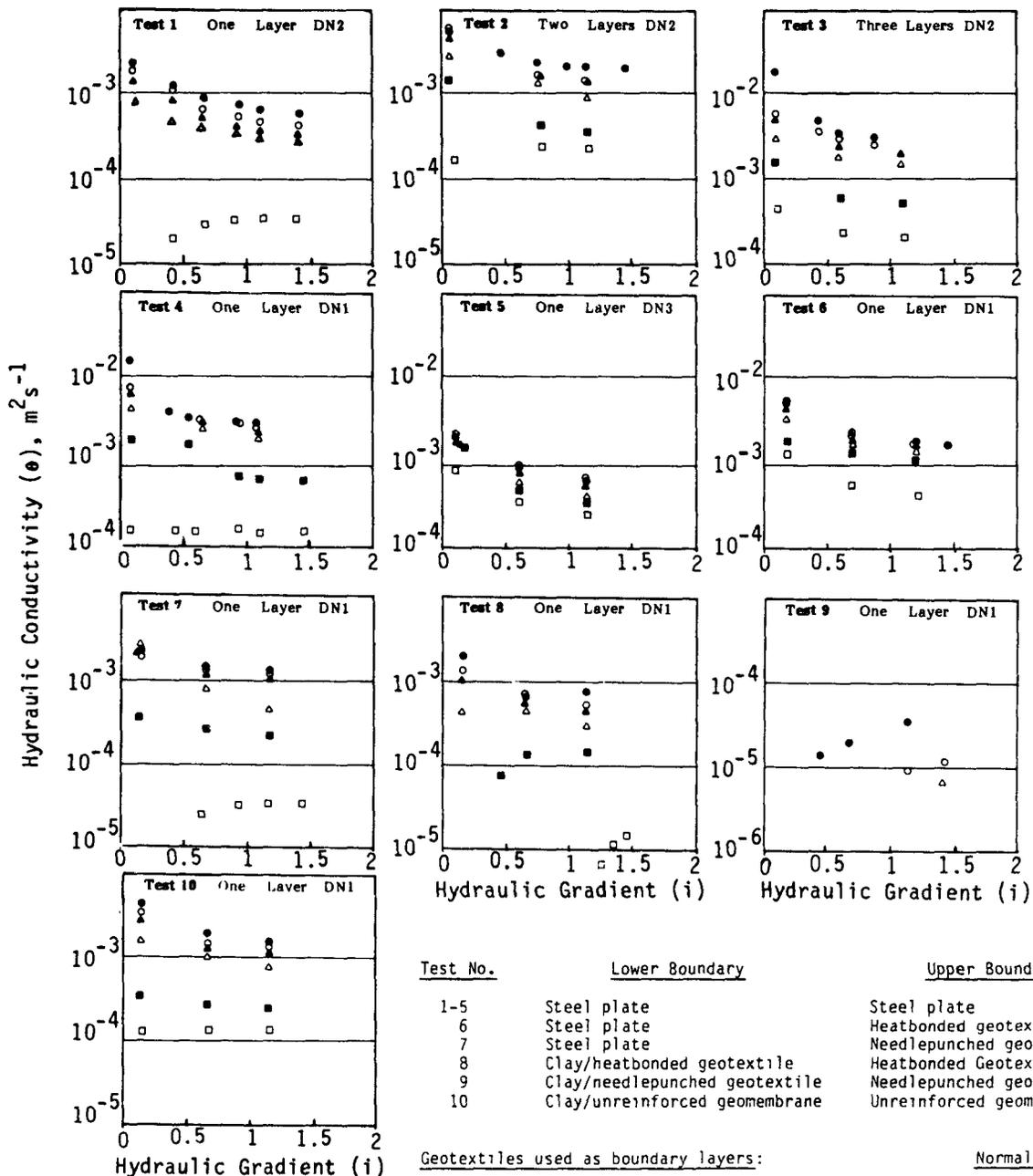
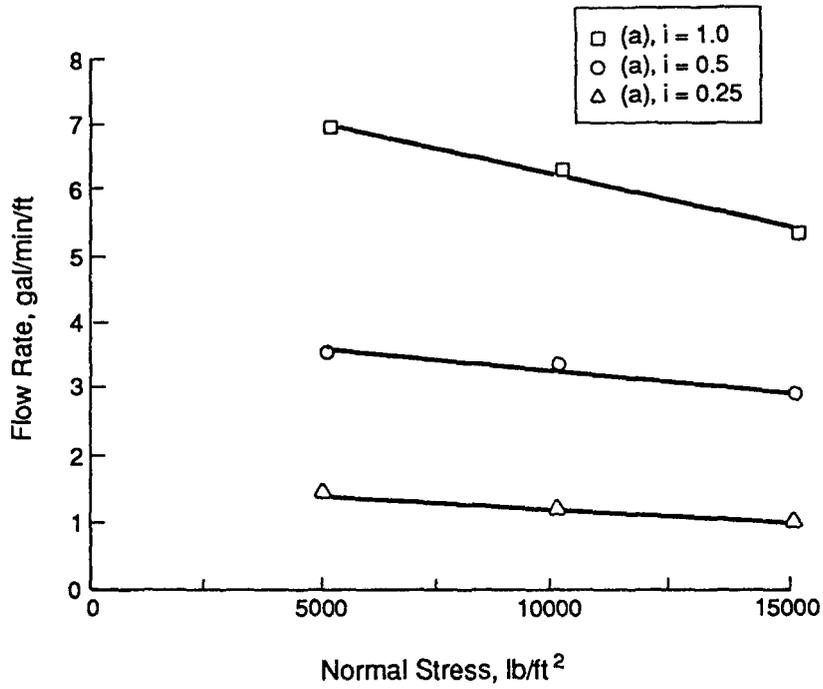
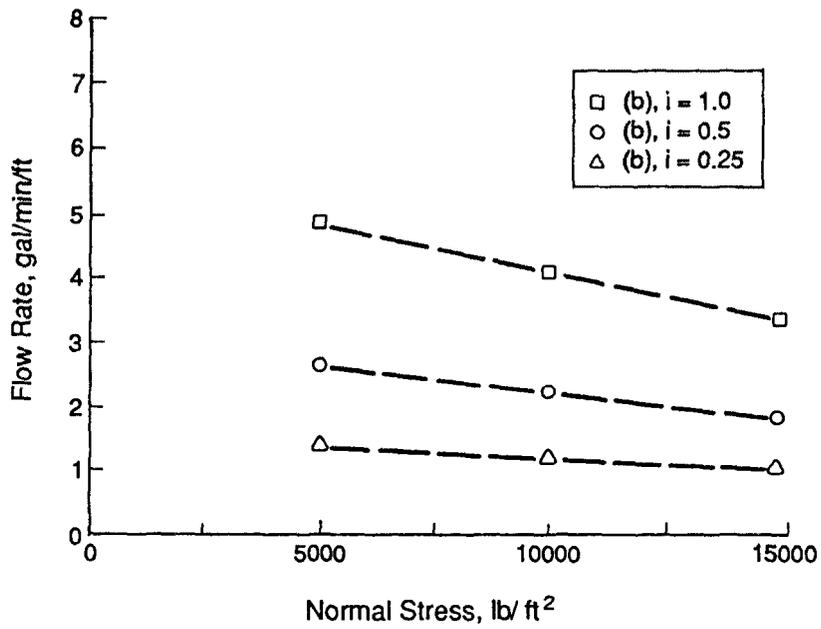


Figure 5-42. Results of transmissivity tests at 20°C on nets DN1, DN2, and DN3 performed under a range of normal stresses with various boundary conditions. (Source: Williams et al, 1984, p 402).



(a) HDPE-Geonet-HDPE Cross Section



(b) HDPE-Geonet-Geotextile-Clay Cross Section

Figure 5-43. In-plane flow rate tests of a 0.25-in. thick geonet under different boundary conditions. (Source: Koerner, 1988).

these trial cross sections needs to be investigated. For example, a geotextile serving as a filter between a geonet and an overlying soil liner could creep due to triaxial stresses potentially resulting in further intrusion into the geonet or opening of the voids which would allow extrusion of the clay into the drainage system. In addition, the effect of organic waste constituents being absorbed by synthetic drainage materials on the short-term and long-term drainage properties of cross sections containing these materials needs to be investigated.

5.6 BIODEGRADATION AND OTHER BIOLOGICAL STRESSES

In-service FMLs and other materials used in the construction of on-land containment units for the storage or disposal of hazardous and toxic wastes or materials contact soil and liquid, which are biological in nature. Overall, relatively few data have been obtained either in the laboratory or from the field to show that biological factors have contributed to failure or have had adverse effects on the performance of FMLs. It is recognized, however, that FMLs are relatively new and have been in service for only a few decades. There is concern regarding the service life of FMLs in these environments over extended time periods.

The biological effects on FMLs that have been observed are:

- Loss of monomeric plasticizer from buried polymeric FMLs through biodegradation. The polymer content in these FMLs have not exhibited such degradation. The effect on the total composition, e.g. if it is PVC, is embrittlement.
- Variations in the biodegradability of different plasticizers and compounding oils.
- The adherence of fungi to some FMLs which probably reflects the presence of particles and chemically active groups on the surface of the FML. However, the effect does not penetrate the thickness of the FML.

Burial tests, such as the burial test in ASTM D3083 which is appropriate for testing natural and some synthetic fabrics, e.g. rayon and coated natural fabrics, have been performed on synthetic polymers and polymeric products and synthetic fabrics, but the exposure times (30 days) are far too short to cause degradation of these materials. Long-term exposure (e.g. years) are generally needed for assessing the biodegradability of synthetic polymers such as those used in geosynthetics and pipe.

Early in the EPA waste disposal program there was concern regarding the biodegradability of plastics and rubber products that would be placed in landfills. Such products as tires and polyethylene wastes were recognized as being particularly resistant to degradation in landfills (Gutfreund, 1971). A number of research programs in the USA and Europe were initiated to investigate methods of degrading polyethylenes by biological means. Albertsson

(1978a,b) observed that, with specially prepared unprotected HDPE containing trace amounts of carbon-14, a small amount of microbial conversion of the ^{14}C in the polyethylene to $^{14}\text{CO}_2$ took place. The HDPE had a 0.958 density, contained no antioxidant or carbon black and was either made into thin films of 0.8-mil thickness or pulverized to maximize surface area. Other researchers (Colin et al, 1976; Potts, 1978) have found that only the low molecular weight fractions are metabolized by microbial action.

Data on long-term burial of commercial HDPE FMLs are not available. Colin et al (1986) exposed commercial nonwoven geotextiles to accelerated soil-burial for up to 7 years and examined the recovered samples by burst strength testing, optical microscopy, and infrared spectroscopy. The specimens were based on polypropylene, polyethylene terephthalate (PET), and a mixture of polypropylene and bicomponent fibers (nylon-coated polypropylene). None of the samples showed a significant decrease in strength outside the experimental error.

Note: The subject of the longevity of FMLs and other polymeric construction materials in service in waste containment units is discussed more fully in Chapter 4.

5.7 ACCELERATED AGING AND WEATHERING TESTS

FML liners in service in many surface impoundments, including water reservoirs and cooling and wastewater ponds, are not covered with soil. They are thus exposed to the weather, that is, to the ultraviolet and infrared radiation of sunlight, oxygen, ozone, temperature variation, wind and wave action, and rain. Considerable information has been accumulated over the years on the weathering characteristics of polymeric compositions (Davis and Sims, 1983; Hawkins, 1972). Considerable data have also been accumulated on the weathering of some plastic and rubber FMLs in service (Strong, 1980).

The effects of weathering can take extended time for trends to develop; consequently, accelerated test methods that correlate with actual service are needed. Clark (1971) discusses artificial weathering devices and their correlation with weather exposure.

In this section the comparative results of roof exposure of eight FMLs for 3.37 years and accelerated outdoor exposure of ten FMLs are reported and discussed.

5.7.1 Roof Exposure Tests

To determine the effect of weathering on FMLs, such as would occur on the slopes of an uncovered surface impoundment, Haxo et al (1985b) exposed 6 x 6-in. specimens of 11 different polymeric FMLs on a rack placed on Matrecon's laboratory roof in Oakland, California, at a 45° angle to the south. Three specimens of each FML were hung on boards so that only one side was exposed to the sun. The rack with the test specimens is shown in Figure

5-44. The specimens were hung loosely to allow them to change dimensions freely. These 11 FMLs were based on the following polymers:

- Butyl rubber (fabric-reinforced) (31 mil).
- CPE (30 mil).
- CSPE (nylon-reinforced) (30 mil).
- ELPO (20 mil).
- EPDM (2 FMLs) (30 and 62.5 mils).
- Neoprene (2 FMLs) (31 and 62.5 mils).
- Polyester elastomer (7 mil).
- PVC (2 FMLs) (20 mil).

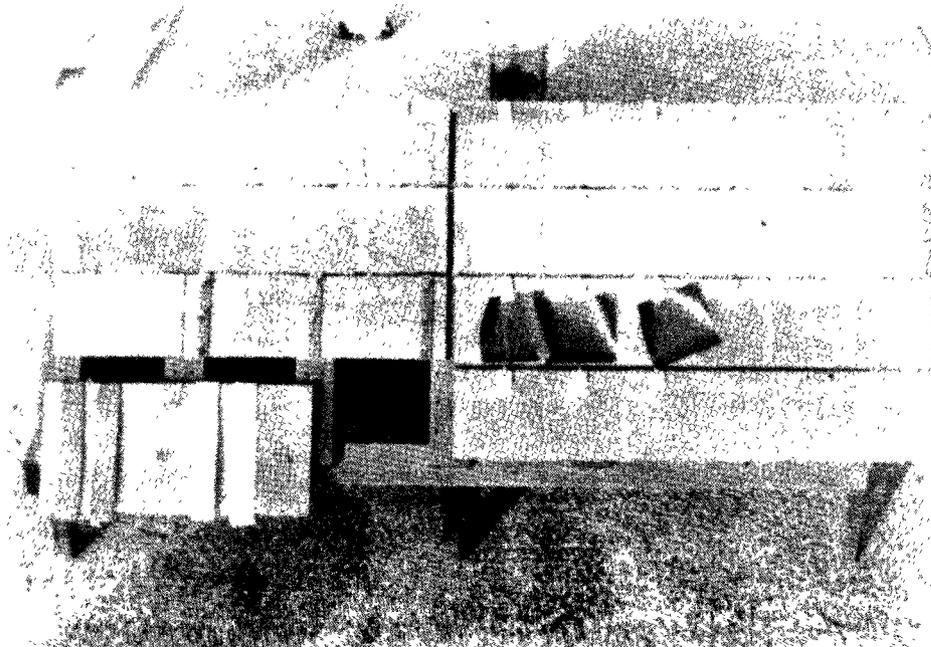


Figure 5-44. Rack loaded for exposing FML specimens. The rack was exposed at a 45° angle to the south. (Source: Haxo et al, 1985b, p 154).

One specimen of each of the FMLs was removed after 343, 745, and 1231 days of exposure, and the following properties were determined:

- Weight.
- Dimensions.

- Volatiles, in accordance with Matrecon Test Method 1 (Appendix G).
- Extractables, in accordance with Matrecon Test Method 2 (Appendix E).
- Tensile properties, in accordance with ASTM D412/D638, using a special dumbbell which has the same width as that of the ASTM D412 Die C/ ASTM D638 Type IV dumbbell but which has a shorter overall length, a shorter narrow section, and smaller tab ends. Two specimens were tested in each direction. (Note: At the time this work was performed, it was desired that all FMLs be tested in accordance with the same test procedure; thus, fabric-reinforced FMLs were tested with dumbbell-type specimens. The preferred test specimen for testing limited-size fabric-reinforced FML sample is a 1-in. strip specimen in accordance with ASTM D751, Method B.)
- Tear strength, in accordance with ASTM D624 using Die C specimen (unreinforced FMLs only). Two specimens were tested per direction.
- Hardness, in accordance with ASTM D2240.

Changes in surface characteristics, including cracking and checking, were also observed.

Changes in the properties of the FML samples after 1231 days of exposure are presented in Tables 5-63 and 5-64. The results are comparative as the samples were all subjected to the same exposure. The results indicate some of the differences in the weatherability of different polymeric FMLs. Some of the major effects of the exposure were:

- With only a few exceptions, the specimens lost weight and extractables content; the largest losses were sustained by the two PVC FMLs which lost plasticizer. The CSPE increased in weight and volatiles, perhaps due to moisture absorption, but appeared to lose in extractables. The polyester elastomer FML lost significantly in weight and, at the same time, increased in extractables content which may indicate some degradation of the polymer.
- The moduli (i.e. stresses at 100 and 200% elongation) of all the FMLs increased. The amount and mechanism of increase varied with the individual FML. The CSPE and PVC FMLs increased the most, and one EPDM, the ELPO, and the polyester FMLs increased the least. The increase in modulus by the CSPE FML was the result of crosslinking which took place during the exposure period; on the other hand, the increases in the moduli of the PVC FMLs were due to loss of plasticizer.
- All FMLs, except for the butyl rubber, lost in elongation. The butyl FML was reinforced with a fabric which controlled the elongation at break. The CSPE and neoprene FMLs sustained the greatest losses. The decrease in the elongation of the CSPE FML was due to crosslinking.

TABLE 5-63. EFFECT OF EXPOSURE ON ROOF OF LABORATORY IN OAKLAND,
CALIFORNIA, ON PROPERTIES OF POLYMERIC FMLS
Butyl, CPE, CSPE, ELPO, and EPDM

Polymer	Butyl	CPE	CSPE	ELPO	EPDM	EPDM
Compound type ^a	XL	TP	TP	CX	XL	XL
Fabric type	Nylon	...	Nylon	...	...	...
Thread count, epi ^b	20 x 10	...	8 x 8	...	...	...
Nominal thickness, mil	31.3	30	30	20	62.5	30
FML number ^c	57R	77	6R	36	8	26

	Exposure time, d	Butyl	CPE	CSPE	ELPO	EPDM	EPDM
<u>Analytical properties</u>							
Volatiles ^d , %	0	0.29	0.14	0.51	0.15	0.38	0.50
	1231	0.30	0.33	2.57	0.06	0.45	0.62
Extractables ^e , %	0	6.36	9.13	3.77	5.50	23.41	22.96
	1231	5.71	6.32	3.32	5.33	21.31	21.75
Solvent ^f	...	MEK	n-heptane	acetone	MEK	MEK	MEK
<u>Dimensional properties</u>							
Weight, % change	1231	-3.32	-3.15	1.80	-1.93	-3.91	-3.11
Area, % change	1231	-1.29	-7.33	-6.04	-1.38	-3.25	-2.87
<u>Physical properties^g</u>							
Tensile at fabric break, ppi	0	72.7	...	35.9	...	...	...
	1231	116	...	138	...	...	...
Tensile at ultimate break, psi	0	^h	2198	56.1 ⁱ	2620	1593	1900
	1231	...	97	172	96	113	108
Elongation at ultimate break, %	0	42	403	243	665	510	450
	1231	102	81	52	95	91	94
Stress at 100% elongation, psi	0	...	900	30.5 ⁱ	932	335	358
	1231	...	139	265	119	142	119
Stress at 200% elongation, psi	0	...	1180	50.4 ⁱ	1018	770	878
	1231	...	135	...	116	131	121
Tear strength, lb	0	...	7.38	...	8.56	12.75	7.40
	1231	...	116	...	98	96	87
Hardness, durometer points	0	71A	80A	77A	32D	58A	58A
	1231	-2A	+4A	-3A	+6D	+7A	+3A

^aXL = crosslinked; TP = thermoplastic; CX = semicrystalline thermoplastic.

^be_{pi} = Ends per inch. Data are for machine and transverse directions, respectively.

^cMatrecon identification number; R = fabric-reinforced.

^dDetermined in accordance with Matrecon Test Method 1 (see Appendix G).

^eDetermined in accordance with Matrecon Test Method 2 (see Appendix E).

^fMEK = methyl ethyl ketone.

^gValues for tensile properties and tear resistance are averaged for machine and transverse directions.

^hBulk of FML's strength is in the nylon fabric. The butyl coating over the fabric tended not fail catastrophically, and no useful value could be obtained for tensile at ultimate break.

ⁱReported value is in ppi.

Source: Haxo et al, 1985b, pp 243-45.

TABLE 5-64. EFFECT OF EXPOSURE ON ROOF OF LABORATORY IN OAKLAND,
CALIFORNIA, ON PROPERTIES OF POLYMERIC FMLS

Neoprene, Polyester Elastomer, and PVC

Polymer		Neoprene	Neoprene	Polyester	PVC	PVC
Compound type ^a		XL	XL	CX	TP	TP
Nominal thickness, mil		31.3	62.5	7	30	30
FML number ^b		43	82	75	11	59
	Exposure time, d					
<u>Analytical properties</u>						
Volatiles ^c , %	0	0.45	0.19	0.26	0.15	0.31
	1231	1.03	0.76	2.74	0.42	0.13
Extractables ^d , %	0	13.69	13.43	0.13	33.90	35.86
	...	9.93	11.45	3.92	26.27	27.78
Solvent ^e	1231	acetone	acetone	MEK	CCl ₄ +CH ₃ OH	CCl ₄ +CH ₃ OH
<u>Dimensional properties</u>						
Weight, % change	1231	-3.11	-1.31	-6.23	-15.61	-10.31
Area, % change	1231	-3.86	-2.31	-1.42	-10.28	-10.75
<u>Physical properties^f</u>						
Tensile at ultimate break, psi	0	1785	1755	6768	2878	2558
	1231	88	92	70	97	111
Elongation at ultimate break, %	0	320	400	575	357	375
	1231	63	63	83	77	86
Stress at 100% elongation, psi	0	460	383	2585	1420	995
	1231	184	188	110	161	185
Stress at 200% elongation, psi	0	1038	790	2733	2013	1580
	1231	149	168	107	128	145
Tear strength, lb	0	5.41	11.13	5.92	11.20	9.89
	1231	86	82	103	134	144
Hardness, durometer points	0	57A	57A	45D	29D	26D
	1231	+14A	+12A	+7D	+18D	+13D

^aXL = crosslinked; CX = semicrystalline thermoplastic; TP = thermoplastic.

^bMatrecon identification number.

^cDetermined in accordance with Matrecon Test Method 1 (see Appendix G).

^dDetermined in accordance with Matrecon Test Method 2 (see Appendix E).

^eMEK = methyl ethyl ketone; CCl₄+CH₃OH = 2:1 blend of carbon tetrachloride and methyl alcohol.

^fValues for tensile properties and tear resistance are averaged for machine and transverse directions.

Source: Haxo et al, 1985b, pp 246-47.

5.7.2 EMMAQUA Testing

As part of a test program to assess the durability of FML field seams in various environmental conditions that simulated over a short period (i.e. 52 weeks or less) conditions that FMLs may encounter in service, seam samples were exposed for 1 year in the accelerated outdoor exposure test, EMMAQUA, (Equatorial Mount with Mirror for Acceleration with Water Spray) (Morrison and Parkhill, 1987). This accelerated exposure test is described and discussed in Section 4.2.2.5.4, and in ASTM D4364 and G90. During this period of time, 32 representative seam samples were exposed to an accumulated total solar radiation energy of 1.45 million langleys (cal cm^{-2}), i.e. 60,648 MJ/m². This level of exposure is reportedly equivalent to approximately 8 years of conventional outdoor exposure at the latitude of Phoenix, Arizona, where the exposure test was run. At 6 months in the EMMAQUA test, by which time the samples had been exposed to 660,430 langleys (27,632 MJ/m²), and at the completion of the exposure, the samples were inspected and rated on a scale of 1 (extremely poor condition) to 10 (as-received condition) for the following:

- General appearance.
- Delamination of seam.
- Checking/crazing.
- Blistering.
- Warping.

Results of the visual inspections are summarized in Table 5-65. At the end of exposure the peel strengths of the samples were determined; retention of peel strength averaged approximately 70-80% of the values of the unexposed samples.

The results of the exposure indicated that the 1-year EMMAQUA exposure period may be too long. Exposure under the accelerated weathering conditions was too severe for some materials, thus producing results that may not reflect exposure to natural weathering. For example, several polyethylene samples suffered severe thermal degradation. Morrison and Parkhill (1987) reported that their organization, U.S. Bureau of Reclamation, has routinely conducted outdoor exposure tests on FMLs and never observed this type of degradation. The 80-mil HDPE extrusion lap-welded field seam, Sample No. 32, had melted enough to prevent testing of the seam; the LLDPE field seam, Sample No. 34, contained two areas where the material appeared to have melted. The thermal degradation appeared to have occurred between 6 and 12 months of exposure. Consequently, further studies are recommended to determine if the EMMAQUA exposure is truly representative of the long-term natural weathering of FMLs. It should be noted that consideration is being given to requiring FMLs, intended for exposure to natural weathering (as in surface impoundments), and factory seams of these materials to pass a weathering test (EMMAQUA exposure) of a minimum of 1,000,000 langleys with a rating of 7 or better on a scale of one for extremely poor condition to 10 for

TABLE 5-65. RATINGS IN VISUAL INSPECTIONS OF SELECTED SAMPLES EXPOSED TO EMMAQUA CONDITIONS

Sample number	FML ^b	General appearance		Delamination of seam		Checking/crazing		Cracking		Blistering		Warping		Remarks
		6 mos.	12 mos.	6 mos.	12 mos.	6 mos.	12 mos.	6 mos.	12 mos.	6 mos.	12 mos.	6 mos.	12 mos.	
1	36-mil CPE(R)	8	6	9	8	10	10	10	10	9	7	8	7	Some blisters inside seam area at 6 months.
5	36-mil CSPE(R)	9	8	10	10	10	10	10	10	10	10	9	8	...
9	38-mil EIA(R)	9	8	10	10	10	10	10	10	10	10	9	8	Sample was stiff.
10	30-mil EPDM(R)	9	9	10	10	10	10	10	10	10	10	9	9	...
11	30-mil CPE	8	7	10	10	10	9	10	10	10	10	8	7	...
13	30-mil LLDPE	7	4	10	10	10	7	9	6	10	10	8	4	At 12 months sample contained two places where it appears to have melted.
14	30-mil PVC	8	7	10	10	9	7	10	10	10	10	8	7	...
16	30-mil PVC/CPE	8	7	10	10	10	10	10	10	10	10	8	6	Sample was stiff.
30	30-mil HDPE	8	7	8	8	10	10	10	10	10	10	8	5	Sample was brittle.
32	80-mil HDPE	8	5	10	10	10	9	10	10	10	10	8	8	Sample was very brittle and contained large area which appears to have melted.

^aKey to rating system: 10 as received; 9 excellent; 8 good; 7 good to fair; 6 fair; 5 fair to poor; 4 poor; 3 poor to very poor; 2 very poor; 1 extremely poor.

^bR = fabric-reinforced.

Source: Morrison and Parkhill, 1987, pp 78-80.

"as-received" condition. A rating of 7 or better means that there are no checks greater than 0.006 in. in width in the exposed sample when bent around a 0.5-in. diameter mandrel. Under the EMMAQUA exposure, the total solar radiation energy of 1,000,000 langleys can be achieved in approximately 8 months.

5.8 COMPATIBILITY TESTING OF FMLS IN ACTUAL WASTE CONTAINMENT UNITS

An effective way of assessing the compatibility of an FML with the waste which it may be used to contain is to place a sample of the FML in the pond or drainage system of a containment unit containing the same type of waste liquid or leachate. If the proposed unit is a surface impoundment, mounting large samples of the candidate FML on racks and placing the racks on the slope of the existing impoundment, which contains waste liquids of the type to be impounded, would yield exposure conditions similar to those of a liner in actual service. Placing the racks on the north slope with part of the samples in the waste liquid and part in the air would also allow a section of the samples to be exposed at the interface. Such an exposure would assess the effects of "real world" exposure and the accumulated effects of many months of variable conditions due to weathering and changes in the composition of the waste liquid. The results of a one-year coupon exposure test, which was performed by Matrecon for a client, showed substantially more severe effects than a four-month EPA Method 9090-type immersion test performed in the laboratory with a "representative" sample of the wastewater; however, the results of comparing the different FMLs yielded the same choice of FML to use in lining a proposed pond.

Tratnyek et al (1984) described a methodology for exposing removable coupons under various conditions, including compatibility tests and monitoring the conditions of an FML and other materials of construction during actual service in a facility.

5.9 SIMULATED EXPOSURE TESTING OF ADMIXED LINER MATERIALS

As part of the two simulated service research programs discussed in Sections 5.4.1.1 and 5.4.1.2, asphalt concrete and soil cement samples were exposed to MSW leachate and various hazardous wastes. The results of these tests are discussed in the following subsections. It should be noted that these research programs were intended to determine chemical compatibility and thus tested only limited-size samples. Potential mechanical problems, such as a tendency to crack or brittleness, were not assessed.

5.9.1 Exposure to MSW Leachate

Haxo et al (1982) exposed 22-in. diameter samples of two types of asphalt concrete and a soil cement to MSW leachate for up to 56 months in landfill simulators. The simulator design is presented schematically in Figure 5-11. An analysis of the leachate generated by the simulators is presented in Table 5-7. The two types of asphalt concretes tested included a paving asphalt concrete and a hydraulic asphalt concrete. The paving asphalt concrete contained 7.1 parts of asphalt (60-70 penetration grade) per 100

parts of aggregate. The aggregate was Watsonville granite proportioned to meet the 0.25-in. maximum gradation for dense-graded asphalt. The original voids ratio was 6.4%. Specimen thickness was 2.2 inches. The hydraulic asphalt concrete contained 9.0 parts of asphalt (60-70 penetration grade) per 100 parts of the same aggregate used to make the paving concrete. The original voids ratio was 2.9%. Specimen thickness was 2.4 inches. Soil from the Radum quarry near Pleasanton, California, was used with Type 5 (sulfate-resistant) portland cement for preparing the soil cement. Since the fines content of the Radum soil was lower than optimum for soil cement, a few percent of nonswelling clay (kaolin) was added. The soil cement specimens were 4.5 in. in thickness and were made of 95 parts of soil, 5 parts of kaolinite clay, 10 parts of portland cement, and 8.5 parts of water.

One of the asphalt concrete liners developed a leak which was probably related to inadequate compaction at the center of the specimen where the leak occurred. This result indicates that thicker asphalt concrete liners or double lifts are needed to prevent leakage. The 2 to 4-in. specimen design thickness was selected for the research program to accelerate the test conditions. Both asphalt concretes lost considerably in unconfined compressive strength, as is shown in Table 5-66. These losses were greater than were anticipated from the 24-h water immersion at 60°C and were probably the result of absorption of water and dissolved organics which took place over the prolonged exposure and stripping of asphalt from the aggregate. The asphalt extracted from the concretes hardened, though it did not harden as much as asphalt extracted from a sample exposed to weather and air. This result probably reflects the anaerobic environment at the bottom of the simulators.

TABLE 5-66. UNCONFINED COMPRESSIVE STRENGTH OF ADMIXED LINER SPECIMENS BEFORE AND AFTER EXPOSURE TO WATER AND TO MSW LEACHATE

Exposure	Paving asphalt concrete		Hydraulic asphalt concrete		Soil cement	
	psi	%	psi	%	psi	%
Original strength, psi	2805	100	2715	100	1910 ^a	100
Water soak for 24 h at 60°C	2230	80	2328	86	1323 ^{a,b}	69 ^b
In simulators for 12 months	423	15	349	13	1188	62
In simulators for 56 months	258	9	172	6	1182	62

^aMeasured on specimen molded in accordance with ASTM D558.

^bWater soak at room temperature.

Source: Haxo et al, 1982, p 61.

The soil-cement liners lost some of their compressive strength (Table 5-66) and hardened considerably during exposure. Whereas satisfactory cores could not be cut from the unexposed soil cement, the exposed liners could be cored like a portland cement, indicating continuation of cure during exposure. The results of the permeability testing, which are presented in Table 5-67, indicate that the soil cement had possibly become less permeable during exposure. However, these results may be related to variations in compaction. A small leak developed in the second liner after approximately 1 year of exposure.

TABLE 5-67. PERMEABILITY OF SOIL-CEMENT SAMPLES BEFORE AND AFTER EXPOSURE TO MSW LEACHATE

Property	Soil cement ^a
Density, g mL ⁻¹	2.169 (dry) ^b
Density, lb ft ⁻³	135.4 (dry) ^b
Coefficient of permeability ^c , cm s ⁻¹	
Unexposed	1.5 x 10 ^{-6b}
After 12 months of exposure	1.5 x 10 ⁻⁸ (T) 4.0 x 10 ⁻⁷ (B)
After 56 months of exposure:	
Area in which leak detected	1.2 x 10 ⁻⁵ (T) 2.7 x 10 ⁻⁵ (B)
Area in which no leak detected	4.3 x 10 ⁻⁷ (T) 1.2 x 10 ⁻⁵ (B)

^aT = top; B = bottom.

^bMeasured on a specimen molded in accordance with ASTM D588.

^cDetermined in a back-pressure permeameter (Vallerga and Hicks, 1968).

Source: Haxo et al, 1982, pp 148-49.

5.9.2 Exposure to Hazardous Wastes

Haxo et al (1985b) exposed hydraulic asphalt concrete and soil cement samples to various hazardous wastes. The combination of wastes and admixed liners that were tested included the following:

Waste identification		Combinations tested	
Type	Name	Hydraulic asphalt concrete	Soil cement
Acidic waste	"HNO ₃ -HF-HOAc"	X	...
Alkaline waste	"Spent Caustic"	X	X
Lead waste	...	X	X
Oily waste	"Slurry Oil"	...	X
	"Oil Pond 104"	...	X
Pesticide	"Weed Killer"	X	X

Two cells were tested for each liner-waste combination. Analyses of the wastes are summarized in Appendix J. The cell used to expose the liner samples is presented schematically in Figure 5-45.

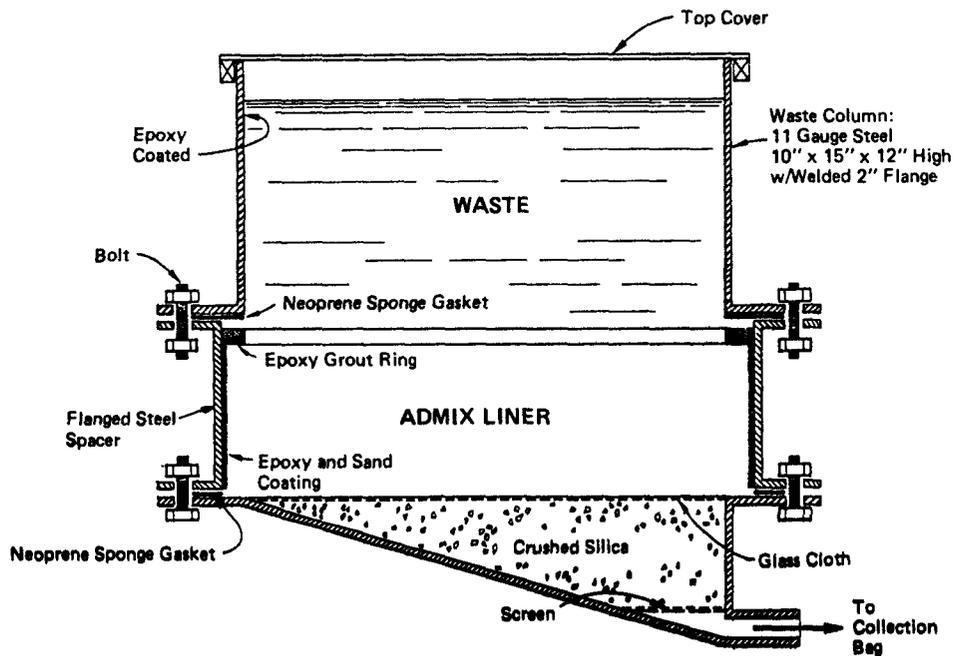


Figure 5-45. Design of cells for long-term exposure of admix liners to different hazardous wastes. The area of the liner specimen in contact with the wastes measured 10 x 15 inches. (Source: Haxo et al, 1985b, p 76).

The hydraulic asphalt concrete mix included dense-graded aggregate to 0.25-in. maximum size and 9 parts of asphalt AR-4000 per 100 aggregate. The

water permeability of six cores taken from unexposed samples ranged from 2.8×10^{-8} to 1.7×10^{-9} cm s⁻¹. Liner thickness was 2.5 inches. The soil cement was a compacted mixture of 12 parts of Type 5 (sulfate-resistant) portland cement, 13.4 parts of water, and 100 parts of a "waste fines" from a local quarry. Permeability of a core taken from an unexposed liner was 5.7×10^{-8} cm s⁻¹. Liner thickness was approximately 4 inches.

In spite of the low permeability and good mechanical properties of the asphalt concrete, the asphalt concrete liners were deficient in several exposures. Both specimens in contact with the strong acid ("HNO₃-HF-HOAc") developed leaks; some of the aggregate at the surface was dissolved, and the asphalt itself hardened severely during exposures that were relatively short (40 and 199 days). Leaks also developed in the specimens below the "Spent Caustic" and lead wastes. The lead waste contained sufficient oily constituents to cause the asphalt concrete to become almost a slush. Some seepage also occurred through the specimens. Combinations of the asphalt concrete and the oily wastes were eliminated in the screening tests. Results also indicated that a thickness of 2.5 in. may be insufficient even for water and compatible dilute wastes.

The soil-cement specimens showed good resistance to "Spent Caustic," the lead waste, the two oily wastes, and the pesticide waste. Soil-cement had been eliminated from exposure to the strong acid waste ("HNO₃-HF-HOAc") in the screening tests. No seepage occurred in any of the specimens. In the five specimens recovered and tested, actual increases in compressive strength occurred. It must be recognized that these specimens were all small and not subject to shrinkage or cracking that would be experienced in large installations.

5.10 SIMULATED EXPOSURE TESTING OF SPRAYED-ON FMLS

As part of the two simulated service research programs discussed in Sections 5.4.1.1 and 5.4.1.2, limited testing of sprayed-on asphalt FMLs was performed after exposure to MSW leachate and various hazardous wastes. The results of these tests are discussed in the following subsections.

5.10.1 Exposure to MSW Leachate

Haxo et al (1982) exposed two types of asphaltic sprayed-on FMLs for up to 56 months to MSW leachate in landfill simulators (Figures 5-11 and 5-12). An analysis of the leachate generated by the simulators is presented in Table 5-7. The first type of sprayed-on FML was a catalytically-blown asphalt that was cast in place at 425°F on a sand bed covering the aggregate in the base of the simulator. The second type was an asbestos-filled anionic asphaltic emulsion that had been sprayed on a nonwoven polypropylene fabric. Both types of liners were approximately 0.30-in. thick.

The effect of the exposure on the asphalt in these FMLs is presented in Table 5-68. However, it should be noted that to perform these tests, the asphalt is heated and the volatile content removed. Consequently, these data do not reflect the properties of the in-service asphaltic FML.

TABLE 5-68. PROPERTIES OF ASPHALT IN SPRAYED-ON FMLS
AFTER 12, 43, AND 56 MONTHS OF EXPOSURE TO MSW LEACHATE

Property	Type of asphalt	
	Catalytically- blown	Emulsified
Viscosity at 25°C in sliding plate viscometer at shear rate of 0.05 sec ⁻¹ :		
Original, MP	8.5	4.5 ^a
After 12 months, MP	10.4	2.9
After 43 months, MP	12.2	3.1
After 56 months, MP	17.4	3.1
Change from original, MP	+8.9	-1.4
Penetration at 25°C at 100 g and 5 seconds:		
Original	36 ^b	46 ^{a,b}
After 12 months ^e	34	55
After 43 months ^e	31	53
After 56 months ^e	27	53
Change from original	-9	+7
Softening point, °C:		
Original	89	...
After 12 months	89	...
After 56 months	101	...

^aAsphalt extracted from unexposed specimens stored 12 months.

^bCalculated from viscosity data.

Source: Haxo et al, 1982, p 150.

The catalytically-blown asphalt sample exposed for 12 months appeared little affected by the exposure. The sample exposed for 50 months had a nonhomogeneous appearance. Some areas had become quite weak or "cheesy" and cracked easily when bent while other areas remained tough and flexible. Samples from two weak areas and one "normal" area were tested for volatiles and viscosity. The weaker area had absorbed approximately three times as many volatiles as the other two areas. All three areas had approximately the same viscosity. The cheesy areas became less pronounced as the sample dried out in storage.

As with the catalytically-blown asphalt, the FML based on an asphaltic emulsion that had been sprayed on nonwoven fabric showed no deterioration after one year of exposure to MSW leachate, even though analyses showed that it contained 4.8% moisture. The asphalt extracted from this FML was lower in viscosity after 12 months of exposure to leachate than before exposure. The

viscosity at the low shear rate, 0.001 sec^{-1} , was substantially unchanged, indicating a lower shear susceptibility than for the unexposed specimen. At 56 months the asphalt emulsion liner continued to show no visible deterioration. Analyses showed that this FML had absorbed additional leachate and contained 8% leachate compared with the 4.8% after one year of exposure.

5.10.2 Exposure to Hazardous Waste

Haxo et al (1985b) exposed an emulsified asphalt that had been applied on a nonwoven polypropylene fabric mat to three hazardous wastes, including a pesticide, an alkaline, and a lead waste. Two cells were tested for each FML-waste combination. Analyses of the wastes are presented in Appendix J. The cell used to expose the samples is presented schematically in Figure 5-15. This type of FML was not tested with an acidic waste included in the research program because it caused the asphalt to harden severely in a preliminary exposure test, and it was not tested with the oily wastes because of the high mutual solubility of the asphalt and such wastes. This FML functioned satisfactorily with the pesticide and the alkaline wastes; however, when the cell containing the lead waste was dismantled, the gravel below the liner was wet and stained, indicating that some seepage had occurred. The results of testing the FML samples and the extracted asphalt are presented in Table 5-69. The volatiles content of the samples exposed to the alkaline and lead wastes increased significantly.

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TABLE 5-69. EFFECT OF EXPOSURE TO HAZARDOUS WASTES
ON AN EMULSIFIED ASPHALT SPRAYED-ON NONWOVEN FABRIC^a

Waste type Waste name Matrecon waste serial number		Alkaline "Spent Caustic" (W-2)		Lead ... (W-4)		Pesticide "Weed Killer" (W-11)
Exposure time, days	None	671	1480	656	1348	487
<u>Asphaltic liner:</u>						
Volatiles content of liner, %	0.26	12.9	15.3	18.6	21.5	1.45
Water vapor permeability ^b , metric perm cm	6.7 x 10 ⁻²	...	...	...	...	...
<u>Extracted asphalt:</u>						
Viscosity at 25°C, P x 10 ⁶						
at 0.05 s ⁻¹	6.1	4.40	8.14	5.52	6.49	5.4
at 0.01 s ⁻¹	5.9	4.22	8.03	5.56	6.91	5.4
at 0.001 s ⁻¹	5.7	4.00	7.72	5.92	7.53	5.4
Shear susceptibility	-0.02	-0.02	-0.02	0.02	0.04	0.00
Penetration ^c at 25°C	41	47	37	43	40	43

^aLiner covered with 1.5 in. of silica sand on which the waste was placed. Analyses of wastes are summarized in Appendix J.

^bASTM E96, Method BW.

^cCalculated from viscosity at 0.05 s⁻¹ by formula of Carre and Laurent (1963):

$$(\text{Pen})^{2.6} = \frac{9.5 \times 10^{10}}{\eta}$$

Source: Haxo et al, 1985b, p 103.

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CHAPTER 6

FMLS AND RELATED MATERIALS OF CONSTRUCTION IN SERVICE ENVIRONMENTS

6.1 INTRODUCTION

As is discussed in Chapter 5, the bulk of available information related to the compatibility of FMLS with various waste liquids and their durability in service environments is based on laboratory or small-scale pilot tests. Furthermore, in selecting a liner, the chemical compatibility of an FML with the waste to be contained is determined by performing laboratory testing, e.g. immersion tests performed in accordance with EPA Method 9090 (EPA, 1986). Although the EPA is developing expert systems to aid in selecting a liner (Rossman and Haxo, 1985), these systems are largely based on laboratory results combined with general knowledge of the liner materials and wastes and liquids to be contained. The relationship between data generated in laboratory or small-scale pilot tests and field performance of FMLS in waste containment units is still poorly defined because specific data on the performance and durability of full-scale liner systems are limited.

Data based on laboratory and small-scale pilot studies suffer from serious limitations when used to predict compatibility, service lives, and durability of lining materials in actual full-scale service. Some of these limitations include:

- Samples of liner materials tested in laboratory studies are very small in size in comparison with the amount of material required for lining a full-scale TSDF. In a laboratory there is no way to measure the effect of variations (e.g. in ply adhesion, composition, etc.) in the materials themselves on their ability to function in a service environment.
- Exposure conditions in a laboratory are highly controlled in contrast to the variability of conditions in a field situation. In TSDFs, waste liquids and leachates can be highly variable, varying in both content and concentrations, and can also vary greatly with time and with depth and location within a given containment unit. In addition, the level and temperature of the waste and the exposure temperature vary with time, particularly in surface impoundments.
- In contrast to field seaming operations, laboratory seams are prepared carefully under controlled conditions. From laboratory studies, it is not possible to know the effect of variations in seaming workmanship

and seaming conditions on performance. However, it should be noted that at present (1988) there are trends towards more automated seaming equipment and a higher level of quality control and quality assurance.

- In contrast to FMLs in actual service, laboratory samples are not exposed under overburden, nor are they generally exposed under strain or stress.

In order to fully understand the performance and durability of liner systems and their components under full-scale service conditions, detailed on site observations and inspections need to be made, and data resulting from testing samples of observed liners need to be obtained. Though much data on FML performance in various field applications have been collected, these data are proprietary and are not available in the open literature. In addition, even though reports and papers over the past decade have presented the results of field studies, most of these reports are not highly detailed. As a consequence, the EPA undertook several on-site field verification studies and surveys to collect detailed information on the performance of lining materials in waste containment units.

This chapter discusses the objectives of field studies and the various factors that may contribute to an increase in seepage through an installed FML beyond design levels. This chapter also reviews selected field studies of FML performance in different types of containment units and presents data on exposed FMLs which can be related to FML exposures studied in laboratory simulated-service environments. Two field studies of geotextiles and the limited results of an investigation of granular leachate collection and removal systems in MSW landfills and an interview survey to describe potential failure mechanisms in such systems are reviewed.

6.2 OBJECTIVES OF FIELD STUDIES OF LINER SYSTEMS IN CONTAINMENT UNITS

As is discussed in Chapter 7, waste containment units are complex structures involving many layers of different materials, each of which must function properly if the unit is to meet its performance requirements. The components of a closed double-lined landfill can include:

- Supporting structures (including the foundation and embankments).
- An underdrain system.
- A liner system comprised of:
 - A bottom liner.
 - A top liner.
 - A leachate collection and removal system (LCRS) between the two liners for detecting and removing liquids that have leaked through the top liner.

--An LCRS on top of the liner for controlling the leachate head acting on the lining system.

- A cover system.
- A groundwater monitoring system.

Each component depends upon the other components to function properly; also, the components interact with each other. For example, the competence of the foundation and the embankments has to be maintained in order to support the liner system, which in itself is not a structural component. An FML must retain its integrity and not allow liquids to enter the foundation and the embankments which could cause it to fail and which, in turn, could cause a catastrophic failure of the liner.

Because polymeric materials have only been used in constructing waste containment units for approximately 20 years, on-site field studies of the performance of liner systems need to be conducted for the following reasons:

- To assess the performance of waste containment units, with particular reference to the performance of the individual components.
- If a failure has occurred, to determine the cause of failure, including determining the type of failure, the mechanism of the failure, and the conditions that led to the failure. Such an investigation would be similar to an autopsy.

Only by analyzing failure can knowledge develop regarding the limitations of FMLs and the other materials used in constructing an FML-lined containment unit. This information can be used to point out needs for improving resins, FML manufacturing techniques, seaming techniques and other construction practices, and the overall design requirements.

The function of a lining system for a waste containment unit is to prevent the migration of liquids and the dissolved constituents that are contained into the environment, particularly the groundwater. A lining system is said to have failed once it can no longer meet the design requirement of controlling the migration of liquids and dissolved constituents so as to protect human health and the environment. FMLs can fail in one of two ways:

- An increase in the permeability of the liner to the contained liquids and the dissolved constituents.
- A breach in the liner, which would allow free liquids to flow through the liner.

An increase in the permeability of a liner could arise from chemical incompatibility of the FML to the contained waste liquid due to the swelling or dissolution of the liner or its components. Evidence of this type of failure

has been seen in laboratory testing. On the other hand, a breach in the liner can arise from one of many causes, including seam failure, cracks in the FML, tears, pinholes, etc. Some of these failures may reflect inherent weaknesses or defects in the FML or changes in the properties of the FML resulting from exposure to the chemical environment; most, however, appear to be caused by combinations of stress and various factors relating to design and construction. Potential modes of FML failure and factors that could contribute to failure are discussed in the next section.

Field studies of FML performance can be approached from the engineering point of view and the materials point of view. In the materials approach, the relationship between the analytical and mechanical properties of an FML and its field performance in waste containment units is analyzed. Failures need to be analyzed to determine whether or not the failure is related to changes in the FML caused by exposure to the service environment (e.g. to sunlight and weathering on a slope or to a waste on the floor of the unit). These changes in the FML would be reflected by a change in the balance of the FML's properties and/or a single property. Such a change in the FML can result from changes in composition (e.g. swelling or extraction of plasticizer), from degradation of the polymer (e.g. oxidation), or from long-term responses resulting from simultaneous exposure to a variety of mechanical and chemical stresses (e.g. the development of stress-cracks). Except in cases where these changes result in a significant change in permeability, these changes themselves will not result in failure but will result in changes in the FML's balance of properties which make the FML more susceptible to failure by mechanical stresses.

An important goal of the materials approach is to develop criteria for predicting the long-term serviceability and the chemical compatibility of an FML with a particular leachate or waste liquid based on the results of laboratory testing. To develop such criteria, a correlation needs to be established between measurable properties of an FML and the performance of that FML in a specific environment. Given this correlation between properties and performance, the rate of change in the properties of an FML exposed in a laboratory test could then be used to predict the service life of that FML under well-defined service conditions. For example, if it were demonstrated that a 50% loss of a certain property correlated with a high degree of confidence with FML failure, then using the rate at which that property changes in laboratory testing (which itself has been correlated with the rate of change under service conditions) the approximate service life could be predicted. In addition, given such a correlation, it will be easier to improve and develop compounds and resins that will have improved characteristics for long-term service in waste containment applications.

No such correlation for FMLs in service environments, however, has been developed. First of all, only a limited amount of data is available in the open literature regarding the effects of the service conditions on FMLs. Because of the proprietary nature of waste containment operations and the manufacture and installation of FMLs and because of the potential repercussions resulting from open knowledge of a liner failure, almost no data are available in the open literature regarding FML failures from strictly

materials causes. In addition, it should be noted that different types of polymeric compositions respond differently to exposure conditions and if they degrade they can be subject to very different types of degradation. These differences complicate the issue because a property (or balance of properties) that may correlate with performance for one type of FML may not correlate with performance for another.

From a materials point of view, the ultimate goal of field studies on FMLs is to develop a correlation between measurable properties and field performance. However, to do this, field studies are needed for the following reasons:

- To assess the field performance of in-service FMLs to determine whether or not these materials can function adequately in service environments. At the time the EPA initiated research on FMLs in the early 1970's, there was concern about whether or not FMLs could successfully control the migration of waste constituents from a well-engineered containment unit.
- To assess the changes in properties that have occurred in the in-service FML in order to assess the deterioration that may have occurred.
- To determine what FML properties correlate with field performance. In the chemical compatibility testing performed to date, i.e. that described in Section 5.4 and testing performed in accordance with EPA Method 9090 (EPA, 1986), it has been assumed that measuring changes in hardness, tensile properties, tear resistance, volatiles, extractables, etc. will be correlatable with field performance. However, if the FML is subject to degradation after long-term exposure by stress-cracking, changes in the properties mentioned above will probably not be directly correlatable with field performance.
- To determine what level of change in a property or a balance of properties correlate with either the success or failure of an in-service FML.
- To determine whether the responses of FMLs in field-simulated laboratory and small-scale pilot tests are similar to their responses in service environments.
- To determine what service conditions affect the performance of an FML, and in particular, to determine what chemical stresses are the most aggressive.

In the engineering approach, it is assumed that FMLs can function adequately in service environments. Thus, the performance of the FML is assessed in terms of how it functioned as a component of engineered and constructed systems. In the case of a failed FML, the design requirements, construction practices, and management practices that may have contributed to failure are analyzed. For example, the mechanical properties of a failed FML

can be analyzed to determine whether they were sufficient for the mechanical conditions resulting from construction, installation, and service and to determine how those mechanical conditions could be changed so as to reduce mechanical stresses on the FML. This information can be used to develop and verify design equations for evaluating the required mechanical properties of an FML under specific mechanical conditions, e.g. the ability of an FML to support its own weight on the side slopes [see Richardson and Koerner (1987)]. One example analyzing field experience from an engineering perspective is the variety of responses to field experience indicating that thin FMLs (i.e. those ≤ 20 mils) which were being installed during the early 1970's were susceptible to puncture. Even though no single test method has been correlated with the incidence of punctures in FMLs, engineers and FML manufacturers responded to the field experience by:

- Changing the construction of the sheeting by increasing the thickness and/or using fabric reinforcement. In addition, FMLs based on polymers that result in sheetings with a higher puncture resistance have also been introduced.
- Changing design requirements to decrease the localized stresses caused by objects in contact with the FML, e.g. by including stricter requirements for subgrade finishing and by requiring bedding layers or geotextile protectors.
- Changing construction practices to reduce the incidence of puncture, e.g. during the placement of the soil layer on top of an FML.
- Increasing the role of CQC and CQA inspection to ensure that the design requirements are being met and that the recommended construction practices are being followed.
- Developing stricter management procedures for reducing the incidence of puncture, e.g. by not allowing vehicles to travel directly on top of an FML, etc.

Field studies from the engineering perspective are necessary to develop better designs, construction practices, and management practices to reduce mechanical stresses on an FML and thereby reduce the potential for failure and to develop knowledge about what mechanical properties (e.g. strength, friction angle against a soil) are required given a specific application.

6.3 POTENTIAL MODES FOR FML FAILURE AND CONTRIBUTING FACTORS

As was mentioned in the previous section, if an FML fails, failure will occur in one of two ways:

- An increase in the permeability of the liner to the contained liquids and dissolved constituents.
- A breach in the liner, which would allow free liquids to flow through the liner.

This section discusses these types of failures and then discusses the various types of factors that could contribute to FML failure.

6.3.1 Types of FML Failures

6.3.1.1 Changes in the Permeability Characteristics of the FML--

A significant increase in the permeability of an FML to the liquids and the dissolved constituents with which the FML is in contact could arise due to chemical incompatibility after prolonged exposure. Evidence of this type of failure was seen in a laboratory test in which a highly alkaline waste was sealed inside a pouch fabricated from an ELPO FML. As is discussed in Section 5.4.1.6.2, after approximately 1 year of test, the rate at which water entered the pouch increased dramatically, indicating a change in the permeability of the FML.

6.3.1.2 Mechanical Failure--

6.3.1.2.1 Puncture--Breaches in FMLs can occur due to puncture by impact of tools or sharp rocks falling, or by sharp angular rocks in the subgrade that have become exposed because soil fines have migrated downward over time, or because of inadequate subgrade preparation or selection of cover materials. Puncture during operations, by man or vehicle, is of concern but can largely be mitigated through good installation and operation procedures. Burrowing animals can puncture FMLs below the surface and hooved animals seeking water can puncture exposed liners.

6.3.2.1.2 Tear--Tear damage is similar to puncture damage in its occurrence and can be initiated by a puncture followed by stress at the hole. Tear, like puncture, can occur due to operations or to animals. The propagation of tears and punctures can result in catastrophic generation of breaches.

6.3.1.2.3 Cracks--Cracks can develop when an FML is simultaneously exposed to environmental stresses (e.g. ozone, sunlight, or a waste liquid) and mechanical stresses. For example, cracks can develop in an FML exposed on a berm and in exposed areas with folds. Cracking can also develop from static stress and dynamic fatigue such as might occur with alternating thermal expansion and contraction. As with punctures, these cracks can initiate tears that can result in catastrophic failure.

6.3.1.2.4 Abrasion--The continuous or near continuous action of abrasion caused by wind or wave action on an FML can have a significant wearing effect over time. In arid regions, sand particles carried by the wind have a sand blasting effect on the FML. Runoff entering the pond from the surrounding topography may contain sticks, branches, rocks, and other debris which could abrade, tear, or even puncture the FML. Allowing liquids that are being placed in a unit to splash directly onto an FML during placement can have the same effect.

6.3.1.2.5 Seam failure--Factory and field seams can split open due to inadequate adhesion and due to excessive stresses on the FML which can arise from subsidence, wind and wave action, gas pressure underneath the unit which has not been properly vented, shrinkage, hydrostatic pressure, slope sloughing, and thermal expansion and contraction. Some seams can be greatly weakened during service due to the absorption of organics by the adhesive or entrance of organics into the interface between the sheets of FML that were seamed.

6.3.2 Factors That Could Contribute to FML Failure

The occurrence of breaches in the liner may arise from defects in the FML. However, by far the most prevalent breaches are likely to be the result of a sequence of events, all of which contribute to the development of a breach. For example, a breach in a seam on the slopes can develop because of a sequence involving the materials, the slope of the unit sidewall, the placement of the FML, the seaming workmanship, inadequate QA/QC, unusual stresses on the seam which could pull the seam apart, and possibly chemical effects due to incomplete fusion at the bond interface of the seam, or softening of the FML. Another example would be the tearing of an FML on a slope due to the sloughing of a protective soil cover. The sloughing could be related to design of the sidewalls at too steep a slope, excessive rainfall resulting in saturation of the soil, insufficient provision for drainage through the soil, and an inadequate coefficient of friction between the soil and the FML. Factors that could contribute to the development of breaches in FMLs are listed in Table 6-1. Some of these factors are discussed in the following subsections.

6.3.2.1 Material Factors--

6.3.2.1.1 Chemical incompatibility--The durability and service life of a given FML in a waste containment unit can depend to a great extent on the specific liquids which contact the FML from the time it is installed through the rest of its service life. For example, dissolved organic constituents in a leachate, even in minor amounts, can be preferentially absorbed by organic liner materials and may, over extended periods of time, result in significant swelling and softening of FMLs.

Two types of chemical incompatibility between an FML and a leachate or a waste liquid include swelling of the FML and extraction of components of the FML compound. Swelling is the absorption of constituents of a waste liquid or leachate by an FML. Even though swelling generally does not affect the molecular structure of an FML, it can soften the FML. Swelling can potentially cause significant losses in strength, elongation, creep and flow resistance, and puncture resistance. In some cases, there may also be an increase in permeability. A severe situation exists at the top liquid line of a surface impoundment where the FML can be subject to alternating cycles of swelling and drying out. Data showing the tendency of FMLs to absorb significant amounts of organics, even from dilute aqueous solutions, are presented in Chapter 5.

TABLE 6-1. POTENTIAL FACTORS THAT COULD CONTRIBUTE TO THE FORMATION OF BREACHES IN AN FML IN SERVICE IN A WASTE CONTAINMENT UNIT

Type of factor	Factor
Material	<ul style="list-style-type: none"> Defects in sheeting (e.g. holes, foreign materials) Sensitivity of the selected material to the service environment (chemical incompatibility, inadequate UV resistance, etc. Environmental stress-cracking Degradation of compound or polymer Inadequate physical properties including response to multiaxial strain Creep Dimensional instability (shrinkage) Crazing, cracking Inadequate seaming system
Site	<ul style="list-style-type: none"> Subsidence Gas formation caused by decomposition of organic materials in soil High water table (reverse hydrostatic pressure) Chemical reactivity of subsoil (e.g. solubility in acids)
Design and engineering	<ul style="list-style-type: none"> Improper selection of materials (FML, soil for soil liner) Inadequate specification of materials Inadequate compatibility testing Improper use of materials Supporting structure problems Stress fatigue and cracking Inadequate protection against ice
Construction	<ul style="list-style-type: none"> Inadequate subgrade compaction Inadequate subgrade finishing Poor quality of seams (e.g. holidays, fish mouths, inadequate strength) Inadequate anchoring Inadequate sealing around structures
Quality control/ quality assurance	<ul style="list-style-type: none"> Inadequate inspection of construction, allowing disregard of specifications and poor construction quality Inadequate inspection of materials
Service environment	<ul style="list-style-type: none"> Attack by weathering, ozone Chemical attack by constituents of the waste Attack by wind and wave action Biological attack, including biodegradation Attack by animals and insects
Operational practice	<ul style="list-style-type: none"> Inadequate maintenance of protective cover Inadequate control of incoming wastes Inadequate control of methods of placing waste in unit Inadequate maintenance of run-on management systems Improper cleaning procedures Vandalism

Contact with a liquid can also result in plasticizers being extracted from the FML. FMLs, such as those based on PVC, which contain large amounts of monomeric plasticizer(s), are highly susceptible to extraction and evaporation of the plasticizer. Such loss of plasticizer can result in embrittlement, shrinkage, and given excessive stress levels, breakage of the FML. The use of higher molecular weight plasticizers does much to reduce this effect.

Chemical incompatibility can also result in an increase in the permeability of the FML. An increase during service is difficult to observe and would be difficult to distinguish from small breaches. Through careful monitoring it may be possible to observe such an increase in FML permeability in an LCRS underneath the liner, perhaps as an increase in the concentrations of organics permeating the FML. This would probably also show up by sampling and measuring the swelling and changes in properties of the liner or coupon exposed on the berm, in the sump, etc. The increase could also be demonstrated by an increase in permeability by long-term laboratory testing. Changes of this type have only been observed in a few cases in laboratory testing, as is discussed in Chapter 5.

The effects of chemical stresses on FMLs are discussed in more detail in Sections 5.3.1 and 5.4.

6.3.2.1.2 Creep--As is discussed in Section 4.2.1.5, creep describes increasing deformation of a material under sustained load. The main factors which influence creep failures are material microstructure, stress level, and temperature. The significance of this type of behavior is that it is difficult to detect and control. Creep can occur with any FML and may thin the FML to result in loss of strength and increased vapor transmission. In cases where a material absorbs liquids from a waste and softens, the material would be more likely to undergo creep over extended service.

6.3.2.1.3 Shrinkage--Three types of shrinkage can occur with FMLs during installation and during service and result in excessive stresses that may cause breaches in the FML or at seams:

- Hot Shrink. This is related to the memory a polymeric sheeting has while it was being formed at high temperatures (225° to 400°F). Temperatures on a dark colored sheeting in the hot sun can approach 180°F and, at this point, the sheet begins to shrink sometimes as much as 2 to 5% of its original length. (Fabric reinforcement is used to help reduce and control this type of shrinkage).
- "Snapback". This is a rapid recovery of some rolled FMLs when they are being unrolled at the job site or fabrication facility. "Snapback" represents the memory of sheeting resulting from stresses introduced into an FML at the time it is being wound as a roll immediately after production, or immediately after fabrication. Wind-up of sheeting usually occurs at room temperature. "Snapback" usually results in a shrinkage of approximately 1% of the length of

the sheeting. (If the sheeting is unrolled and allowed to relax in-place for one hour, recovery is complete and "snapback" will not occur.)

- Long-Term Shrinkage. FMLs that contain a volatile component, such as a plasticizer, can lose this component over time. The losses can occur by the processes of volatilization, absorption, or extraction. Since the volatile component represents a given volume of the compound, as this disappears, some type of compensation has to take place. Either dimensions will change or large forces will develop which could result in splitting of the FML or the opening of seams. In addition, shrinkage can result in uplift of the FML off the subgrade support at the foot of the slope (i.e. in bridging) which can result in excessive stresses in these areas.

6.3.2.1.4 Tendency towards environmental stress-cracking--Stress-cracking is defined as external or internal cracking and breaking of a plastic caused by tensile stresses less than its short-term mechanical strength. Under certain conditions of stress and exposure to soaps, oils, detergents, or other surface-active agents, certain grades of PEs in particular may fail by cracking in a relatively short time. This phenomenon was first recognized in PE cable covers and is discussed in Sections 4.2.1.11 and 4.2.2.5.4. Proper selection of the PE resin or addition of one of a variety of rubbery polymers can eliminate this deficiency.

6.3.2.2 Factors Related to the Site--

Site-related factors are frequently factors that could have been mitigated by adequate design provisions. However, these factors may not have been recognized during the site investigation, or the site investigation could have been inadequate.

6.3.2.2.1 Subsidence--Subsidence is the settling or sinking of the land surface due to many factors, such as the decomposition of organic material, consolidation, drainage, and underground failure. If subsidence occurs in a landfill or at the bottom of a surface impoundment where sufficient liquid head exists, it is doubtful whether the FML can move or elongate to compensate without breakage. Subsidence occurring above the waterline in a surface impoundment might not result in catastrophic failure if the coefficient of friction between the liner and the soil is not high enough to prevent slippage. The FML may compensate over a short term, but the situation created is not good as long-term creep or seam failure can result.

6.3.2.2.2 Generation of gases underneath the unit--The presence of organic material in a soil below an FML can generate gases through natural decay processes. If gases are generated and not vented from underneath an FML-lined surface impoundment, they may collect and push the FML upward from the subgrade resulting in a "whale back." Large portions of an FML can rise up like a balloon out of the liquid. Eventually "whale backs" can rupture (e.g. at the seams) or will require rupturing to release the trapped gases.

6.3.2.2.3 Water table--If not accounted for properly in the design, a rising water table can result in built-up hydrostatic pressures below the liner and eventually cause uplift or bursting of the liner.

6.3.2.3 Design and Engineering Factors--

These factors are related to the design's inability to account for:

- Site-specific conditions, such as the type of soil and the quality of the bedrock underneath the site and the climatological conditions that could result in heavy rains, freezing of support soils, freezing of the waste, etc. In colder climates where ice can form on the surface of an impoundment, the formation of ice can damage a liner if taken protective measures were not included in the design. In the spring months when ice breaks up, large floating chunks can easily puncture and rip the surface of an FML. Rip-rap and other forms of slope protection have been used to protect the FML.
- Limitations in how a material such as an FML should be used in a design for a containment unit. For example, a highly plasticized FML used without a protective soil cover to line a surface impoundment located in a region with high levels of solar radiation would probably fail after a short service life.
- Adequate mechanical compatibility between the different components of the liner system, such as the proper selection of the sidewall slopes and bedding layers between an LCRS and an FML. Low coefficients of friction between layered components of liner and drainage systems on slopes may result in serious slippage of the waste on the liner and failure of the liner.
- The effects of exposure to the constituents of the waste liquid or leachate on the properties of the FML.

Ultimately the design for a waste containment unit needs to minimize the mechanical stresses on an FML because a material under prolonged stress below its tensile strength will lose strength and may ultimately fail. This type of long-term failure would probably occur when the material was stressed biaxially. Several FMLs have been shown to have rather high elongations or when stretched in one direction at a time, but it has been observed that biaxial stresses can cause an FML to break or split at low elongations.

6.3.2.4 Factors Related to Construction--

6.3.2.4.1 Poor subgrade compaction--Compaction of the subgrade is an essential step in obtaining a relatively firm and unyielding support for the FML. If compaction is poor, then wave action or foot traffic can easily cause sloughing of the side slopes. Subsidence and differential settlement can result from added pressures created as the impoundment or landfill is filled, causing localized strains and possible failure of the FML.

6.3.2.4.2 Inadequate finishing of the subgrade--Inadequate finishing of the subgrade could result in the FML being installed on a surface with sharp, pointed edges that could puncture the FML.

6.3.2.4.3 Poor quality of the seams--According to the available information, seams in an FML in places where the FML is attached to structures (e.g. penetrations) are areas that are particularly vulnerable to damage. Poor quality seams can be a result of attempting to seam the FML under adverse conditions (e.g. during a storm) or using inadequately trained crews. These practices can result in seams of insufficient strength, in seam holidays, and "fish mouths" which are places where there are wrinkles in one of the sheets seamed together. The quality of the seaming operation can significantly affect the ability of the unit to perform as required.

6.3.2.5 Factors Related to Quality Control/Quality Assurance--

Quality control and quality assurance are performed to ensure that the various components of the lining system meet both materials and construction specifications. These activities force the construction and installing contractors to consider the quality of their workmanship throughout the construction of the unit. Thus, construction decisions that might be made on the basis of contractor preference, to save time, or to meet a certain construction schedule would have to be considered in light of their effect on workmanship. In addition, quality assurance and quality control make the contractor aware of his level of workmanship, and if there are difficulties in meeting the specifications, the problem can be corrected prior to a potential failure.

6.3.2.6 Factors Related to the Service Environment--

6.3.2.6.1 Weathering--FMLs exposed directly to the weather, e.g. on the slope of a surface impoundment, can be subject to damage from heat and infrared, UV light, oxygen, ozone, and moisture. These factors generally operate in combination, with oxygen and moisture being the major contributing factors. Damage of the FML generally occurs from polymer degradation, embrittlement, shrinkage related to the volatilization of compound components, and cracking. Ozone can cause cracking of many polymers, particularly of certain rubbers (e.g. butyl) that contain unsaturation. Damage of this type occurs in areas where the rubber sheeting is under stress.

Most damage that occurs as a result of weathering is caused by improper formulation or misuse of a material, i.e. using a material for outdoor exposure that should be covered. Considerable information is available on the durability and service life of exposed FMLs in which the principal environmental conditions are UV light, oxygen, ozone, and heat (Strong, 1980).

Plasticized compositions may become stiff and brittle on exposure to weather and to waste liquids. Impact or movement may cause the FML in these areas to break and thus develop breaches, through which liquids can flow. Loss of plasticizer can also cause shrinkage and tensioning of the FML.

6.3.2.6.2 Wind and wave action--Large area surface impoundments are susceptible to failure from the action of wind and waves. Repeated pounding of waves on side slopes can eventually cause sloughing. Waves can crest over the tops of dikes and infiltrate behind the FML thus weakening the slope structure. Geotextiles, rip-rap, and control of the height of the maximum waterline can avoid failures.

6.3.2.6.3 Biodegradation--This uncertain factor needs to be observed in field verification studies as biodegradation may occur in FMLs and the materials of construction used in liner systems. These effects are long-term, and few have been observed except under very special circumstances, as is discussed in Section 4.2.1.12. In general, the high molecular weight polymers, such as those used in FMLs and other geosynthetics and plastic pipe, are highly resistant to biodegradation. Biological attack has been observed with some plasticized FML compositions due to the susceptibility of some plasticizers and other monomeric constituents of the compound to biodegradation. Biocides are sometimes included in compounds to reduce this type of degradation. It has also been observed that fungal growth can take place on the surface of a polymeric FML or product without degrading the mass of the composition.

6.4 DIFFICULTIES IN FINDING AVAILABLE SITES FOR STUDY AND MATERIAL SAMPLING

FML-lined sites that can be studied or sites where samples can be taken have been difficult to locate. A number of questions are involved in studying and sampling in-service FMLs, including proprietary concerns on the part of the site owner/operator, the installation contractor, and the FML manufacturer. This is particularly true in cases where there have been problems with the lining system. It is well recognized that open knowledge of problems in a waste facility could affect public relations between the owner/operator and the surrounding communities and could affect the commercial interests of the installation contractor (if problems are related to workmanship) and the FML manufacturer (if problems are related to the FML's ability to perform or to shortcomings in the recommended seaming methods). However, it is the type of information that the engineering profession needs to improve the design of waste impoundment facilities.

Even given the willingness of the various parties to cooperate, there may still be questions of liability. For example, it is possible to patch the sampled area of certain FMLs that have been exposed to weathering for many years on the slopes of a surface impoundment. However, if the patch does not hold, there are questions about who will assume liability for the failed patch and whether it voids the original warranties applied to the installation and the material.

Lastly, there are also technical and practical problems. For example, there are no effective and economic methods of sampling FMLs in service at the bottom of a landfill. In addition, it is not technically feasible to repair an FML that has been exposed to wastes (Haxo, 1987).

The most convenient and most complete situation to use as a field study is a lined unit that is being dismantled. Usually no liabilities are involved, and there are no limits to the number of samples or to the areas from which samples can be cut except the construction schedule.

Decommissioning of lined waste containment units under Superfund Remedial Actions offers an excellent opportunity for collecting information on the performance and durability of lining materials. Efforts should be made to incorporate liner recovery and testing into decommissioning operations when such sites become available.

6.5 FIELD STUDIES OF FMLS

In this section, field studies of FMLs in service in containment units are reviewed. A table is presented for each group of cases as an easy reference guide and is followed by detailed discussion of the observations and test data where available.

The following is a list of the types of materials referenced in the case histories presented in this section:

<u>Type of material</u>	<u>Number of cases</u>
PVC	10
CPE	6
EPDM	3
CSPE	3
Butyl	2
ELPO	1
LDPE	1
HDPE	1
Asphaltic membrane	1

6.5.1 Field Studies Conducted by Matrecon

Table 6-2 describes nine field sites studied by Matrecon. The principal objective of these studies was to investigate the effect of service on the properties of the FML. Samples were taken from the liners at each site and subjected to laboratory testing to assess the physical and analytical properties of the exposed samples. Unless stated otherwise, the methods used in testing the sample FMLs are listed in Table 6-3. Testing was performed as soon as possible after receipt at the laboratory, and the samples were kept in a moist condition until testing. Data on three sites are reported almost in their entirety to give examples of a detailed planned study and investigation of an in-service liner.

6.5.1.1 PVC FML in MSW Demonstration Landfill--

A demonstration landfill in Crawford County, Ohio, was constructed in the spring of 1971 and lined with a 30-mil PVC FML. It had been designed

TABLE 6-2. SUMMARY OF FML FIELD STUDIES PERFORMED BY MATRECON

FML type	Type of waste	Type of unit	Location	Years of exposure	Comments on FML
30-mil PVC, unreinforced	Refuse waste	Demonstration landfill	Crawford County, OH	6	Good retention of original properties.
15-mil PVC, unreinforced	Brewery sludge	Sludge lagoon	Northeast U.S.A.	7	Deterioration due to exposure to weathering; good retention of properties when buried and exposed to sludge.
7-mil LDPE, unreinforced 45-mil CSPE, unreinforced 30-mil CPE, unreinforced	MSW leachate	Municipal solid waste landfill	Boone County, KY	9	LDPE unaffected; unreinforced CSPE swelled; CPE stiffened.
30-mil CSPE, unreinforced	MSW leachate	Landfill cells	Georgia	4	Some swelling and curing.
100-mil HDPE, unreinforced	Aqueous solution of organics, chlorinated hydrocarbons	Waste lagoon	Northeast U.S.A.	5	Maintained integrity, but was torn by equipment during cleanup operations.
20-mil PVC, unreinforced	Calcium sulfate sludge, ammonia and chlorides	Industrial sludge lagoon	Northeast U.S.A	9	Mechanical puncturing; field seams failed.
20-mil PVC, unreinforced	Municipal sanitary waste	Landfill	Pennsylvania	6	Good retention of physical properties; slight stiffening.
60-mil EPDM, unreinforced	Sludge from production of TNT	Surge pond	Illinois	18	Field seams opened on slopes; "whale" formation from gas generation under liner; anchor trench pull-out.
30-mil PVC, unreinforced	Industrial wastewater treatment sludge from manufacture of dyes and plastics	Industrial landfill	New Jersey	4	Stiffened, but still functional; torn by equipment during cleanup.

to compare conventionally-processed solid waste with a shredded waste and a rough compacted waste. The three types of MSW were placed in cells completely lined, including the top of the cells, with PVC FMLs. A layer of clay was placed on top of the FML which was on the bottom of the unit.

TABLE 6-3. METHODS^a USED IN TESTING FML SAMPLES RECOVERED DURING CASE STUDIES CONDUCTED BY MATRECON

Property	Test method
<u>Analytical properties</u>	
Volatile	MTM-1 (Appendix G)
Ash	ASTM D297
Specific gravity	ASTM D792
Extractables	MTM-2 (Appendix F)
<u>Mechanical properties</u>	
Thickness	b
Tensile properties	ASTM D638, Type IV specimen at 20 ipm
Tear resistance	ASTM D624, Die C specimen
Hardness	ASTM D2240
Seam strength in shear	ASTM D882, 1-in. wide strips
Seam strength in peel	ASTM D413, 1-in. wide strips, 90° peel, 2 ipm

^aUnless stated otherwise in text.

^bReported thickness values are values resulting from averaging thicknesses of specimens used in mechanical property testing.

One objective of the demonstration landfill was to determine the effect of water content on consolidation and decomposition of the refuse, but the cells were flooded with water in a heavy rainfall just before the cells were to be sealed. As a consequence, the refuse in all cells was flooded and probably remained so from 1971 until they were opened in May 1977. When the cells were opened, and the clay that was placed on top of the FML was tested, it was found to have a low permeability. Thus, it appeared that the leachate in the cell had not contacted the FML on the floor of the unit.

The results of testing both the FML exposed at the top of the cell under two feet of clay and the FML exposed at the bottom of the cell are reported in Table 6-4. The FML beneath the refuse appeared to have swollen and softened slightly. There was also an indication that the FML at the top may have lost some plasticizer. The sheeting itself had sustained considerable distortion during its exposure due to rough ground or to the pea gravel on which it was placed. Even though there was no retained sample for comparison, the test values of the exposed sheeting indicated that the overall properties, including the seam strength, probably changed little during the exposure.

TABLE 6-4. PROPERTIES OF 30-MIL POLYVINYL CHLORIDE FML
RECOVERED FROM A DEMONSTRATION LANDFILL IN CRAWFORD COUNTY, OHIO

Matrecon FML identification number	96	97A
Exposure	Top of fill	Bottom of fill
<u>Analytical properties</u>		
Volatiles, (2 h at 105°C), %	0.41	1.33
Specific gravity (dry basis)	1.260	1.265
Ash (dry basis), ASTM D297, %	6.14	6.01
Extractables, (dry basis) ASTM D3421, %	34.10	34.43
<u>Physical properties</u>		
Thickness, mil	30	28
Tensile strength, psi	2630	2515
Elongation at break, %	350	340
Stress at 100% elongation, psi	1270	1135
Stress at 200% elongation, psi	1790	1695
Tear resistance, ppi	372	342
Hardness, Durometer points	70A	72A
Puncture resistance		
Force at puncture, lb	41.4	37.3
Deformation at puncture, in.	0.66	0.65
Seam strength in shear		
Strength at break, ppi	49.5	45.5
Locus of break ^a	SE	SE/BRK

^aSE = Break at seam edge; BRK = break in specimen outside of seam area.

6.5.1.2 PVC FML in Sludge Lagoon--

A disposal unit which contained a brewery sludge and which had been lined with a 15-mil PVC FML was being closed after having been in operation for 6.5 years. Both weathered and buried samples were obtained from the site. Inspection indicated a broad range of effects upon the PVC FML, i.e. from complete deterioration, where the FML had been exposed to the weather,

to almost no apparent deterioration where the FML had been under either soil or sludge. The FML that had been exposed to the weather on the berm had become so brittle that it fragmented on touch. No retained sample was available, however, to use as a control for assessing changes. Also, it is not certain whether any of the FML had been exposed to anaerobic conditions.

The results of testing four areas of the recovered FML are reported in Table 6-5. The samples taken from under the soil or sludge ranged in volatiles content from approximately 1% to more than 8%, indicating swelling. They also ranged in extractables from 29 to 36.7%, indicating that a PVC FML, even under a cover, can lose plasticizer. These results indicate that the PVC FML should have been covered and probably should have been thicker than 15 mils.

TABLE 6-5. PROPERTIES OF 15-MIL PVC FML EXPOSED AT A SLUDGE LAGOON IN THE NORTHEAST FOR 6.5 YEARS

	Covered by soil or sludge		Exposed to weather	
<u>Analytical properties</u>				
Volatiles, %	8.15	3.13	8.46	3.41
Ash (db), %	4.35	3.97	5.83	...
Specific gravity (db)	1.31	1.25	1.32	...
Extractables (db) ^a , %	29.0	36.7	25.8	24.8
<u>Physical properties^b</u>				
Thickness, mil	15	16	16	11.6
Tensile at break, ppi	43.0	45.5	38.6	32.1
Elongation at break, %	225	375	175	7
Stress at 100% elongation, ppi	34.7	21.0	35.5	...
Stress at 200% elongation, ppi	41.9	29.3	...	...
Tear resistance, Die C, lb	6.7	5.0	6.8	...
Hardness, durometer points	86A	75A	81A	...

^aExtractions performed with a 2:1 blend of carbon tetrachloride and methyl alcohol (Appendix E).

^bTensile and tear values are averages of machine and transverse directions.

6.5.1.3 CPE, CSPE, and LDPE FMLs in a Pilot-Scale MSW--

The closure of the Boone County Field Site provided an opportunity to recover CSPE, CPE, and LDPE FMLs that had been exposed to an MSW landfill

environment for more than nine years (Emcon, 1983). This site had been operated by the Solid and Hazardous Waste Research Division of the EPA from 1971 through 1980 (Wigh and Brunner, 1981).

Three samples of a CSPE FML and one sample of an LDPE FML were taken from Test Cell 1; six samples of a CPE FML were also taken from Test Cell 2-D, four of which had been exposed on the bottom of the cell, and two of which had been exposed to the weather. All three FMLs were unreinforced, and all samples, except the two exposed to weathering, had been exposed to leachate. No retained samples of the original materials were available, nor were any test data available on the specific lots of sheetings used in these cells. The results of testing samples of the LDPE, CSPE, and CPE FMLs exposed to leachate and the CPE exposed to weathering are presented in Table 6-6. Test results for all the CSPE samples were very similar and are averaged in the table.

Test Cell 1 was a trench-type cell, 45.4 m long by 9.2 m wide (Wigh and Brunner, 1981). The CSPE FML lined the bottom of the unit. A slotted collection pipe was installed above the transverse center line of the cell. An 18-in. thick clay liner was installed on top of the CSPE FML and the collection pipe. A second slotted collection pipe was installed in a trench in the soil liner directly above the collection pipe on the floor of the cell. To prevent leachate from by-passing the upper collection pipe and flowing into the lower pipe, the base and sides of the trench were lined with a 6-mil LDPE strip.

During the 9-year operation of the cell, leachate that permeated through the soil liner contacted the CSPE FML. The quantity that permeated through the soil and was collected was a fraction of one percent of the amount generated in the cell. The leachate collected in the lower pipe was more dilute than the leachate that was collected above the clay liner. The CSPE FML samples showed a substantial absorption of the dilute leachate, which is indicated by the volatiles contents which ranged from 23.9 to 28.4%. For the sample that had a 28.4% volatiles content, this is equivalent to a 39% increase in weight or an increase of 57% in volume based upon the original composition. This FML was based on a potable-grade compound; industrial-grade CSPE FMLs which exhibit significantly lower water absorption had not been developed.

The LDPE film was clear after the surface stain was removed by washing and appeared to be unaffected by the nine years of exposure to the MSW leachate. The sample, which had been in direct contact with the more concentrated leachate, showed little swelling, and its properties appeared to be normal for an LDPE FML of 6 to 7 mils thickness.

The samples of the CPE FML taken from the bottom of Cell 2-D had been in direct contact with the leachate generated in the cell and were stiff and leathery. They showed a significant absorption of the leachate, as is indicated by their volatiles contents which ranged from 16.7 to 18.8%. The volatiles content of 18.8% is equivalent to an increase of 23% in weight based upon the original, or an increase of 31.7% on the volume basis.

TABLE 6-6. EFFECTS ON CSPE, LDPE, AND CPE FMLS OF EXPOSURE IN MSW CELLS AT BOONE COUNTY FIELD SITE FOR 9 YEARS

Property	In Cell 1		In Cell 2-D	
	CSPE ^{a,b} below clay layer	LDPE ^c above clay layer	CPE ^a under waste	CPE ^a above ground
<u>Analytical properties</u>				
Volatiles, %	26.5	...	18.8	6.63
Ash (db) ^d , %	22.4	0.15	13.36	13.21
Specific gravity (db)	1.446	...	1.372	1.34
Extractables (db), % Solvent	3.27	1.10	4.81	4.42
	-----n-heptane-----			
<u>Physical properties</u>				
Thickness, as received, mil	43.8	7.0	41.5	34.0
Thickness, after drying, mil	45.7 ^e	6.6	39.2	...
Tensile at yield, ppi	...	9.9	...	...
Breaking factor, ppi	52.6	10.6	49.8	64.3
Elongation at break, %	325	285	280	305
Stress at 100% elongation, ppi	19.2	9.6	26.9	37.2
Stress at 200% elongation, ppi	32.4	9.65	39.8	49.1
Tear resistance, lb	6.5	2.9	7.3	7.2
Hardness, Durometer points	57A	...	67A	71A
Puncture resistance				
Force at puncture, lb	34.2	7.0	36.6	46.4
Deformation at puncture, in.	0.89	0.37	0.78	0.68

^aNominal thickness = 30 mils.

^bAverages of the results on three samples of the CSPE FML; all three were taken from below the clay layer and had been in contact with full-strength leachate.

^cNominal thickness = 6 mils.

^dDry basis.

^eSpecimens shrank and became thicker.

Data indicated that the samples exposed on the bottom of the cell may have been based on two different compositions. Two of the samples consistently had somewhat lower ash contents, lower volatiles, lower extractables, and lower stresses at 100 and 200% elongation values. These differences indicate the range of lot to lot variation. In spite of the significant swell of the CPE sample that had been exposed at the bottom of the cell, the properties of the swollen CPE were reasonably good.

Compared to the CPE samples that had been exposed to the leachate in the cell, the weathered samples showed significantly higher tensile strength, stress at 100 and 200% elongation values, and puncture resistance (Table 6-6). The lower values for the leachate-exposed CPE probably reflect the swelling by leachate; however, crosslinking or a loss of plasticizer during exposure may have contributed to the higher values of the weathered samples.

6.5.1.4 CSPE FML in Pilot-Scale MSW Landfill Cells--

Two pilot-scale landfill cells at Georgia Institute of Technology were constructed and put into operation as part of a research study on the effect of leachate recycling on the consolidation and stabilization of municipal solid waste (Pohland et al, 1979). The cells consisted of two adjoining concrete structures. Both had a 10 x 10-ft base, were 17 ft in height, and were fully-lined with an unreinforced CSPE FML. One cell was left open at the top, and the other sealed. Two drain systems were incorporated in the bottom of each cell, one in the gravel layer above the FML and one in the gravel layer between the FML and the concrete base. Shredded MSW was added to the cells and compacted to a density of 540 lb yd⁻³. Another layer of gravel with the leachate distribution system was placed above the compacted waste. Two feet of soil were then added to cover the cell. The amount of rainfall reaching the open cell was monitored, and an equivalent amount of water was added to the closed cell.

After four years of operation, the cells were emptied and the FMLs recovered. The FMLs were exposed to a variety of conditions within the two cells, the different effects of which could be measured. The FML in the cell open at the top encountered weathering and sunlight exposure at the level of the soil cover, and exposure to the waste. The FML in the sealed cell encountered the moist air in the cell above the soil, the soil, and the refuse.

The data on the different exposures are presented in Table 6-7. In particular, they show the greater absorption of leachate and moisture by liners in the soil and in the waste. They also show the difference between the liner that was on the north wall facing south and that on the south wall facing north. The sheeting on the north wall yielded the greatest increase in modulus and in cure. The lower ash number for the samples exposed at the bottom of the cells are probably due to incomplete volatilization of the test specimens at the time of analysis.

TABLE 6-7. EXPOSURE OF CSPE FML WITHOUT FABRIC REINFORCEMENT IN PILOT-SCALE MSW LANDFILL CELLS AT GEORGIA INSTITUTE OF TECHNOLOGY

Cell	Open cell				Closed cell		
	N	SE	N	SW	SW	N	E
Compass orientation							
Level in cell	Above soil	Above soil	In soil	Below waste	Above soil	In soil	Below waste
Thickness, mil	29.1	29.1	31.9	52.8	33.1	34.3	39.0
<u>Analytical properties</u>							
Volatiles, %	3.62	9.01	13.8	23.7	2.3	19.0	26.5
Ash ^a (db), %	41.9	39.9	40.3	38.2	40.6	40.7	38.3
Extractables (db), % Solvent	...	1.50	...	...	2.00	...	...
-----acetone-----							
<u>Physical properties^b</u>							
Tensile at break, psi	2380	2190	1740	1335	1770	1450	1450
Elongation at break, %	360	350	545	485	570	545	485
Set after break, %	95	72	227	170	206	206	154
Stress at 100% elongation, psi	655	610	405	320	420	280	335
Stress at 200% elongation, psi	930	740	510	420	510	375	450
Tear resistance, ppi	200	140	187	151	213	159	138
Puncture resistance							
Thickness, mil	30.7	22.0	34.5	40.3	32.7	36.4	41.2
Force at puncture, lb	36.8	27.9	33.4	41.6	27.3	33.9	39.0
Deformation at puncture, in.	0.88	0.51	1.33	1.61	1.12	1.72	1.71
Hardness, Durometer points	76A	78A	64A	56A	75A	60A	51A
Seam strength							
Shear, ppi	33.4	...	35.5	30.0	40.5	34.3	22.2
Peel, average, ppi	17.4	...	14.2	12.4	14.2	15.8	13.8

^aDetermined by thermogravimetric analysis.

^bTensile and tear values are averages of machine and transverse directions.

6.5.1.5 HDPE FML in a Hazardous Waste Lagoon--

Samples of a 100-mil HDPE FML were recovered from a waste lagoon in the northeastern United States after 4.75 years of service (Nelson et al, 1985). Samples were removed from different locations in the lagoon and tested to determine the effects of exposure on the physical properties of the FML. The recovery was performed during closure of the lagoon in a Superfund Remedial Action. The site was single-lined unit. The impounded waste liquid was predominantly aqueous and contained significant amounts of organics, particularly chlorinated hydrocarbons, which increased in concentration with depth.

Overall, the FML appeared to be in satisfactory condition. No evidence indicated that it had cracked or failed, but it did show considerable waviness and distortion on the berm and slopes. The results of testing the samples indicated that the samples from the bottom of the lagoon showed an absorbed waste content of about 2%; they also showed a 10% loss in tensile strength at yield and similar losses in the stress at 100% elongation and in the stress at 200% elongation values and a 30% loss in modulus of elasticity. The samples taken from the slopes of the lagoon showed essentially no changes in physical properties. Construction equipment was used in an attempt to remove the waste without damaging the liner, but the liner on the bottom of the lagoon was, nonetheless, destroyed during the cleanup operations. The following subsections discuss the sampling and analysis of the waste, sampling of the FML, and the results of testing the FML samples.

6.5.1.5.1 Sampling and analysis of the waste--The decommissioning justification document (EPA, 1983) indicated that in July 1983 sediment samples of the lagoon waste were collected from a small boat from each of the four corner areas, as is indicated in Figure 6-1. The sump, which is located at the northwest corner, is the deepest point of the lagoon, and the southwest corner is the shallowest. Aqueous waste samples were collected at the northwest corner, the center, and the southeast corner (Figure 6-1). Different depths were sampled at each point.

The sediment that was directly on the lagoon liner underwent limited testing. Data on its physical and chemical properties, which are presented in Table 6-8, show the range in sediment composition at the four sampling points. The low flash point and high energy value for the sump sediment indicate the presence of organic solvents, which tend to be aggressive to most lining materials.

The aqueous waste samples were analyzed more thoroughly. Tests were run for inorganic and organic priority pollutants, priority pollutant pesticides, PCBs, and other inorganics. Samples were taken from three or four depths at each of the three collection points. Concentrations of most constituents increased with depth, showing that the lagoon waste had stratified. Samples taken from the greatest depth at each collection point are of greatest interest in terms of the FML, since they represent the waste closest to the liner on the lagoon bottom. Data on the organic constituents of these

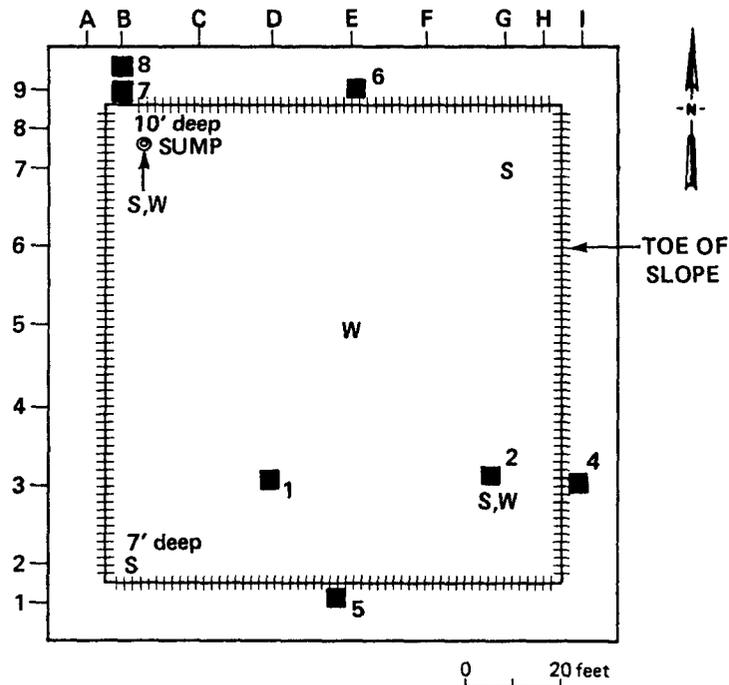


Figure 6-1. Lagoon lay-out showing grid pattern used in sampling, points of sample collection, and location of sump (⊙). Locations at which liner was sampled are indicated by ■ and the liner sample number, sediment samples are indicated by S, and aqueous waste samples are indicated by W. The toe of the slope is indicated by a hatched line (++++). (Source: Nelson et al, 1985).

TABLE 6-8. PHYSICAL AND CHEMICAL PROPERTIES OF SEDIMENT SAMPLES COLLECTED FROM A WASTE LAGOON LOCATED IN THE NORTHEASTERN UNITED STATES^a

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 ^b , BTU/lb	7880	...	...	...
Total residue, %	19.84	56.83	7.89	13.19

^aData taken for the decommissioning justification document.

^bDry-weight basis.

samples, which are the most concentrated for each sampling point and hence the most aggressive, are summarized in Table 6-9. Because inorganic chemicals are not generally aggressive to polymeric FMLs, the high concentrations (greater than 50 ppm) of copper, nickel, zinc, and iron should not affect the HDPE. On the other hand, phenols and petroleum hydrocarbons (71 and 2100 ppm, respectively, in the sample from the lagoon sump) could have some impact on the FML. The total organic carbon (TOC), which was greater than 6000 ppm in all three of the deepest samples, could also affect the FML. The analyses of organic priority pollutants indicated the presence of several aggressive chemicals at concentrations greater than 50 ppm in the sample from the sump. Chlorinated solvents are known to cause swelling and deterioration of physical properties in HDPE FMLs. The analyses of aqueous waste samples from the greatest depth at the three sampling locations resulted in the detection of only minute amounts of the PCB Aroclor 1254 in two of the samples.

TABLE 6-9. CHARACTERISTICS AND COMPONENTS OF THE WASTEWATER THAT ARE POTENTIALLY AGGRESSIVE TO FMLS

Waste component or characteristic	Sampling point and depth ^b		
	G-3 3.0 ft	E-5 4.0 ft	Lagoon sump 6.5 ft
Organic priority pollutant, mg L ⁻¹ :			
Chloroform	2.65	3.2	56.6
Ethylbenzene	3.30	9.6	1080
Methylene chloride	102	140	325
Tetrachloroethane	1.7	3.8	182
Trichloroethane	28.6	90.2	9100
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 ⁻¹	20	32	71
Total organic carbon, mg L ⁻¹	6950	8230	17200
Petroleum hydrocarbons, mg L ⁻¹	26.0	27.8	2100
pH	9.7	9.6	9.8
Flash point, °C	>60	>60	>60

^aData taken from the lagoon decommissioning document.

^bSamples were taken from the greatest depths at three locations in the lagoon (see Figure 6-1).

6.5.1.5.2 Sampling of the FML liner--The liner was inspected and samples were collected for analysis and testing on February 2, 1984. The FML on the upper area of the lagoon was distorted and buckled but in good condition. In the lower area of the lagoon slopes, the FML was scratched and had

many holes and tears. In one place a rock had penetrated the FML. Samples of tears and creases were collected from these areas. Two samples were removed from the sludge mixture on the floor of the lagoon. An 18-in.-wide strip was cut from the northwest corner of the lagoon; the strip ran from the bottom of the lagoon to near the top. A sample of HDPE that had not been exposed to waste was cut from a roll of sheeting left from construction. The outer weathered layer was pulled back and a sample was cut from the inside of the roll. Samples collected are described in Table 6-10 and their locations in the lagoon are shown in Figures 6-1 and 6-2. No sample could be obtained from the bottom of the sump where the highest concentration of organic constituents were measured.

TABLE 6-10. FML SAMPLES COLLECTED FROM THE 100-MIL HDPE LINER FOR A LAGOON LOCATED IN THE NORTHEAST

Sample number	Location in lagoon	Size, in.	Feature
1 ^a	Lagoon bottom, south-center	14 x 16	...
2	Lagoon bottom, southeast corner	10 x 19	...
3 ^a	Retained sample from roll stored on site, northeast of lagoon	10 x 15	...
4	Lower slope, southeast corner	10 x 12	Sample with crack/tear
5	Lower slope, south side	14 x 11	Sample with tear next to extrusion line
6 ^a	Lower slope, north side	6 x 26	Pleated sample with two sharp creases
7 ^a	Bottom to midway of slope, northwest corner	18 x 69	Strip cut from bottom to top, bottom half
8 ^a	Midway to top of slope, northwest corner	18 x 114	Strip cut from bottom to top, top half

^aAnalyzed and physically tested.

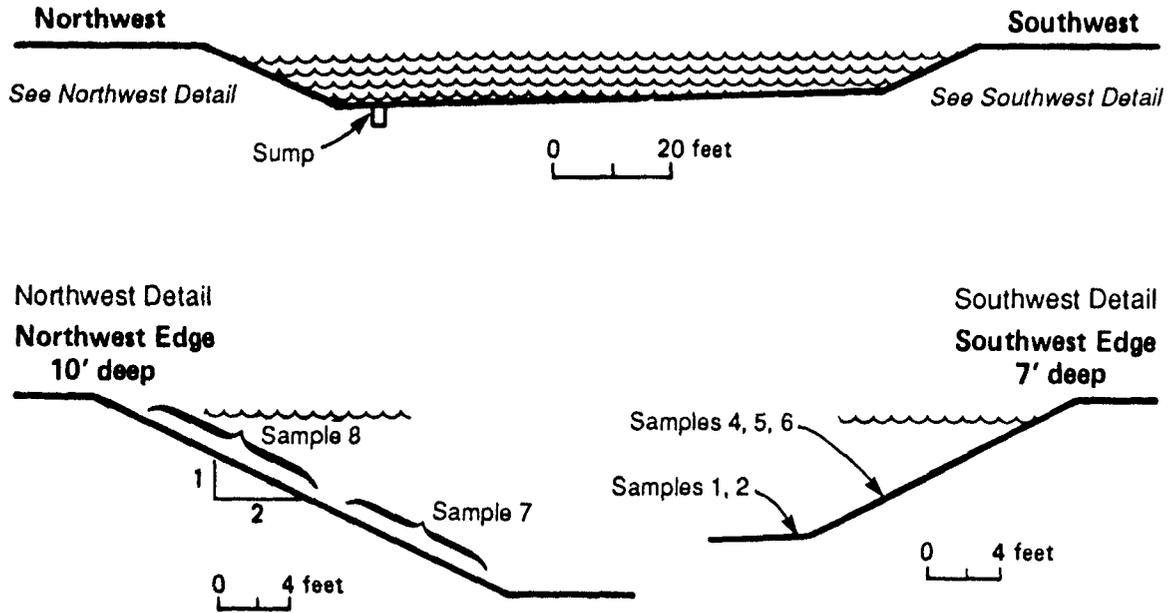


Figure 6-2. Cross section of the lagoon from the northwest to southwest corners. The approximate depths at which FML samples were collected are shown in the details.

6.5.1.5.3 Analytical and physical testing of the FML samples--The FML samples were photographed, measured, and diagrammed upon receipt at the laboratory. Descriptions of these samples and their respective locations in the lagoon are presented in Table 6-10. The following samples were selected for full testing:

- Sample 1, exposed liner from bottom of lagoon.
- Sample 3, retained, unexposed FML left in roll on site.
- Sample 7, cut from the lower end of the strip, i.e. at the slope bottom.
- Sample 8-mid, cut from the middle section of the strip, midway up slope.
- Sample 8-top, cut from the top of the strip at top of slope.

These samples were tested as follows:

<u>Property</u>	<u>Test method</u>
<u>Analytical properties:</u>	
Volatiles content	MTM-1 ^a (Appendix G)
Extractables content	MTM-2 ^a (Appendix E)
Specific gravity	ASTM D792
Thermogravimetric analysis	...
Differential scanning calorimetry	...
Headspace GC analysis	...
<u>Physical properties:</u>	
Tensile properties	ASTM D638, Type IV dumbbell, 2 ipm
Modulus of elasticity	ASTM D882, modified ^b
Tear resistance	ASTM D1004, 2 ipm
Puncture resistance	FTMS 101C, Method 2065 (U.S. GSA, 1980)
Hardness	ASTM D2240

^aMTM = Matrecon Test Method.

^bModified so as to allow for the use of 0.5 x 6-in. strip specimen with an initial jaw separation of 2.0 in. at the standard strain rate of 0.1 in./in. min.

Results of the testing are summarized in Table 6-11. To assess the effect of depth on the volatiles content of the liner, additional volatiles testing was performed on specimens cut at 2-ft intervals along the strip, which consisted of Samples 7 and 8 (Table 6-12).

In addition to the volatiles and extractables analyses of the HDPE samples removed from the lagoon, thermogravimetric analysis (TGA), differential scanning calorimetry (DSC), and specific gravity determinations were performed. The results are presented in Table 6-13 where they are compared with data from Matrecon's database on HDPE sheeting for U.S. and German-produced HDPE FMLs. The following observations were made:

- The sample from the lagoon bottom had a lower amount of crystallinity than the retained sample from the roll and the creased sample from the side slope.
- The retained and the creased samples had lower melting points and slightly higher crystallinity than the similar German sample.
- Overall, the data on the retained liner sample and those in the database on German membranes appeared similar to each other and different from those on the U.S.-produced sample.

TABLE 6-11. PROPERTIES OF HDPE LAGOON LINER AFTER APPROXIMATELY 4.75 YEARS IN SERVICE

Properties	Direction of test	Unexposed sample of similar HDPE ...	Sampling location in lagoon and sample number				
			Retained sample ^a , No. 3	Slope top, No. 8-top	Slope midway up, No. 8-mid	Slope bottom, No. 7	Lagoon bottom, No. 1
<u>Analytical properties</u>							
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 h at 105°C		...	0.03	0.07	0.26	0.36	0.36
Extractables, %		...	0.00	1.26	0.80	1.18	0.80
<u>Physical properties</u>							
Thickness, mil		103.0	102.3	93.4	103.6	100.6	92.4
Tensile at yield, psi	Machine Transverse	2445 2440	2705 2700	2720 2835	2725 2700	2650 2665	2445 2440
Elongation at yield, %	Machine Transverse	20 15	17 15	18 15	17 15	15 18	15 17
Tensile at break, psi	Machine Transverse	4635 4445	3530 4065	4810 4355	4510 4885	3605 2735	3710 3885
Elongation at break, %	Machine Transverse	1025 1010	785 860	965 875	925 985	760 640	810 845
Stress at 100% elongation, psi	Machine Transverse	1765 1710	1920 1945	1960 1965	1925 1925	1875 1965	1795 1790
Stress at 100% elongation, psi	Machine Transverse	1765 1720	1930 1940	1955 1963	1920 1925	1870 1955	1835 1790
Modulus of elasticity, 10 ⁴ psi	Machine Transverse	7.86 7.87	8.69 8.20	8.98 8.68	8.72 8.51	8.37 7.54	5.97 6.06
Tear, ppi	Machine Transverse	839 850	900 885	920 910	910 890	855 875	830 830
Puncture resistance:							
Thickness, mil		98.5	106	98.5	101	100	93.1
Force at puncture, lb		131	148	139	135	134	118
Deformation at puncture, in.		0.73	0.66	0.72	0.62	0.61	0.59
Hardness, Durometer points:							
Instant reading		...	60D	58D	59D	59D	58D
5-second reading		55D	57D	55D	56D	56D	54D

^aSample from unused roll left onsite.

TABLE 6-12. VOLATILES CONTENT OF SPECIMENS OF THE HDPE FML TAKEN AT INCREASING DEPTHS IN THE WASTE LAGOON

Volatiles	Retained sample, No. 3	Sampling location along slope from top to bottom								Lagoon bottom, 8 ft ^c
		Slope top, 0 ft ^a	Slope, 4 ft ^a	Slope, 6 ft ^a	Slope, 8 ft ^a	Slope, 10 ft ^b	Slope, 12 ft ^b	Slope, 14 ft ^b	Slope, 16 ft ^b	
Total volatiles, %	0.15	0.22	0.24	0.35	0.51	0.56	1.08	1.26	1.00	2.26
Over desiccant at 50°C, %	0.12	0.15	0.12	0.14	0.29	0.30	0.73	0.82	0.64	1.90
In oven for 2 h at 105°C, %	0.03	0.07	0.12	0.21	0.22	0.26	0.35	0.44	0.36	0.36

^aCut from Sample 8 section of 18-in. wide strip taken from top to bottom of slope.

^bCut from Sample 7 section of 18-in. wide strip taken from top to bottom of slope.

^cCut from Sample 1 taken from the lagoon bottom which was about 8-ft deep at that point.

TABLE 6-13. COMPARISONS OF THE TGA, DSC, AND SPECIFIC GRAVITY OF THREE HDPE FMLS

Analytical properties	HDPE lagoon FML sample				A similar German liner		U.S. FML (domestic material)
	Bottom ^a , No. 1	Top, No. 8	Retained, No. 3	Creased ^b , No. 6	Smooth	Rough	
<u>Thermogravimetric analysis</u>							
Volatiles, %	0	...	0	...	0	0	0
Polymer, %	97.6	...	97.7	...	98.1	98.6	97.7
Plasticizer, %	0	...	0	...	0	0	0
Carbon black, %	1.7	...	1.8	...	1.9	1.4	2.3
Ash, %	0.7	...	0.5	...	0	0	0
<u>Differential scanning calorimetry</u>							
T _m ^c , °C	131	...	130	129	123	124	119
ΔH _f ^d , cal/g	29.8	...	35.3	36.0	33.6	33.7	24.8
Crystallinity ^e , %	43.6	...	51.6	52.6	49.1	49.2	36.2
Specific gravity	0.936	0.947	0.943	...	0.943	0.939	0.957

^aSample had thoroughly dried out during shelf aging before being tested.

^bSample taken at the apex of the crease in the pleat.

^cMelting temperature of crystalline phase.

^dHeat of fusion of crystalline phase.

^ePercent crystallinity based on ΔH_f value of 68.4 cal/g for 100% crystalline HDPE.

The results of the volatiles and extractables measurements indicated that the HDPE FML had absorbed constituents of the waste. Also, as could be seen by the relatively low modulus and hardness values for the sample exposed at the lagoon bottom, the HDPE FML had softened on exposure. Since the impounded waste liquid contained significant amounts of organics that could be absorbed to some extent by the HDPE, as can be seen by the data reported in Table 6-9, tests were explored as methods of identifying which organics in particular were absorbed. To detect the volatile organics, headspace GC and GC pyroprobe were explored as qualitative tests. The headspace GC method is described in Section 4.2.2.5.1 (p 4-94). A large variety of organics appeared to have been absorbed. Some of the volatiles specifically listed in the analyses in Table 6-9 were identified by headspace GC, and some non-volatile plasticizers were also identified, indicating the potential usefulness of the HSGC procedure.

6.5.1.5.4 Discussion and conclusions--The amount that the FML swelled (as evidenced by the volatiles content) increased with depth into the lagoon. The bottom sample (No. 1) contained about 2.3% volatiles, and the sample from the top of the strip (No. 8) contained approximately 0.2% volatiles. The retained sample from the roll (No. 3) also had about 0.2% volatiles. All five of the tested areas (the four exposed to waste and the retained sample) showed good physical properties, but the sample from the bottom of the lagoon (No. 1) was the softest (lowest durometer and modulus) and showed the lowest values for several physical properties. The sample from the bottom end of the slope strip (No. 7) had low values in tensile at break in the transverse direction. This sample was observed during testing to be quite scratched, which probably explains the low values. Data for other FML properties from this area are much higher. The sample from the top of the strip (No. 8) showed higher tensile properties than the retained sample (No. 3).

The exposed FML sample from the lagoon bottom showed a small amount of swelling (about 3%) and 10% loss in both tensile at yield and in modulus. These changes do not demonstrate incompatibility, but they do indicate that the waste at the bottom of the lagoon had the greatest impact on the FML.

Much buckling and distortion of the FML was observed, especially on the north slope of the lagoon. The day the samples were taken was cold but sunny, which should have minimized any thermal expansion. On a hot day, this buckling would have been greatly increased. Though not in itself a significant problem, buckling adds stress on seams, allows movement of the underlying earthwork by creating cavities, and increases the chance of mechanical damage by introducing folds.

The FML showed no cracking such as that encountered with environmental stress-cracking; it lost in tensile strength at yield and in ultimate tensile strength, but it did not crack at folds or bends.

No evidence was apparent to indicate that the HDPE FML lost its integrity. All visible seams looked secure. The only evidence of degradation was mechanical damage in areas where the FML had probably been worked on with a bobcat. The presence of rocks directly underneath the liner

aggravated this damage. The FML in this impoundment was not able to withstand the clean-up operations.

The DSC data indicated that the amount of PE crystallinity in the HDPE FML changed during exposure, a factor that should be checked in future testing.

6.5.1.6 PVC FML in an Industrial Sludge Lagoon--

In August and September, 1982, Malcolm Pirnie, Inc. (Roberts et al, 1983) collected samples of a 20-mil PVC FML from an industrial sludge lagoon. The lagoon was scheduled to be excavated and relined due to failure of the lining system and, as such, it was possible to obtain samples of the exposed FML.

The site, located in the northeastern United States, was constructed in 1973. The lagoon covered approximately 22,000 square feet with a side slope of 2:1. The PVC FML was fabricated by the supplier in two pieces and seamed in the field by the installer. All seams were made using a bodied solvent. The FML was designed to be covered but it was observed that the cover material had sloughed off at the top of the berm. The lagoon was used as a settling basin where a slurry waste was pumped in, the solids allowed to settle, and the liquid pumped back into the plant.

The waste disposed of in the lagoon was a calcium sulfate sludge, the result of the neutralization of sulfuric acid with lime. The sludge also contained ammonia and chlorides. A general analysis of the waste liquid in the lagoon is presented in Table 6-14; this is probably the best representation available of the liquid in contact with the inside of the FML on the saturated sludge portion of the lagoon slope.

TABLE 6-14. GENERAL ANALYSIS OF SLUDGE LIQUID

pH	8.0 - 9.0
Specific conductance, $\mu\text{mhos cm}^{-1}$	15,000 - 60,000
Chlorides, mg L^{-1}	4,500 - 5,000
Sulfates, mg L^{-1}	15,000 - 20,000
Ammonia, mg L^{-1}	1,000 - 7,000

Six FML samples were taken from the upper edge of the lagoon in August, 1982. Subsequently, 12 additional samples were taken from the lagoon side and bottom in September, 1982, when the lagoon was being excavated. The FML

sampling locations are shown in Figures 6-3 and 6-4. Field observations on the FML samples are presented in Table 6-15.

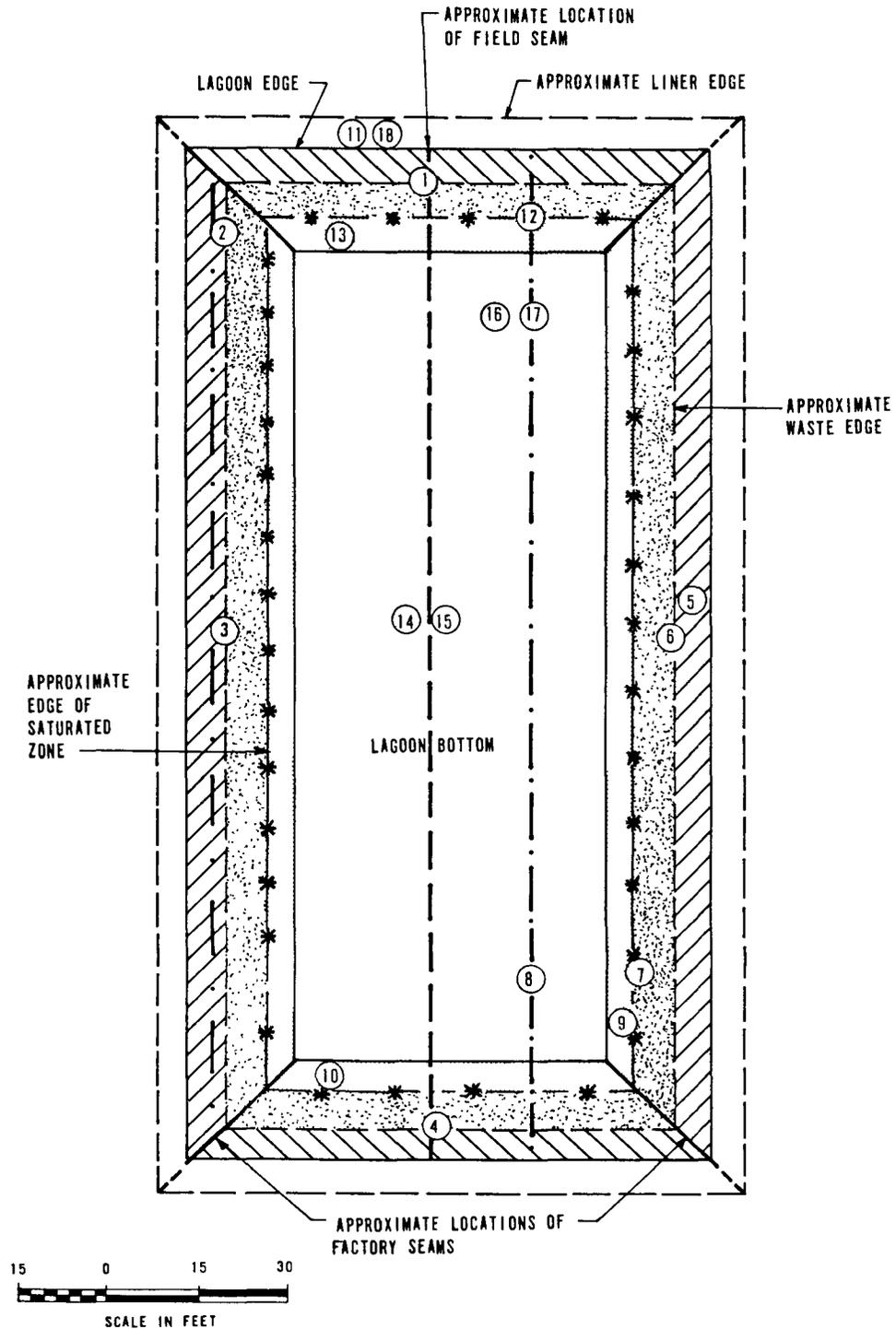


Figure 6-3. Plan view of lagoon containing a calcium sulfate sludge showing sampling locations. (Source: Roberts et al, 1983).

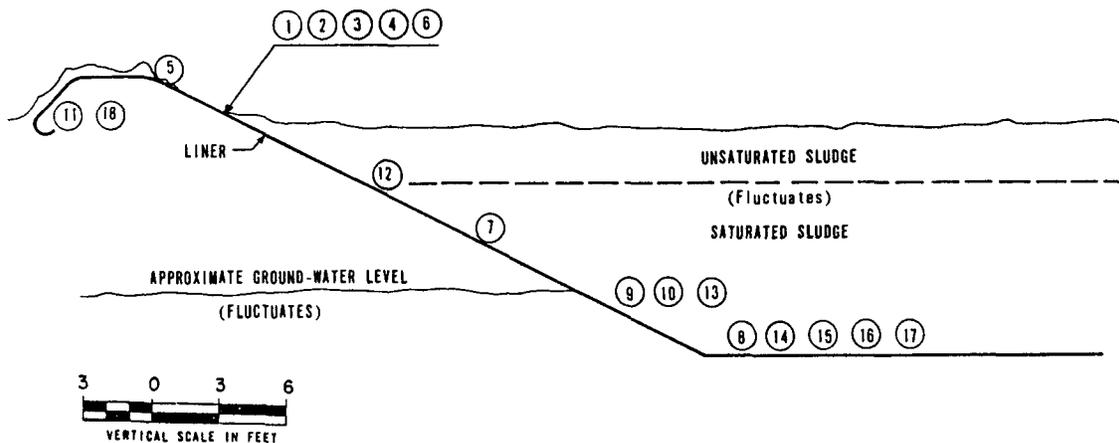


Figure 6-4. Idealized cross section of lagoon showing sample locations. (Source: Roberts et al, 1983).

The following samples were selected for testing:

- Sample 1 (upper and lower halves).
- Sample 3 (upper half).
- Sample 4 (upper and lower halves).
- Sample 5 (seamed area).
- Sample 6 (upper half).
- Sample 7 (seamed area).
- Sample 11 (seamed area).
- Sample 12 (upper and lower halves).
- Sample 15 (seamed area).
- Sample 17 (seamed area).

6.5.1.6.1 Inspection and testing of the FML samples--Samples of the FML exposed to weathering were generally brittle and dry. During the sample collection, the brittleness was evident through cracking and splitting of the material. However, it was possible to roll up the FML samples, probably because of the warm weather. The tautness of the FML indicated that localized shrinkage of the FML had occurred. Tensile test specimens from the

TABLE 6-15. FIELD OBSERVATIONS OF FML SAMPLES FROM AN INDUSTRIAL SLUDGE LAGOON

Sample number	Location in lagoon	Seams	Conditions of sample
1	North side of lagoon Upper half weather-exposed Lower half exposed to unsaturated sludge	Factory seam in both halves	Upper half cracked, brittle Lower half supple
2	West side of lagoon, northern corner Upper half weather-exposed Lower half exposed to unsaturated sludge	Factory seam in upper half	Upper half brittle, ripped; shows discoloration; lower half supple
3	West side of lagoon Upper half weather-exposed Lower half exposed to unsaturated sludge	Factory seam in upper half	Upper half brittle, cracked, grass growing through hole in FML; lower half supple
4	South side of lagoon, Upper half weather-exposed Lower half exposed to unsaturated sludge	Factory seam in both halves; unadhered field seam in upper half; intact field seam in lower half	Upper half brittle, cracked; lower half supple
5	East side of lagoon Completely exposed to weather	Factory seam	Discolored, supple
6	East side of lagoon Upper half weather-exposed Lower half exposed to unsaturated sludge	Factory seam in upper half	Upper half brittle, cracked; lower half supple
7	East side of lagoon near lagoon bottom Completely under saturated sludge	...	Dimpled sludge in spots; layover hydrogen sulfide smelling, peat- like black soil
8	Bottom sample from southern end of lagoon	...	Dimpled, supple
9	East side of lagoon near lagoon bottom Completely under saturated sludge	...	Dimpled, supple, layover peat- like black soil similar to #7, lay under layered sludge
10	South side of lagoon near lagoon bottom Completely under saturated sludge	...	Two creases in sample; layover peat-like black soil similar to #7
11	Under north berm-folded portion Exposed to soil, same possible exposure to sludge	Factory seam	Dry, fairly stiff
12	North side of lagoon on slope Upper half in unsaturated sludge Lower half in saturated sludge	Factory seam	Lower half dimpled, supple
13	North side of lagoon on slope Completely under saturated sludge	...	Dimpled, supple
14	Bottom sample from lagoon center	...	Dimpled, supple
15	Bottom sample from lagoon center	Factory seam	Dimpled, supple
16	Bottom sample from northern end of lagoon	...	Dimpled, supple
17	Bottom sample from northern end of lagoon	Factory seam	Dimpled, supple

Source: Roberts et al, 1983.

top of Sample 1 cracked along the edges when they were dried out. An attempt was made to avoid the cracks by dieing specimens from a warmed sample, but these also cracked. The result of the tensile and tear testing reflect this brittleness.

Sample 5, which was taken near the discharge pipe, was discolored and not brittle. This lack of brittleness was in contrast to the rest of the weather-exposed samples. Their brittleness, because of the loss of plasticizer, is shown by low values for extractables content and elongation and high hardness values. Sample 6, located adjacent to Sample 4, was brittle and is a better example of west-facing exposure. Sample 5 is considered to be nonrepresentative of a weather-exposed sample because of exposure to the discharge material.

Results of the testing are summarized in three tables. Table 6-16 presents data on the samples exposed to the weather arranged in order of decreasing severity, i.e. south-facing exposure was the most severe, followed by west-facing, then east-facing, with north-facing the least severe. In Table 6-17, the data are presented in a vertical cross section arranged from the top of the lagoon to the bottom.

6.5.1.6.2 Potential Use of soil-exposed specimen as a control--The soil-exposed specimen (Sample 11) was collected as a possible control sample. However, the extractables content of the sample, which was 26.50%, is low for this type of FML and the modulus values are high, which indicates that exposure probably affected its properties. Due to the nature of the cleaning operations at the lagoon, the sample may have been exposed at some point during the operation to the weather and possibly to the sludge. Because of the rather large apparent loss in plasticizer, the sample is likely to have undergone moderately severe exposure conditions; therefore, it could not be used as a control.

6.5.1.6.3 Inspection and testing of the seams--Factory seam samples from different levels in the lagoon and one sample of the field seam were collected. All seams were made with a bodied solvent. The factory seams are approximately 1 in. wide and the field seam approximately 2 in. wide. All seam samples appeared to run parallel to the machine direction; thus, testing across the seam constituted a transverse direction test with respect to the sheeting. All factory seams were observed to be in good condition.

The seams were tested in both shear and peel modes, the results of which are reported in Table 6-18. Seam strength tested in shear of the factory seams generally was good ranging from 74% to 99% of the breaking strength of the FML. Specimens broke either at the seam edge or in the liner material. The brittle weathered samples and the samples from the bottom of the lagoon had the lowest seam strength in shear; the sample exposed mainly to soil (#11) had the best strength. All of the seams tested in peel delaminated in the plane of the adhesive or "glue line", leaving traces of bodied solvent on both sides. The lowest peel strength, 17.7 ppi, was measured in samples from the bottom of the lagoon; the highest, 27.0 ppi, from a weather-exposed sample.

TABLE 6-16. PHYSICAL AND ANALYTICAL PROPERTIES OF WEATHERED SAMPLES OF PVC FML EXPOSED IN A CALCIUM SULFATE SLUDGE LAGOON

Sample number	11	1 Upper	6 Upper	5	3 Upper	4 Upper	
Lagoon location	N-side	N-side	E-side	E-side	W-side	S-side	
Exposure condition	Under soil	Weather	Weather	Weather	Weather	Weather	
Average thickness, mil	18.8	16.0	15.6	19.3	16.0	18.2	
<u>Analytical properties^a</u>							
Volatiles (as received):							
Total, %	1.09	3.15	3.96	3.22	5.18	2.28	
Step 1, over desiccant at 50°C, %	0.75	1.37	3.68	1.04	4.26	1.56	
Step 2, in oven at 105°C for 20 h, %	0.34	1.78	0.28 ^b	2.18	0.92	0.72	
Extractables (db), %	26.50	18.91	20.23	30.52	20.54	21.91	
Ash (db), %	7.54	8.19	...	6.45	7.50	8.41	
<u>Physical properties, as received</u>							
		<u>Direction of test</u>					
Tensile at break, psi	Machine	2940	2430	2500	3310	3390	2925
	Transverse	3135	3015	2470	3205	3155	2795
Elongation at break, %	Machine	260	5	25	205	80	115
	Transverse	285	25	20	225	55	70
Set after break, %	Machine	165	1	20	125	50	90
	Transverse	165	15	3	130	50	50
Stress at 100% elongation, psi	Machine	2345	2810	...	2895
	Transverse	2280	2585	...	2645
Stress at 200% elongation, psi	Machine	2700	3240
	Transverse	2715	3405
Tear resistance, ppi	Machine	535	235	295	560	515	595
	Transverse	580	170	327	495	355	430
Puncture resistance:							
Thickness, mil	19.8	16.7	16.8	18.3	17.4	16.0	
Force at puncture, lb	37.6	9.2	16.2	33.1	25.2	26.4	
Deformation at puncture, in.	0.44	0.22	0.35	0.42	0.26	0.28	
Hardness, Shore D							
Instant reading	45	52	52	52	53	55	
5-second reading	38	49	50	38	48	47	

^adb = Dry basis.

^bAt 105°C for 4 hours.

Source: Roberts et al, 1983.

TABLE 6-17. PHYSICAL AND ANALYTICAL PROPERTIES OF SAMPLES FROM A VERTICAL CROSS SECTION OF PVC FML EXPOSED IN CALCIUM SULFATE SLUDGE LAGOON

Sample number	11	1 Upper	1 Lower	4 Lower	12 Upper	12 Lower	7	15	17	
Lagoon location	N-side	N-side	N-side	S-side	N-side	N-side	W-side	Center	N-end	
Exposure condition	Undersoil	Weather	Weather/waste interface	Weather/waste	Unsaturated waste	Saturated waste	Saturated waste	Lagoon bottom	Lagoon bottom	
Average thickness, mil	18.8	16.0	20.3	20.8	21.2	21.6	20.4	19.8	20.7	
<u>Analytical properties^a</u>										
Volatiles (as received):										
Total, %	1.09	3.15	6.51	3.66	10.58	9.87	7.14	4.27	3.43	
Step 1, over desiccant at 50°C, %	0.75	1.37	5.10	3.14	8.62	8.27	5.60	3.42	2.49	
Step 2, in oven at 105°C for 20 h, %	0.34	1.78	1.41	0.52	1.96	1.60	1.54	0.85 ^b	0.94	
Extractables (db), %	26.50	18.91	21.50	26.10	31.02	32.71	32.44	34.98	35.15	
Ash (db), %	7.54	8.19	7.90	9.32	6.89	6.67	7.13	7.08	6.69	
<u>Physical properties, as received</u>										
	<u>Direction of test</u>									
Tensile at break, psi	Machine	2940	2430	2915	2780	2610	2505	2605	6460	2760
	Transverse	3135	3015	2575	2495	2315	2335	2440	2320	2550
Elongation at break, %	Machine	260	5	220	275	300	295	280	310	265
	Transverse	285	25	220	295	310	330	300	315	290
Set after break, %	Machine	165	1	125	105	95	70	85	70	60
	Transverse	165	15	110	130	100	90	90	80	70
Stress at 100% elongation, psi	Machine	2345	...	2350	1885	1635	1500	1740	1265	1625
	Transverse	2280	...	2090	1720	1340	1205	1580	1245	1415
Stress at 200% elongation, psi	Machine	2700	...	2830	2350	2105	2010	2210	1805	2208
	Transverse	2715	...	2460	2065	1750	1630	2010	1700	1975
Tear resistance, ppi	Machine	535	235	520	495	345	330	380	260	325
	Transverse	580	170	355	415	330	310	360	270	295
Puncture resistance:										
Thickness, mil	19.8	16.7	20.4	21.1	21.2	21.6	21.2	19.7	20.5	
Force at puncture, lb	37.6	9.2	31.6	40.1	35.2	32.3	31.8	26.1	32.6	
Deformation at puncture, in.	0.44	0.20	0.33	0.64	0.66	0.71	0.63	0.69	0.67	
Hardness, Shore D										
Instant reading	45	52	49	39	40	36	40	34	39	
5-second reading	38	49	47	32	28	25	30	24	24	

^adb = Dry basis.

^bAt 105°C for 4 hours.

Source: Roberts et al, 1983.

TABLE 6-18. SEAM STRENGTH OF PVC FML EXPOSED IN CALCIUM SULFATE SLUDGE LAGOON

Sample number Exposure conditions	1 Upper Weather	1 Lower Weather/waste interface	3 Upper Weather	4 Upper Weather/waste interface	4 Lower Weather/waste interface	5 Weather	7 Saturated waste	11 Soil	12 Upper Unsaturated waste	15 Bottom	17 Bottom
Breaking factor, ppi											
Transverse direction	48.3	49.7	52.1	51.7	52.5	62.0	49.4	54.3	48.7	45.6	52.4
Factory seam strength:											
Shear, ppi	43.9	46.8	40.3	38.4	44.2	51.8	44.8	53.8	47.2	40.0	43.7
Locus of break ^a	SE-BRK	SE-BRK	SE	SE	SE	SE	SE	SE	SE	SE	SE
Percent of breaking factor	91	94	77	74	84	84	91	99	97	88	83
Peel, ppi	27.0	21.3	26.1	25.5	25.0	26.6	21.1	25.8	23.5	17.7	20.7
Locus of break ^a	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD	AD
Field seam strength:											
Shear, ppi	...	...	...	...	45.9	...	...	...	...	...	...
Locus of break ^a	...	...	...	...	SE-AD	...	...	...	...	...	...
Percent of breaking factor	...	...	...	...	87	...	...	...	...	...	...
Peel, ppi	...	...	...	...	13.0	...	...	...	...	...	...
Locus of break ^a	...	...	...	...	AD	...	...	...	...	...	...

^aSE = broke at seam edge; AD = delaminated in the plane of the adhesive bond; SE-BRK = broke at either seam edge or in sheeting.

Source: Roberts et al, 1983.

The field seam collected had a section that had not been properly bonded. This appeared to be a "holiday" or section without adhesive. The bonded section showed good shear strength at 87% of the breaking strength of the material. This is higher than the factory seam shear strength for the same sample; the test method, however, does not take the seam width into account. At 13.0 ppi, the peel strength of the field seam sample was approximately half the peel strength of the factory seam, which could be a result of differences between factory and field seams or an indication of a loss in properties. No information was available on the peel strength of the field seams at the time of installation.

6.5.1.6.4 Conclusions--The results of testing the recovered PVC FML are similar to those from laboratory and pilot-scale studies. Properties of the PVC FML samples from the sludge lagoon vary considerably depending upon sample location, and the condition of the samples reflects the degree to which they are weather-exposed. However, neither the properties nor their variability were unexpected in light of test values from previous laboratory testing (Haxo, 1981; Haxo, 1982).

Exposure to the weather was the most significant degradation mechanism to the FML. The sample on the north side (south facing) showed the most severe effects. Samples of the FML under the sludge, which underwent minimal or no exposure to the weather (saturated sludge and lagoon bottom samples), showed normal properties for PVC FMLs. Samples exposed to the weather showed evidence of shrinking and physical deterioration and had low values for thickness, indicating a loss of plasticizer. The extractables content of the exposed samples ranged from 18.9 to 30.5% depending on directional orientation. Since the amount normally compounded in PVC sheeting ranges from 30-35%, these results clearly indicate that the weathered samples have lost plasticizer.

After nine years of exposure under the waste, the samples on the lagoon bottom had values comparable to unexposed 20-mil PVC sheetings, indicating good retention of properties. Therefore, it appears that the type of sludge being impounded did not affect the integrity of the PVC FML. However, if a retained sample of the original sheeting had been available, these results could have been expressed as changes in properties due to exposure or percent retention of unexposed test values. Instead, data for the various samples can only be compared with each other and with data for unexposed 20-mil PVC sheeting, as reported in the literature.

Factory seams in the installed FML maintained their integrity during the long-term exposure; however, the field seams did not. All factory seams tested in shear broke at the seam edge or broke in the sheeting out of the seam area reflecting the strength of the FML. Some of the field seam specimens tested in shear, however, delaminated in the plane of the seam adhesive, as well as breaking at the seam edge. When tested in peel, which is a more severe test, all of the test specimens for both types of seams delaminated in the plane of the adhesive. The manner in which the field seam test specimens broke in shear and the evidence of a "holiday"

indicate an inadequate seaming operation and emphasize how critical field seaming is to a successful lined impoundment and the importance of a rigorous CQA program.

Mechanical puncturing, inadequate protection from exposure to the weather due to the sloughing of the protective cover, and poor field seaming contributed to the deterioration and failure of the FML liner. In addition, the sloughing of the protective soil cover indicated inadequate friction between the soil and the FML for a slope of 2:1.

6.5.1.7 PVC FML from a MSW Landfill--

A sample of a 20-mil PVC FML, which had been in service for approximately six years, was removed in July 1984 from under 12 ft of MSW at a Controlled Sanitary Landfill in Lycoming County, PA. The sample was obtained from the lowest part of the landfill, i.e. in the sump area near the leachate collection. Therefore, it can be assumed that the sample was in contact with leachate for the entire six years. The FML was torn with a backhoe while excavating a leachate pipe. At the time the sample was received by Matrecon's laboratory the sample appeared to have completely dried out. The unpleasant odor of the sample was similar to that of butyric acid. The results of testing the exposed sample for analytical and physical properties are presented in Table 6-19. Table 6-19 also includes data on the properties of Matrecon FML No. 88, which is a 20-mil PVC received in 1976 from the same manufacturer that produced the exposed FML. The formulation is reported to be similar, if not the same as the exposed sample. This can be confirmed by the almost identical analytical properties.

If data for Matrecon FML No. 88 are used as baseline values, then the following changes in properties can be noted:

- Extractables = -5.1%.
- Tensile at break = -10.9%.
- Elongation at break = -7.6%.
- Stress at 100% elongation = -10.4%.
- Stress at 200% elongation = -10.4%.
- Tear resistance = -11.1%.
- Puncture resistance = +31.1%.
- Hardness = no change.

From these data, it can be concluded that the FML may have lost plasticizer and that changes of about 10% have taken place in the physical and analytical properties of the 20-mil PVC FML after six years of exposure as a liner in an MSW landfill. Also, by the time of testing the samples had probably dried

TABLE 6-19. PROPERTIES OF 20-MIL PVE FML EXPOSED AS MSW LANDFILL LINER^a COMPARED WITH AN UNEXPOSED 20-MIL PVC FML

Property	Direction of test	Test results	
		Exposed FML E486	Unexposed FML No. 88 ^b
<u>Analytical Properties</u>			
Volatiles (105°C for 2 h), %		0.14	0.17
Extractables (2:1 CCl ₄ :CH ₃ OH), %		31.74	33.46
Ash, %		2.98	2.80
Specific gravity		1.28	1.255
Thermogravimetric analysis:			
Ash, %		3.0	...
Char, %		13.0	...
Volatiles, %		0.5	...
T _{onset}		290°C	...
T _{max}		350°C	...
<u>Physical properties</u>			
Thickness, mil		20	20.0
Tensile at break, psi	Machine	2950	3395
	Transverse	2670	2910
Elongation at break, %	Machine	275	325
	Transverse	335	335
Stress at 100% elongation, psi	Machine	1700	1870
	Transverse	1410	1600
Stress at 200% elongation, psi	Machine	2360	2600
	Transverse	1940	2190
Tear resistance, ppi	Machine	440	460
	Transverse	385	470
Puncture resistance			
Thickness, mil		20.0	19.9
Force at puncture, lb		37.5	28.6
Deformation at puncture, in.		0.76	0.56
Hardness, Durometer D			
5-second reading		32	32

^aMatrecon sample identification number E486; FML had been exposed for six years.

^bLiner No. 88 from Matrecon Database. Received in 1976.

out and lost whatever moisture and volatile organics that had been absorbed when in service. The PVC FML remained flexible and useful with almost 90% retention of all physical properties.

6.5.1.8 EPDM FML from Emergency Ponds for "Red Water"--

Samples of a 60-mil vulcanized EPDM flexible FML were recovered for analysis and physical testing from different locations within a basin that was being decommissioned after 18 years of service as an emergency pond for "red water" (Haxo et al, 1987).

6.5.1.8.1 Description of the basin and the FML--The basin was constructed in late 1967 and early 1968 to act as a surge pond for "red water" produced as a waste from TNT production. The pond covered an area of 3.1 acres and contained "red water" waste liquid, which was usually concentrated by evaporation and then disposed of by incineration. It must be recognized that the composition of the wastewater in the pond was highly variable with time as the basin was used intermittently. The constituent concentration for selected analytes from a sample collected on May 28, 1981 is presented in Table 6-20.

The basin was last used during TNT production for the Viet Nam war and was dismantled in May 1985, because it was no longer needed. The capacity of the basin was 4.06 million gallons. It had an average depth of about 5 ft, and the dike slope was 3:1. The FML was an unreinforced EPDM FML with a nominal thickness of 60 mils. It was uncovered, that is, no soil cover was placed on the FML. The water table in the area appeared to have been about the same as that of the basin bottom as a partially-filled water drainage ditch ran along the outside of the dike on the north and the east sides.

Most of the field seams along the basin slopes failed, but, from what could be observed of the basin bottom, the field seams were mostly intact; we did not observe a single failure of the factory seams.

The anchor trench along the berm top was completely inadequate for anchoring the top of the FML. In combination with the failure of the field seams, this poor anchorage resulted in large sections of the basin slopes not being covered by the liner.

Gas generation below the FML resulted in the formation of "whales" or areas of the liner which lifted off the floor of the basin. No means for bleeding off the gas appeared to have been incorporated into the pond design, e.g. an underdrain or gas-venting system. It was reported that these "whales" were punctured to release trapped gases shortly before the sampling was started. An attempt had been made earlier to relieve the trapped gases by attaching vent pipes to the FML, but these vents appear to have been ineffective.

6.5.1.8.2 Sampling of the FML--Four major samples were obtained and were designated Samples A, B, C, and D. In addition, seven smaller samples containing holes, apparently caused by rodents, were also collected.

TABLE 6-20. COMPOSITION OF
SURFACE WATER SAMPLE^a

Analyte	Concentration ($\mu\text{g/L}$)
<u>TNT-Related Organics Compounds</u>	
2,4,6-Trinitrotoluene (TNT)	<0.29
2,6-Dinitrotoluene (DNT)	196.0
2,4-Dinitrotoluene (DNT)	1.00
2-Nitrotoluene	5.7
1,3,5-Trinitrobenzene	<2.2
<u>Anions</u>	
Nitrite	<250
Nitrate	433,000
Sulfate	6,690,000
Phosphate	390
<u>Heavy Metals</u>	
Arsenic	<13.0
Cadmium	8.8
Chromium (hexavalent)	1.5
Chromium (total)	125.0
Copper	141.0
Iron	5,360.0
Lead	40.2
Manganese	195.0
Mercury	<0.35

^aSample number: SW109; sample date,
May 28, 1981.

Source: Tom Erdman of the Joliet Army
Ammunition Plant.

The reasons for taking each of the major samples are discussed briefly below:

- Sample A was the major sample from this FML. It was taken from the northeastern dike (southern exposure) and extended from the anchor trench at the top of the dike, down the dike, and on to the basin bottom. A factory seam extended most of the sample length and a field seam extended into the bottom section. Due to its size, the strip was cut into three sections.
- Sample B included a field seam which was partly intact and partly failed. It was taken from the northeastern dike between Sample A and the northeast corner of the basin.
- Sample C was from the basin bottom. Before collection, it was covered with very wet sludge and exposed to very wet mud on the underside. A small strip cut from the liner adjacent to Sample C was collected for volatiles determination.
- Sample D included a partly intact/partly failed field seam from a "whale." Sample D was chosen because "whales" are considered to be sites of stress on the FML and because of the presence of a field seam.

The locations where the samples were collected are shown in Figure 6-5, a simplified drawing based on the "as-built" drawing of the basin.

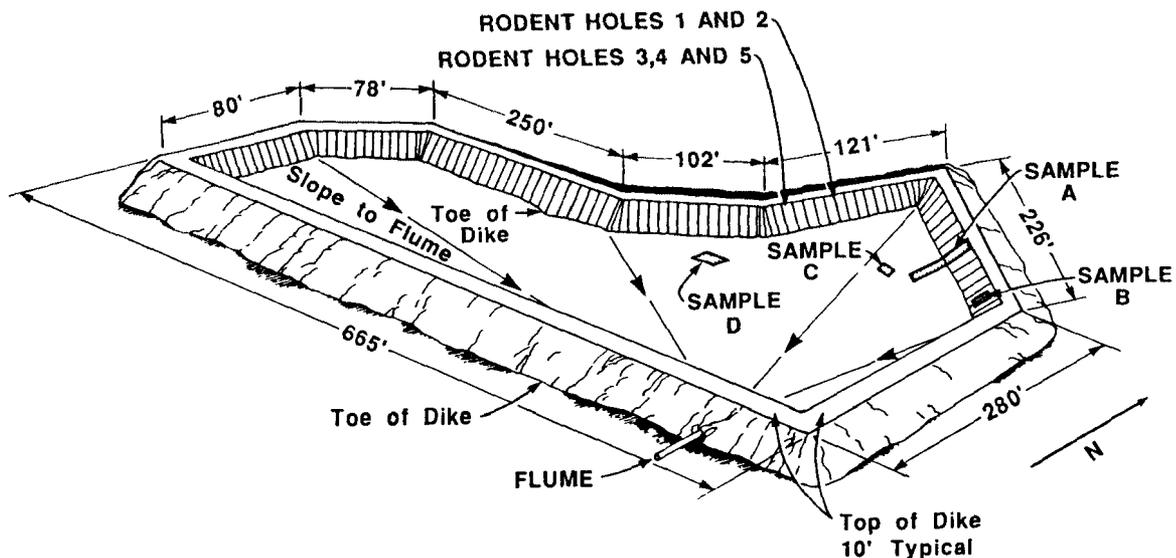


Figure 6-5. Schematic drawing of the basin showing the locations where the FML samples were collected.

No retained sample of the original liner was available for use as a baseline reference. The top portion of Sample A, which was buried in the shallow anchor trench on top of the dike, probably had only a modest exposure to either waste or sun, but it appeared to have aged and lost extractables and thus could not be used as a baseline reference.

6.5.1.8.3 Testing of FML samples--The FML samples were photographed and measured at the laboratory; Sample A, the "strip" sample, was tested in the following areas:

- The upper section of the "strip", was tested in four areas which had been exposed in the anchor trench, at the top of the slope, at mid-slope, and at the toe of the slope, respectively.
- A second section was tested for analytical and physical properties in an area that had been at the bottom of the slope.
- A third section, which had been exposed at the bottom of the basin, was tested for physical properties.

The other three samples were tested as follows:

- Sample B, taken at a field seam, was tested in two areas designated Samples B1 and B2 which correspond to two different layers of the same sheeting. Sample B1 was exposed to the weather and possibly waste; Sample B2 was the underflap part of the intact portion of the field seam.
- The strip taken adjacent to Sample C from the bottom of the basin was analyzed for volatiles immediately upon receipt at the laboratory. Physical tests and additional analyses were later performed on the main portion of Sample C.
- Sample D, cut from a "whale", was tested for analytical and physical properties and the intact part of the seam was tested in the peel mode.

The results of the testing are presented in Table 6-21. The results of testing an unexposed EPDM manufactured in 1972 are also included for comparative purposes (see Section 6.4.1.8.5).

6.5.1.8.4 Inspection and testing of the seams--The seams in the FML were prepared both in the controlled environment of the factory and in the uncontrolled outdoor environment of the field. Roll stock of EPDM sheeting was manufactured and fabricated at the factory into large panels that were then installed in the basin. Vulcanized seams were made to join the sheeting into panels at the factory, while vulcanizable adhesives were used to join the panels to form the liner in the field.

TABLE 6-21. PROPERTIES OF 60-MIL EPDM FML SAMPLES COLLECTED FROM THE EMERGENCY "RED-WATER" BASIN

Property	Direction of test	Preliminary Sample ^a	Strip Sample A						FML on slope with field seam		Basin bottom C	Top of "Whale" D	1972 EPDM liner ^b
			Anchor trench A1-1	Top of slope A1-2	Mid-slope A1-3	Toe of slope A1-4	Basin A2-5	bottom A3-6	Top layer B1	Bottom layer B2			
<u>Analytical properties</u>													
Volatiles, %		0.88	...	1.19	1.35	0.94	0.56 ^c	...	0.77	0.72	0.77 ^c	0.85	0.38
Extractables ^d , %		15.9	13.52	14.65	16.31	16.56	21.60 ^e	21.28	14.26	17.13	21.62	17.72	23.41
Ash, %		...	7.90	...	...	...	7.3	...	...	7.90	7.24	8.04	6.78
Specific gravity		...	1.218	...	...	...	...	1.181	...	1.203	1.180	1.183	1.173
<u>Physical properties</u>													
Tensile at break, psi	Machine	1870	1865	1810	1825	1835	1750	1765	1925	1765	1755	1815	1635
	Transverse	...	1860	1775	1765	1755	1735	1725	1765	1730	1730	1805	1550
Elongation at break, %	Machine	375	370	280	330	355	415	400	275	345	390	370	520
	Transverse	...	410	290	355	370	455	410	265	350	420	400	500
Stress at 100% elongation, psi	Machine	515	640	790	640	605	445	450	800	505	445	525	350
	Transverse	...	600	725	545	525	390	400	700	460	380	465	320
Stress at 200% elongation, psi	Machine	1150	1230	1480	1290	1260	1000	1015	1555	1150	1045	1165	800
	Transverse	...	1140	1390	1180	1130	890	935	1425	1090	925	1040	740
Tear resistance, ppl	Machine	193	190	160	160	170	190	170	155	170	175	180	206
	Transverse	...	185	150	165	165	180	170	150	170	175	180	211
<u>Puncture resistance</u>													
Thickness, mil		62.5	...	55.6	55.0	53.7	56.5	63.0	69.7	71.3	61.5	56.5	60
Maximum force at puncture, lb		76.2	...	67.4	53.0	51.8	54.0	58.5	89.0	79.0	62.7	56.6	56.9
Deformation at break, in.		1.20	...	1.09	1.07	1.06	1.17	1.21	1.00	1.14	1.31	1.15	1.46
Maximum force, normalized for 100-mil thickness, lb		122.0	...	121.2	96.4	96.5	95.6	92.9	127.7	110.8	102.0	100.2	94.8
<u>Hardness, Duro A points</u>													
1-second reading		70	69	72	68	67	64	65	71	65	63	69	...
5-second reading		67	66	70	66	64	63	63	67	61	61	66	57

^aPreliminary sample received 1-5-84. Direction of test uncertain but is believed to be the machine direction; sample taken from top of slope by Mr. T. Erdman of the Joliet Army Ammunition Plant.

^bBaseline reference--FML No. 8 (Haxo et al, 1985).

^cValues of 0.83% and 1.23% were obtained, respectively, on small samples of A2-5 and C that had been collected and sealed in small tins to prevent loss of volatiles.

^dExtractables were determined with methyl ethyl ketone.

^eValue of 22.28% was obtained on the small sample of A2-5 collected for volatiles determination.

The vulcanized factory seams appeared, after exposure to "red water" and weather, to have maintained their initial properties. The factory seam was 3.2 in. wide, and the edges of both the top and bottom sheets were beveled to a thickness of about 30 mils up to 0.75 inches in from the edge of each sheet.

The field seam was 6 in. wide and was bonded with a vulcanizable adhesive. A low temperature vulcanizable tape was placed along the edge of the top sheet. In addition to its function in bonding the sheets together, the tape also served to round the edge of the top sheet. However, the tape along and adjacent to the edge of the top sheet opened in many of the field seams. This opening may have been caused by differential shrink and swell of the sheeting and the adhesive.

Many of the areas tested for physical properties included factory or field seams that were tested for seam strength in shear and peel modes. The location and type of seam samples that were tested and the results of the testing are presented in Table 6-22.

Seam strength in shear mode was measured in accordance with ASTM D882 and D3083, modified for testing exposed FMLs. Testing in peel mode was performed in accordance with ASTM D413 in 90° peel. In both modes of testing, 1-in. wide strip specimens were tested at a jaw separation rate of 2 inches per minute.

6.5.1.8.5 Selection of a baseline reference--No retained sample of the FML was available that could be used as a baseline reference. The samples that were recovered from the basin were 18 years of age; consequently, there was a question as to whether any of these samples was suitable for use as a baseline reference. However, data were available on EPDM FMLs that had been produced in 1972 and tested in earlier work performed by Matrecon for the EPA on a study of liners for municipal solid waste landfills (Haxo et al, 1982; Haxo et al, 1985). A review of the analytical results for an FML produced in 1972 indicated that it was essentially the same as that of the liner installed in the basin in 1967. A comparison of analytical properties of the 1972 EPDM liner with the liner recovered from the basin is given in Table 6-23. The data as a group constitute a fingerprint of the liner, such as is described by Haxo (1983) and in Section 4.2.2.6.

The physical properties for the 1972 membrane are presented in Table 6-21. Tensile strength, stress at 100% elongation, and puncture resistance are comparable to the data obtained on the liner taken from the basin, assuming somewhat higher extractables content. Using these data, one has a baseline reference against which to compare the effects of the exposure on the liner samples recovered from the basin.

6.5.1.8.6 Results and discussion--Data on the samples taken from the various sections of the "strip" sample can be used to assess the effect of

TABLE 6-22. SEAM STRENGTH IN SHEAR AND PEEL MODES OF 60-MIL EPDM SEAM SAMPLES COLLECTED FROM THE EMERGENCY "RED-WATER" BASIN

Seam test	Strip Sample A (type of seam)									
	Anchor trench A1-1 (Factory)	Top slope A1-2 (Factory)	Mid-slope A1-3 (Factory)	Lower slope A1-4 (Factory)	On basin bottom A2-5 (Field)	A3-6		High on slope B1/B2 (Field)	On basin bottom C (Factory)	Top of "Whale" D (Field)
						(Factory)	(Field)			
Seam strength in shear ^a										
Maximum strength ^b , ppi	...	64.0	65.6	68.1	69.2	...	...	64.4	...	...
Strength at break, ppi	...	64.0	65.6	68.1	69.2	...	...	64.4	...	...
Locus of break ^c										
FTB ^d	...	0	0	1 SE	0	...	...	0	...	...
Non-FTB ^d	...	5 AD	5 AD	4 AD	5 AD	...	...	3 AD	...	...
Seam strength in peel ^e										
Maximum strength, ppi	11.7	6.5	7.8	8.2	9.2	10.1	8.8	17.6	8.7	8.9
Locus of break ^c										
FTB ^d	0	0	0	0	0	0	0	0	0	0
Non-FTB ^d	5 AD	5 AD	5 AD	5 AD	5 AD	5 AD	5 AD	5 AD	5 AD	5 AD

^aASTM D882/D3083, modified; five specimens tested per sample, except where otherwise noted. Two specimens of Sample B2 slipped in the clamps during testing; results declared void.

^bMaximum value corresponds to tensile strength at break for all specimens tested.

^cLocus-of-break determined from the following code:

Locus of Break	Description	Classification
CL	Break at clamp edge	FTB ^d
SE	Break at seam edge	FTB ^d
BRK	Break in sheeting	FTB ^d
AD	Delamination in plane of adhesive bond	non-FTB ^d

Number preceding code indicates the number of test specimens that broke in the manner indicated by that code.

^dFTB - Film-tear bond.

^eASTM D413 modified using 1-in. wide specimens which were tested in 90° peel at 2 ipm; five were specimens tested per sample except where noted otherwise.

TABLE 6-23. COMPARISON OF ANALYTICAL PROPERTIES
OF EXPOSED SAMPLE AND BASELINE REFERENCE

Analysis	Joliet Sample C	1972 FML No. 8
Extractables ^a , %	21.62	23.41
Thermogravimetric analysis:		
Polymer + oils, %	57.2	57.4
Polymer (calculated) ^b , %	35.6	34.1
Oil (from extractables), %	21.6	23.4
Carbon black, %	35.2	35.0
Ash, %	<u>7.6</u>	<u>7.5</u>
Total	100.0	100.0
Ash, %	7.24	6.78
Specific gravity	1.183	1.173

^aExtractables consist of oils + extractable curatives and antidegradants (determined with methyl ethyl ketone).

^bCalculated by subtracting the extractables from the thermogravimetric analysis (TGA) determination for polymer + oil.

the different exposures from the top to the bottom of the basin. Some of the basic conclusions that can be drawn are:

- The extractables decrease with increasing distance from the bottom of the basin which has been under "red water" or sludge.
- The sheeting on the top part of the slope, which was exposed to the sun, contains about one-third less of oily plasticizer than was in the sheeting on the floor of the basin. The latter sheeting has the highest extractables values. These high values approximated that of the "baseline reference" (i.e. the 1972 EPDM FML). Also, tensile strength, modulus (stress at 100% elongation), and puncture resistance values tend to increase with decreasing extractables, that is, with distance up from the bottom of the basin, as is shown in Figures 6-6 through 6-8. On the other hand, the elongation at break decreases as the extractables decrease during the exposure, as shown in Figure 6-9.

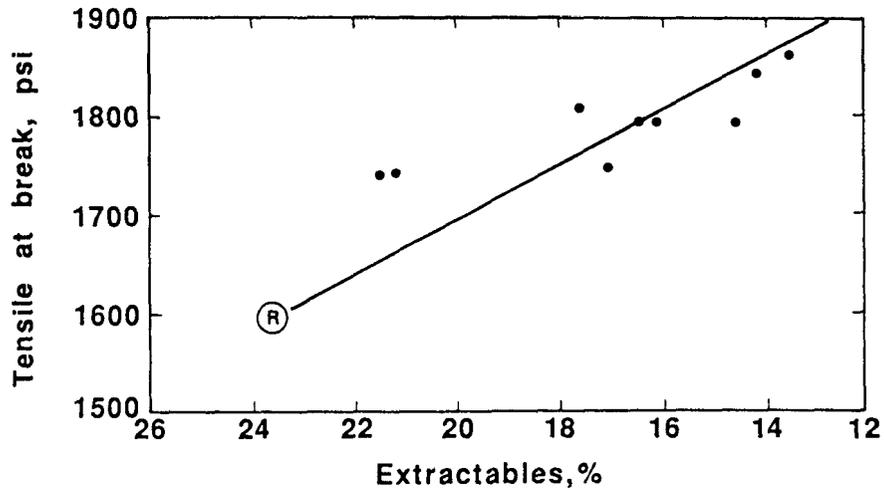


Figure 6-6. Tensile at break of the samples of exposed FMLs as a function of their extractables. Tensile data are the averages of the values obtained in both machine and transverse directions. The samples with the low values for extractables were cut from the liner at the top of the slope. Those with the high values were cut from the liner on the bottom. R = Baseline Reference EPDM, produced in 1972.

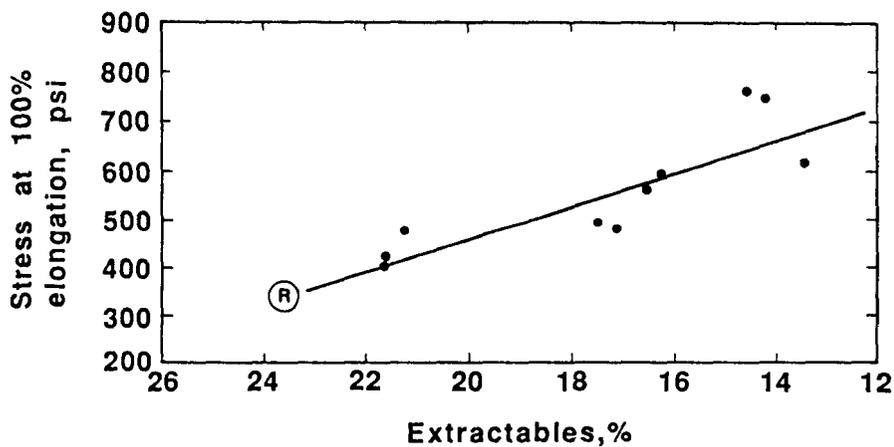


Figure 6-7. Stress at 100% elongation (S-100) of the samples of exposed FMLs as a function of their extractables. S-100 data are the averages of the values obtained in both machine and transverse directions. The samples with the low values for extractables were cut from the liner at the top of the slope. Those with the high values were cut from the liner on the bottom. R = Baseline Reference EPDM, produced in 1972.

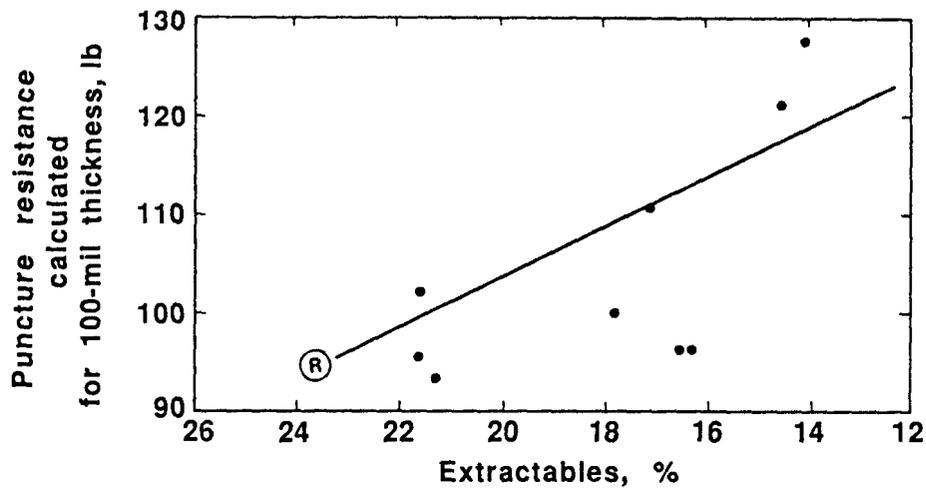


Figure 6-8. Puncture resistance of the samples of exposed FMLs as a function of their extractables. Puncture resistance is the maximum stress value calculated for 100-mil thickness of the FML. The samples with the low values for extractables were cut from the liner at the top of the slope. Those with the high values were cut from the liner on the bottom. R = Baseline Reference EPDM, produced in 1972.

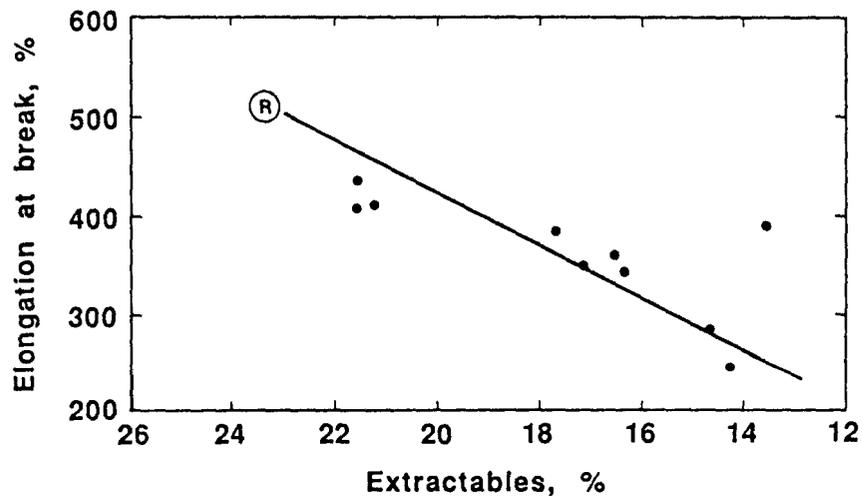


Figure 6-9. Elongation at break of the samples of exposed FMLs as a function of their extractables. Elongation data are the averages of the values obtained in both machine and transverse directions. The samples with the low values for extractables were cut from the liner at the top of the slope. Those with the high values were cut from the liner on the bottom. R = Baseline Reference EPDM, produced in 1972.

- In the case of sheeting protected at the seams by an upper layer of sheeting, the extractables are greater and the tensile strength, modulus, and puncture resistance are less than those of the upper layer. These differences again appear to reflect the higher extraction content of the protected sheeting.
- The factory seam results tend to show increased strength values in both shear and peel modes with increased distance from top to bottom down the slope. The peel adhesion values increased from 6.5 to 10.1 ppi with distance down from the anchor trench; all the failures in the tests were adhesion failures between the sheetings.
- In the case of field seams, there is a difference between the exposure locations. A high value of 17.6 was obtained on an unfailed part of the seam that was high on the slope. This seam had partially failed during exposure. Testing was performed on an unfailed portion of the seam. In this case, the adhesive appeared to have crosslinked more than had the seams in the other locations. In all cases, the preponderant failure was a cohesive failure in the adhesive.

6.5.1.9 PVC FML from an Industrial Landfill--

A 30-mil PVC liner was installed in an industrial landfill in Dover Township, New Jersey in 1981. The liner was in use until 1985 at which time the liner was damaged by heavy equipment during a cleanup to remove drums containing liquid organics. Samples of the liner were taken at that time by the New Jersey Department of Environmental Protection and submitted to Matrecon for testing.

Industrial wastewater-treatment sludge and drummed chemical waste from the manufacture of dyes and plastics were stored in the landfill. Excavation of the site revealed that many of the drums were badly corroded and some had leaked. The NJDEP reported that toluene, methylene chloride, and ethyl benzene were present in the sludge and drummed waste stored at the facility.

The exposed PVC FML appeared to have stiffened substantially during the four years of exposure in the landfill; this was attributed to loss of plasticizers from the PVC compound. The losses of extractables were somewhat erratic in magnitude, but they generally resulted in lower tensile strength and elongation at break and higher values for stress at 100% elongation tear strength, and specific gravity. Headspace gas chromatography (GC) of the exposed FML samples did not detect the presence of any of the organic solvents (toluene, methylene chloride, and ethyl benzene) reported to have been stored in the landfill. These solvents had probably been absorbed by the FML during service and then volatilized during excavation, transportation, and storage. The headspace GC analysis demonstrated how easily these solvents volatilize, as well as the difficulty of measuring their effects on an exposed liner.

Factory seams were made by dielectric-welding, and the field seams were made with a solvent-cement. The results of the peel testing indicated that the exposure of the liner may have affected the dielectric-weld of the seams. Field seams were not available to test.

6.5.2 Field Studies Conducted by Giroud

Under EPA Contract No. 68-03-1772, Giroud (1984a) reported on 29 case histories of FMLs with varying degrees of detail and data. Eight case studies were chosen for review since they represent a variety of end-uses, materials, and examples of different problems or successes.

Giroud's Case Study 2 is the only one of the 29 reported that provides actual data based on testing of the exposed FMLs. The results of plasticizer loss and change in physical properties over time for a PVC liner are presented. Also discussed are the effects of sun exposure and position on the slope (above or below liquid level) of the liner.

Table 6-24 summarizes the case histories discussed in this section.

6.5.2.1 CSPE FML from Evaporation Pond at a Chemical Plant (Giroud, 1984a - Case 1)--

In March 1981, a 129,000 ft² evaporation pond was constructed in a Middle Eastern county at a chemical plant. The pond was lined with a 40-mil CSPE FML reinforced with polyester scrim. Based on tear specification values of 20 lbs, the reinforcing fabric probably was an 8 x 8 - 250 denier reinforcing scrim. The FML was placed directly on compacted soil on the pond bottom and on a nonwoven needle-punched polyester geotextile on the slopes. The slopes were 2 to 1. The factory and field seams were made using a hot wedge.

The pond remained empty for seven months before being filled. Normal operations consisted of placing liquids that contained acids and salts in the pond and allowing them to evaporate. Eleven months after the first filling, massive failure occurred. Apparently, during the time the pond was empty, animals damaged the FML causing several small holes. Holes were also caused by defective seams, damage to the FML during transportation, and damage during installation. Because the soil beneath the FML was sensitive to acid, cavities developed as acid leaked through the liner. Increased stresses caused seams to give way and the pond emptied rapidly.

The exposed CSPE was difficult to weld and thus to repair. Therefore, the FML was replaced, and the site design was changed to include several single-lined smaller ponds and one large one with a double liner and a geonet LCRS between the liners.

6.5.2.2 PVC FML from a Mining Operation - Uranium Tailings (Giroud, 1984a - Case 2; Giroud, 1984b)--

Nine large evaporation ponds (Ponds 1 through 9) with a total area of approximately 7 million square feet were built and lined with a PVC FML

TABLE 6-24. SUMMARY OF CASE STUDIES BY GIROUD

Liner type	Type of waste	Type of impoundment	Location	Case number	Years of exposure	Comments on FML
30-mil CSPE, reinforced	Acids and salts	Chemical plant	A Middle Eastern Country	1	2	Puncture holes caused by animals; acid sensitive soil formed cavities.
20-mil PVC for bottoms; 40-mil PVC for slopes	Uranium tailings, salts, sulfuric acid (pH 1.5 to 2.0), traces of kerosene	Mining operation (nine ponds)	Sahara Desert	2	2 to 5	Erosion of slopes through wave action; seam failures from defective seams and excessive stresses; mechanical damage; aging of exposed PVC.
20-mil PVC; 40-mil PVC	Uranium tailings	Mining operation (nine ponds)	Sahara Desert	3	2	Improved design as a result of Case 2, resulted in a successful installation.
160-mil, reinforced asphalt membrane	Potable water	Reservoir	Southeastern France	4	5	Defective seaming, delamination and puncturing of membrane
40-mil PVC, oil-resistant	Brine solution: 150 to 310 g/L of NaCl; traces of hydrocarbons	Salt plant	Southeastern France	6	7	Exposed PVC stiffened, shrunk, and seams opened
40-mil butyl rubber, unreinforced	Industrial water storage	Chemical plant	Isere, France	8	10	No problems; success has been reported to be the result of careful design and installation.
60-mil butyl rubber, reinforced	Potable water	Reservoir	Washington, U.S.A.	11	3 to 9	Shrinkage of the FML resulted in opened seams.
20-mil PVC in bottom; 36-mil CPE (reinforced) on slopes	Municipal wastewater	Wastewater	Western U.S.A.	26	4	Blisters in reinforced CPE; seam failure; degradation of reinforced CPE at the water line.

Source: Giroud, 1984a.

between 1987 and 1981. The ponds were constructed for a mining company located in the Sahara Desert region, and were intended to contain uranium tailings with sulfuric acid. The composition of the contained liquid was as follows:

- Salts (magnesium sodium sulfate, iron, alumina) = 100 g L⁻¹.
- Sulfuric acid (pH = 1.5 to 2.0) = 10 to 15 g L⁻¹.
- Traces of kerosene = up to 1 L m⁻³.
- Traces of nitric acid = up to 0.1 g L⁻¹.

Four smaller reservoirs lined with PVC FMLs were also constructed for storing water or acid. All ponds were in operation from 2 to 6 years.

A 20-mil PVC was used as the FML for the bottom of the ponds and a 40-mil PVC for the side walls which had a slope of 2 to 1. A geotextile was placed underneath the FML on the side slopes. The PVC FML was installed without an earthen protective cover. The factory and field seams were made using a hot wedge. A cross section of a typical dike for the ponds is presented in Figure 6-10.

Various problems were observed in the design of the pond; in addition, properties of the PVC FML were studied to evaluate the effects of service. Severe tears caused by shrinkage were observed on exposed slopes.

6.5.2.2.1 Problems--Pond 1: Due to wave action and liquid overtopping the crest of the dikes, much erosion occurred on the slopes. In one area, the anchor trench had eroded to the point that the FML had pulled out of the trench. Large quantities of liquid got behind the liner and caused more instability of the slopes and more of the FML to pull out of the trench. Repairs were made and the corner of the pond was reconstructed.

Pond 2: A seam opened, allowing liquid to leak into the subsoil. The problem was alleged to be caused by defective seaming, excessive stresses as the result of wave action, and shrinkage of the FML caused by aging.

Pond 5: A raft had broken loose and punctured several holes in the liner. Piping of the underneath soil occurred and the FML burst in areas not supported by the soil.

Pond 7: A factory fabricated seam had opened up and the same situation, as noted in Pond 2, had occurred.

It was noted in all ponds that the FMLs were under tension at many locations and was off the supporting soil (bridging) by as much as 1 ft over concave parts of the pond. This phenomenon was alleged to be caused by loss of plasticizer in the PVC FML due to excessive heat on the exposed membrane. This was confirmed by analysis of the various samples described below.

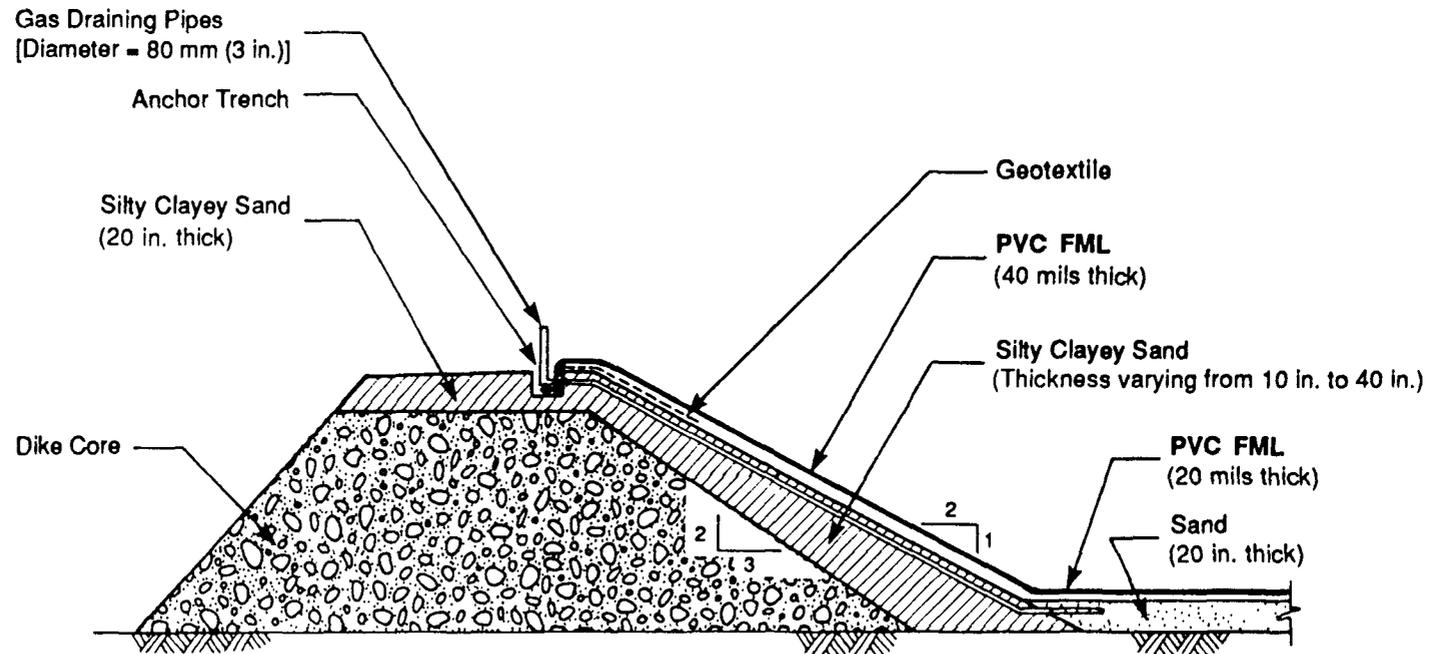


Figure 6-10. Typical cross section of the dikes for the uranium tailings ponds-- Ponds 1-9 (not to scale). (Based on Giroud, 1984a).

6.5.2.2.2 Samples and testing--Approximately 40 samples were removed from the nine large ponds containing acid and 4 smaller reservoirs containing acid and water and tested to determine the effects of exposure.

The plasticizer contents of the samples were compared with the plasticizer content of a control sample. The plasticizer contents were determined by extracting the plasticizer with a mixture of carbon tetrachloride and methyl alcohol. Plasticizer losses were calculated using plasticizer content value expressed as parts of plasticizer per 100 parts of resin. The results of measuring the plasticizer contents of samples exposed on the berms are presented in Figure 6-11 as a function of exposure time.

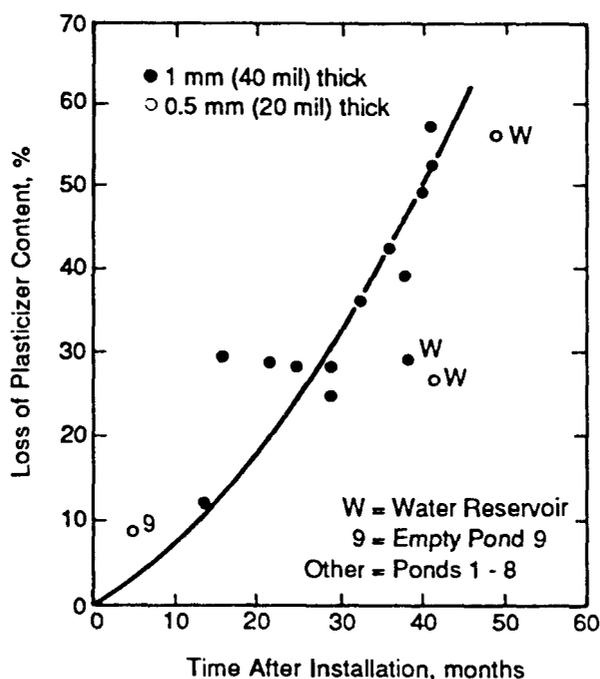
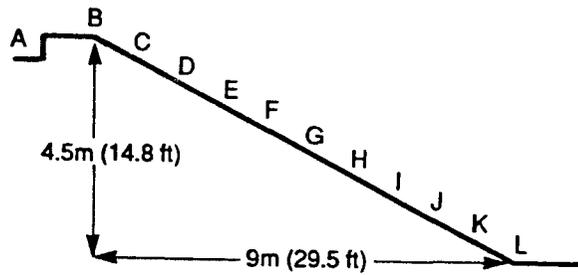


Figure 6-11. Plasticizer loss as a function of time for samples permanently exposed.

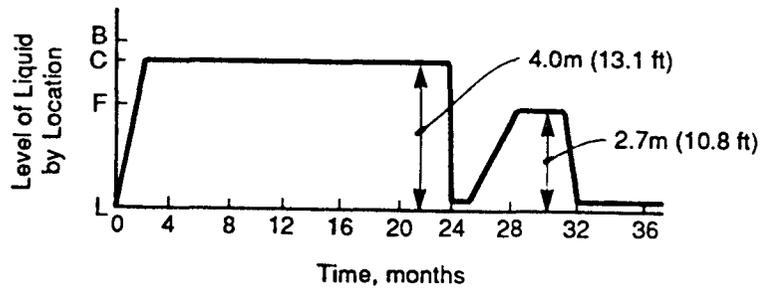
The analyses also indicated loss of the stearate stabilizer as a function of time; values did not indicate any degradation of the PVC resin (Giroud, 1984b).

Twelve samples were taken from different locations in Pond 5 from the anchor trench down the slope to the floor of the pond, as is shown in Figure 6-12, to assess the effects of exposure at different depths. The plasticizer losses, as a function of location on the slope are shown in Figure 6-13.

The tensile properties of the FML samples were determined. Values of elongation at break as a function of plasticizer loss are shown in Figure 6-14.



(a) Cross Section of Dike for Pond 5



(b) Level of Liquid in Pond 5 as a Function of Time

Figure 6-12. Study of the influence of immersion on aging; (a) cross section of dike of Pond 5 showing locations, indicated by letters, where samples were taken; (b) level of liquid in Pond 5 as a function of time. (Based on Giroud, 1984a and 1984b).

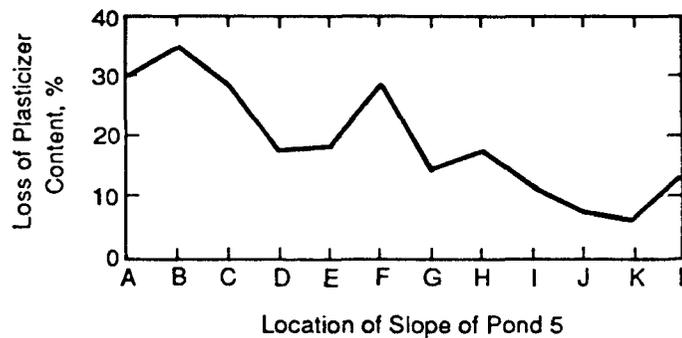


Figure 6-13. Plasticizer loss as a function of location on the slope of Pond 5. (Based on Giroud, 1984a and 1984b).

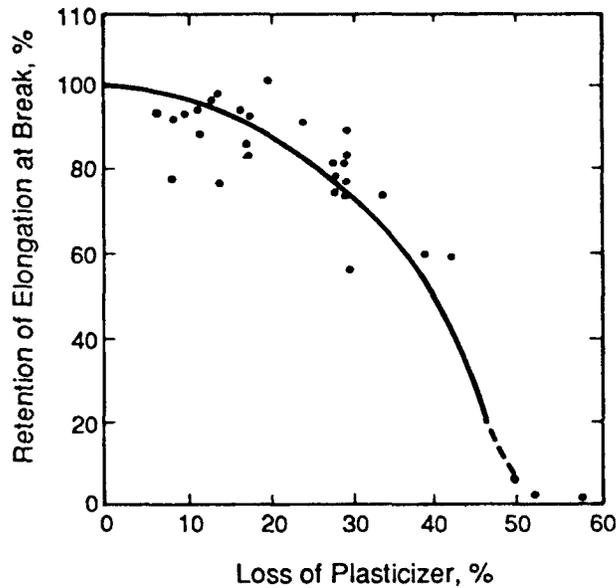


Figure 6-14. Retention of elongation at break as a function of the plasticizer loss. (Based on Giroud, 1984a and 1984b).

6.5.2.2.3 Discussion of results--The action of sun-generated heat with time was the main factor governing aging of the PVC FML. Acceleration of plasticizer loss by exposure to acid spray (at water line and at ore pads) was also observed, but results indicate exposure to acid alone was not as severe as exposure to direct sunlight over time. The study concludes that monitoring plasticizer loss can be used to evaluate the aging of a PVC FML, and elongation at break can be used to evaluate the consequences of plasticizer loss because it is directly related to the flexibility of the FML.

6.5.2.3 PVC FML for a Mining Operation--Uranium Tailings
(Giroud, 1984a - Case 3)--

This is the same site as Case 2. The results of studying the existing evaporation ponds and reservoirs, which are summarized in the previous section, were incorporated in the design of this pond (Pond 10). The following changes were made in the basic design:

- The side slopes at 4:1 were less steep.
- An earthen protective cover was placed on top of the entire PVC FML.
- The PVC FML was extended to cover the crest of the dikes.
- The height of liquid was restricted to control the action of high waves.
- Geotextile was placed under the entire FML.

Figure 6-15 shows a typical cross section of the dike design used in constructing Pond 10.

Samples of the FML are being taken periodically for laboratory testing to determine plasticizer loss and change in physical properties. After two years the performance of the lining system had been satisfactory.

6.5.2.4 Asphaltic FML in a Potable Water Reservoir (Giroud, 1984a - Case 4)--

In October 1979, 237,000 ft² of a 160-mil reinforced asphaltic FML was used to line a potable water reservoir in the southeastern part of France. The slope of the pond was 2.5 to 1, and no cover was provided for the FML. A geotextile and a drainage collection system, consisting of three different types of pipes placed in trenches, were installed underneath the liner. All seaming was done in the field using hot air. Unusual weather conditions resulted in defective seaming because the installer/contractor installed in the rain.

Eighty opened seams were discovered a few days after the reservoir was partially filled the first time. Many rocks had fallen from surrounding mountains and punctured the uncovered FML. Delamination occurred where the asphaltic liner was less than 40 mils in thickness.

Erosion occurred in "selected material" of some of the subgrade and puncture of the liner resulted caused by sharp rocks from below.

Most of the problems were due to a rush in schedule which led to poor design and poor construction.

6.5.2.5 PVC-OR FML in Salt Ponds (Giroud, 1984a - Case 6)--

Two ponds at a salt plant in the southeastern part of France, approximately 35,000 ft² each in size, were lined with a 40-mil unreinforced PVC-OR FML. The liquid was a brine solution with a sodium chloride content of 150 to 310 g L⁻¹ and traces of hydrocarbons. The FML was exposed with no earthen cover. The sides slopes were 3 to 1. A geotextile and an asphaltic liner were installed under the FML. A single collection trench was constructed on top of the PVC FML across the bottom of each pond.

Due to plasticizer loss caused by sun exposure, the PVC-OR FML had shrunk and lifted off its support at the foot of the slope in several places resulting in accumulated tensions which caused the seams to peel open (Figure 6-16). Excessive flaps at the seam areas also resulted in seams peeling open. It was reported that during quick emptying of the ponds, pressure resulted and propagated peeling apart of the seams. Figure 6-17 depicts these phenomena.

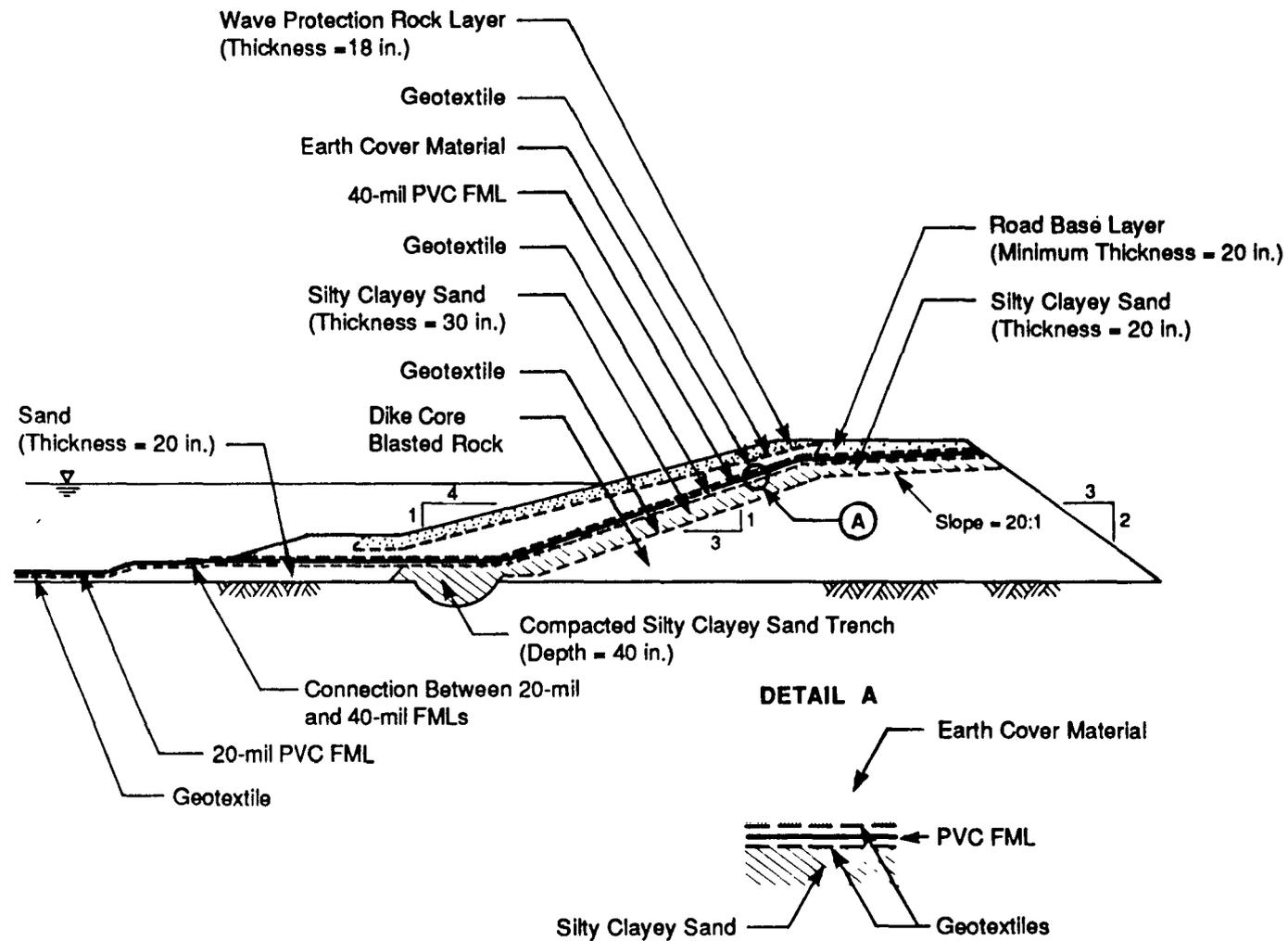


Figure 6-15. Typical cross section of the dike for a uranium-tailings pond--Pond 10 (not to scale). (Based on Giroud 1984a).

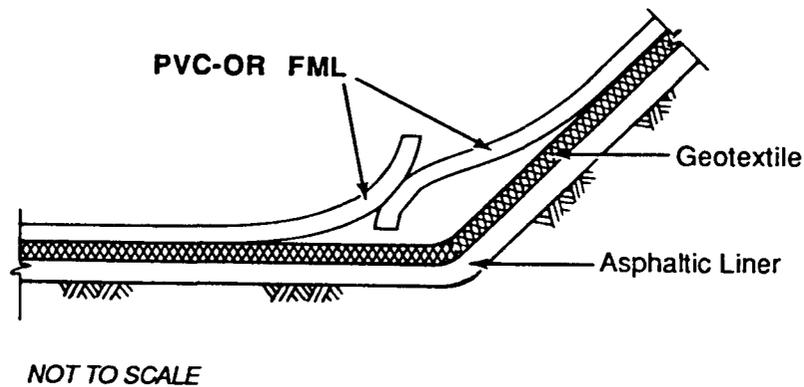


Figure 6-16. Schematic showing FML with a seam being lifted off its support. This phenomenon is known as "bridging". Excessive stresses can result in delamination of the seam. (Based on Giroud, 1984a).

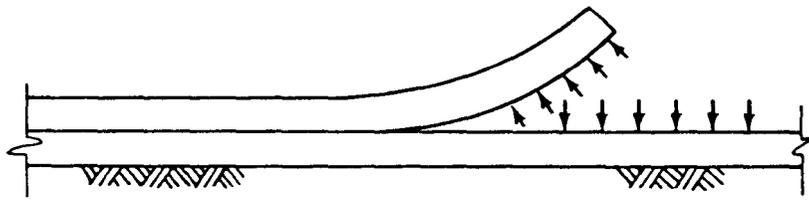
6.5.2.6 Butyl Rubber in Industrial Storage Ponds (Giroud, 1984a - Case 8)--

In 1974, one of the first double-liner systems, approximately 100,000 ft² in area, was installed at a chemical plant in Isere, France, for storage of industrial water. The design of the system from top to bottom consisted of:

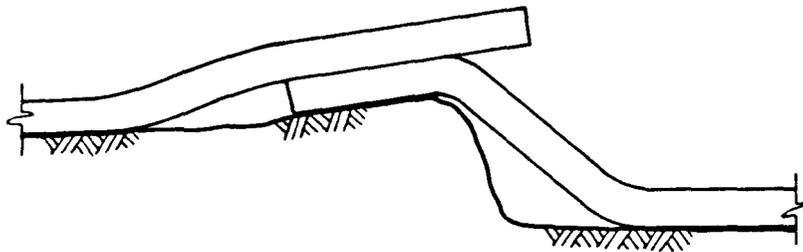
- A 40-mil unreinforced butyl rubber FML.
- A needle-punched nonwoven polyester geotextile.
- An aggregate layer.
- A reinforced asphaltic FML.
- Natural soil.

The slope of the side walls was 2 to 1, and there was a drain between the two liners. The asphaltic FML was sprayed in place onto a needle-punched nonwoven polyester geotextile. The butyl rubber FML had both factory and field vulcanized seams. The field seams were vulcanized in place using a special seaming machine. In this seaming process a bead of nonvulcanized chlorobutyl was placed between the two sheets to be seamed, and heat and pressure were applied for approximately 2 minutes. All seams were carefully inspected.

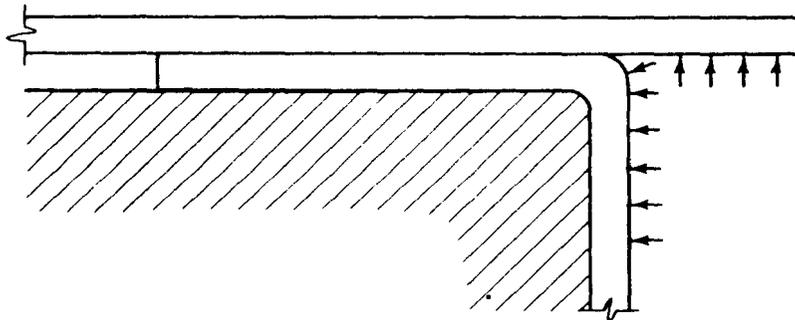
This site was studied in 1984 and no problems were reported. The pond had been in constant operation for 10 years. The success is reported to be a result of careful design and installation.



(a) Mechanism of FML seam opening caused by unbalanced liquid pressure during rapid drawdown



(b) FML seam placed over support irregularity



(c) FML seam placed over edge of collection trench walls

Figure 6-17. Schematic showing stresses on seams with excessive flaps. (Based on Giroud, 1984a).

6.5.2.7 Butyl Rubber FML in Potable Water Reservoir (Giroud, 1984a - Case 11)--

In March 1966, an old cracked concrete potable-water reservoir in the State of Washington, approximately 54,000 sq ft in size, was relined with a 60-mil butyl rubber FML reinforced with a 22 x 14, 210 denier x 420 denier nylon scrim. The liner was not protected by a soild cover, and the slopes were 1.5 to 1. Factory seams were made by a vulcanization process. Field seams were made using a 4-in. wide lap joint, an ambient temperature self-vulcanizing butyl rubber cement, and a 30-mil butyl gum tape. A 2.5-in. wide gum tape was placed over the exposed seam edge as a cap strip. As an experienced installation contractor provided his own crew, the skill level of the installation personnel is assumed to have been high. The weather was reportedly excellent throughout the installation.

The butyl rubber FML failed in 1969 after 3 years of service when both factory and field seams above the water level began splitting from substantial shrinkage of the nylon-reinforced butyl rubber sheet. (The shrinkage can be attributed primarily to the nylon reinforcing fabric which tends to shrink when heated, such as occurs in the sunlight). Some repairs were made as the seams split. However, the liner was removed and replaced with a 6-in. reinforced concrete liner in 1975 because of the excessive maintenance required.

6.5.2.8 PVC and CPE FMLs in a Wastewater Impoundment (Giroud, 1984a - Case 26)--

The slopes of two municipal wastewater impoundments in the western part of the United States were lined with a 36-mil fabric-reinforced CPE FML in October 1980. The bottom of one pond was lined with a 20-mil unreinforced PVC with an earthen cover, while the bottom of the other pond was lined with bentonite. Approximately 150,000 sq ft of the reinforced CPE was required to cover the slopes of each pond. Several dozen blisters appeared in the FML during and shortly after installation. Most of the blisters were in the seam area. Several seams perpendicular to the slope opened; it was necessary to lower the level of the wastewater to perform repairs. The appearance of the opened seams indicated that the primary cause of failure was due to improper seaming. In some cases, severe wave action resulted in water extending over the crest of the dike onto the roadway. This caused weakening and sloughing of the side slope resulting in the opening of other seams due to excessive stresses.

A catastrophic failure occurred along the waterline on one entire side of one of the ponds (approximately 1,000 feet). Apparently, an algae mat would develop at certain times of the year when the waterline was lowered. As the algae dried out on the surface of FML, the top layer of the laminated reinforced CPE split open, allowing water into the fabric layer when the water level was raised. After several repeated cycles of this phenomenon, the FML was completely delaminated and split open in a 12-in. wide area along the entire slope on one side; no remedial measures were taken as litigation is pending.

6.5.3 Field Studies Conducted by Ghassemi

Nine hazardous waste surface impoundment facilities were reviewed and assessed by Ghassemi et al (1984). These facilities represent a range of industries, waste types, environmental settings, types of FMLs, and designs. Five of the case studies are reported in this section because they are examples of FML successes and/or failures. These studies are summarized in Table 6-25.

6.5.3.1 ELPO FML in Ponds Containing Electrolytic Metal Process Liquor (Ghassemi et al, 1984 - Case Study No. 1)--

Two surface impoundments were lined with 20-mil ELPO in 1972 and 1979 to serve an electrolytic metal refining plant located in a semiarid to desert area of the southwest. The waste contained was described as an aqueous acidic waste (pH typically less than 2) resulting from a process liquor and sludge which had a high heavy metals content. The size of the ponds were 16,000 ft² and 48,000 ft², respectively. The smaller pond was originally lined with a 20-mil ELPO in 1972. The FML deteriorated along the slopes by cracking and brittleness attributed to weathering. The FML of the smaller pond was replaced with a 30-mil reinforced CSPE FML in 1981. No deterioration problems have been reported in the larger pond; however, it had been in operation only four years when this survey was conducted.

6.5.3.2 PVC and CPE FMLs in Wastewater and Rinse Water Ponds (Ghassemi et al, 1984 - Case Study No. 2)--

Two FML-lined surface impoundments were constructed to serve a pesticide formulation and packaging facility located in a alluvial valley of the southwestern part of United States with a dry summer subtropical climate. The washdown pond, placed in service in 1979, was lined with two layers of 20-mil unreinforced PVC with a leak-detection systems. This pond contained wastewater originating from the washdown of pesticide formulation-packaging areas and application equipment. The size of the pond is approximately 2,000 ft², and the bottom of the pond is underlain by 1 ft of gravel and a 30-mil unreinforced PVC FML, which is on the bottom of the pond only. The second pond was a rinsewater pond, approximately 7,500 ft² in size, lined with a 20-mil unreinforced CPE FML under which a 1-ft layer of sand and a 10-mil unreinforced PVC-OR FML had been installed. The pond was intended to contain steam cleaning and vehicle washdown wastewater. Leak-detection systems for both ponds consisted of a collection pipe embedded in the granular drainage layer between the FMLs. These pipes were connected to separate monitoring stations. After several years of service the owner installed a 0.25-in. layer of fiberglass over each pond liner to give added protection and a better surface for cleaning.

At the time of the survey, no problems had been noted by the operator or the State regarding the liner systems in both ponds.

TABLE 6-25. SUMMARY OF CASE STUDIES OF FMLS BY GHASSEMI

Liner type	Type of waste	Type of impoundment	Location	Case study number	Years of exposure	Comments on FML
20-mil elasticized polyolefin, replaced with 30-mil reinforced CSPE	Aqueous acidic; pH <2; plus heavy metals	Electrolytic metal refining plant	Southwestern United States	1	9	Cracking and brittleness from weathering
20-mil PVC double-lined; 20-mil CPE plus double-lined	Washdown and rinses of process equipment	Pesticide formulation	Southwestern United States	2	4	No problems
30-mil reinforced EPDM on slopes; 12-mil PVC on bottom	Various inorganic and organic chemicals; pH 1.3 to 1.9; TDS 20,000 to 42,000 mg/L	Fertilizer manufacturing complex	Southwestern United States	4	6	"Whale" formation caused by contact of waste water with calcium carbonate clay soil; mechanical damage
50-mil EPDM	High inorganic nitrogen fluctuating pH	Equalization basins for chemical plant	Mid-Atlantic Coast, United States	8	5	Swelling and chemical attack; seam failure
30-mil PVC on bottom; 30-mil reinforced CSPE on slopes	50% solids, 0.5% sulfuric acid; 0.25% organics (kerosene); pH 1.8 to 2.5	Uranium tailings pond	Northwestern plains state, U.S.A.	9	3	Seam failure in CSPE; punctures, abrasion, and mechanical damage in both

Source: Ghassemi et al, 1984.

6.5.3.3 EPDM and PVC FMLs in Evaporation and Cooling Ponds (Ghassemi et al, 1984 - Case Study No. 4)--

A fertilizer manufacturing complex situated in the southwestern part of the United States had two FML-lined evaporation and cooling ponds. The side walls, which had a slope of 3 to 1, were lined with a 30-mil polyester-reinforced EPDM FML; the bottoms were lined with a 12-mil unreinforced PVC. Approximately 1.6 million ft² of PVC and 300,000 ft² of EPDM were used. Major wastewater constituents found in both ponds included ammonia, organic nitrogen, nitrate, sulfate, chlorides, algicides, oil and grease, surfactants, polymers, and various metals. The pH of the wastewater ranged from 1.3 to 1.9, and the total dissolved solids (TDS) ranged from 20,000 to 42,000 mg L⁻¹.

"Whales" developed in the FML apparently because the acid waste had reacted with the calcium carbonate clay soil under the FML resulting in the generation of gases. The source of the leaks was not described. Attempts were made to release the trapped gases by partially draining the ponds, forcing the gas into one area, placing sandbags around the "whale", then placing a valve in the FML to release the trapped gas. Extensive parts of the PVC FML in each pond were replaced. The ponds continued to have leakage problems as of 1982.

The EPDM FML on the side slopes appeared to hold up better than the PVC, but also exhibited tears and open spots mostly resulting from mechanical damage.

6.5.3.4 EPDM FMLs in Wastewater Ponds (Ghassemi et al, 1984 - Case Study No. 8)--

Two equalization/diversion basins at a chemical plant located in the mid-Atlantic Coast region were lined with a 50-mil EPDM in late 1976. The raw wastewater discharge is characteristically high in organic nitrogen content and had a widely fluctuating pH. The EPDM liner was selected after liner-waste compatibility tests were conducted by the company's corporate engineering group. The liner was exposed with no protective soil cover.

When the FML was inspected in 1981 to determine the cause of its failure, there was strong evidence that there had been a lack of adequate QA/QC during construction and that some deviations from the design specification had gone undetected. The failure of the FML was manifest as extensive swelling and seam separation. In the presence of the particular organics encountered in the waste, EPDM apparently is subject to swelling, especially at the air-waste interface. This problem was not detected during the liner-waste compatibility tests which preceded the liner material selection. The seam separation at and below the water line resulted from a deterioration of the adhesives used, as well as the inadequate overlapping of the sheetings.

6.5.3.5 CSPE and PVC FMLs in Uranium Tailings Pond (Ghassemi et al, 1984 - Case Study No. 9)--

In August 1980, an FML-lined uranium tailings pond was completed to handle wastes from a uranium mining and milling operation in a northwestern

plains state. The waste was 50% solids with the aqueous phase containing 0.5% by weight sulfuric acid, 0.25% by weight (kerosene) and had a pH of 1.8 to 2.5. The size of the pond was 3,100 ft by 3,500 ft (approximately 11 million ft²). The pond was lined with a 30-mil unreinforced PVC FML on the bottom and a 30-mil polyester-reinforced CSPE FML on the side slopes.

Since installation, there have been four instances of documented failure of the liner:

- Four months after installation, a CSPE to CSPE field seam separated for a distance of 300 feet; poor seaming technique in cold weather was said to have caused the problem.
- Several puncture holes (about 50) were noted and patched. These holes were reportedly due to an uneven subgrade surface and mechanical damage.
- A 6-in. hole had abraded through the liner caused by a leak in a discharge pipe.
- Holes and punctures caused by floating debris and wave action.

Immediate corrective actions were taken involving patching of the holes and seams and continuous removal of debris from the pond area. The last inspection recorded was in 1983, with the pond still in service.

6.5.4 Performance of PVC FMLs as Canal Linings

Morrison and Starbuck (1984) studied the performance of buried FMLs, primarily 0.25-mm (10-mil) PVC, used to control seepage from Bureau of Reclamation irrigation canals in Montana, Wyoming, New Mexico, and Nebraska (see also Morrison, 1984). Samples were recovered from canal installations after service for 1 to 19 years and tested. The FMLs in all cases were buried under soil covers which were specified to have a thickness of 250 mm (10 in.) plus 25 mm (1 in.) for each 0.3 meter of water depth.

Results of the study indicate that PVC FML linings are providing satisfactory service for seepage control in canals and are viable alternatives in areas not suitable for concrete or compacted earth linings. Results of the study also indicate that some stiffening of PVC and loss of elongation occurred with time. This stiffening and loss of elongation is caused by the loss of plasticizer used in the PVC compound to impart flexibility. Percent losses ranged from about 12% for 9 years of exposure to 46% for 19 years of exposure. In addition, small holes and tears were noted in most of the recovered samples, all of which had a thickness of 10 mils.

The performance of the PVC FMLs was primarily dependent on three factors:

- Source--Linings originally manufactured with a high plasticizer exhibited less aging.

- Location of exposure in canal--Samples obtained from within the water prism exhibited less aging than those obtained outside the prism.
- Subgrade condition--FMLs placed over smooth subgrade performed better than those placed on a coarser base.

As a result of this study, the Bureau of Reclamation is specifying 0.5-mm (20-mil) PVC FMLs for lining canals rather than 0.25-mm (10-mil) sheeting and recommending a minimum cover depth of 400 mm (16 in.) to protect the FMLs from animal traffic and cleaning operations.

6.5.5 Analysis of a Survey of FML-Lined Waste Containment Units

Data from a survey of lined containment units were reviewed and analyzed by Bass et al (1985) to determine the factors which contributed to either the success or failure of the liner at these facilities. Under a subcontract, five experts from companies in the liner industry provided information on lined facilities with which they had been associated. Each expert was asked to select between 4 and 7 sites and to include both "successes" and "failures" within that group. In order to encourage maximum disclosure of information, especially where "failure" was involved, the identities of the experts and the individual sites have been held confidential. Essentially all of the information provided by these experts was in the form of responses to a questionnaire for each site, which included supporting drawings, design specifications, etc. and a summary report. Altogether, data on 27 containment units were collected. Most of the units selected by the experts were surface impoundments; not all were considered hazardous waste containment units.

The units that were studied varied in geographic location, size, age, in the type of wastes that had been handled, and the type of lining system. Most of the sites (approximately 20) were lined with only a single FML. Some of the sites had both an FML and a layer of compacted clay, with or without a drainage layer between the liners. One site had a triple FML system. FMLs were used in 25 of the 27 units. At one site bentonite was applied at a rate of 25 tons per acre and mixed to a depth of 4 inches. At another site an asphaltic-concrete liner was used. Top layers of soil cement were used at two sites, and a sprayed-on liner FML based on a urethane-modified asphalt was used at another site.

Based on the definitions used in this study, the 27 units selected by the experts included 12 "failures" at 10 sites. At four or five of these sites groundwater contamination apparently resulted from the failures.

For the purpose of this study, a "failure" in the pre-operational period was defined as a condition of the installed lining system which required nonroutine corrective measures to make it suitable for planned operations. A failure during operations was defined as any condition of the lining system which caused (or threatened to cause) groundwater contamination, or otherwise caused operations to cease because of observed abnormalities.

The nature of the "failures" noted included chemical attack of the liner (1 or 2 sites), physical tears or punctures (5 sites), problems with field seaming or other liner installation activities (1 to 3 sites), and large gas bubbles, also referred to as "whales", under the FML (1 site).

A summary description of the failures at case study sites is presented in Table 6-26. The abbreviations used for the different types of FMLs and the number of sites lined with a particular FML type for which information is available are as follows:

<u>Abbreviation</u>	<u>Polymer type</u>	<u>Number of sites</u>
UMA	Urethane-modified asphalt	1
CPE	Chlorinated polyethylene (OR = Oil-resistant)	5
HDPE	High-density polyethylene	7
CSPE	Chlorosulfonated polyethylene	6
PO	Polyolefin	1
PVC	Polyvinyl chloride	9

The suffix (R) after the FML abbreviations in Table 6-26 indicates that the FML is fabric-reinforced. HDPE and PVC liners are usually unreinforced, while CSPE and, to a lesser extent, CPE are usually fabric-reinforced.

In their analysis to identify the causes of the FML failures, Bass et al (1985) recognized not only the immediately-preceding action (e.g. subsoil gas generation in a high water table area leading to "whales"), but prior failures that might be associated with poor design, lack of quality control, or communication failures between companies. They recognized that even failures such as these may be preceded by philosophical or conceptual failures wherein misconceptions or lack of concern about liner systems are a root cause of the subsequent failure. This type of analysis thus recognizes a hierarchy of failure modes with one type of failure potentially leading to another until some ultimate failure (i.e. a breach in the liner) occurs.

Some of the contributing factors, if not causes, for the failures noted by Bass et al (1985) include the following:

- Failure to control operations (at an operating site) so as to safeguard the liner.
- Poor (or inadequate) design work in general.
- Failure to use a qualified design engineer.
- Poor (or inadequate) installation work in general.

TABLE 6-26. SUMMARY DESCRIPTION OF "FAILURES" AT CASE STUDY SITES

Site ID	FML ^a	Nature of "failure"	How detected	Apparent cause	Other contributing factors
V1-2	CSPER (S)	Five holes found in liner caused by owner-operating personnel; minor brine loss	Monitoring well	Carelessness by owner-operating personnel	Lack of clear operating procedures. Possible lack of concern (speculative).
V2-1	CSPER (S)	Chemical attack of liner at liquid surface	Visual	Attack or dissolution by oil-based defoamer	Use of oil-based defoamer not anticipated, thus not in original program. Inadequate control of operations.
V2-2	CSPER (S)	"Whales"	Visual	Gas generation under liner; no allowance made for gas venting in design	Inadequate study of soils and hydrogeology at site; presence of organic matter (in soil) had, however, been noted. Site used before for disposal of organic sludge.
V2-3	CSPE (S)	Liner ripped	Visual	Tank truck slipped down slope	No fence around site. Liner exposed.
V3-1	PO-R (S)	a) Holes and tears in liner	Visual	Liner placed between layers of coarse rock	Poor design.
		b) Escape of dredge material	Visual	Liner placed over coarse rock	Poor control of operations. Poor communication among contractor, installer, and engineer. Job awarded to low bidder (speculative).
		c) Tear in liner panel	Visual	Waves entered construction area and scraped liner against dike	Poor design (subgrade too coarse). Poor control during installation. Wet and windy weather.
V3-2	PVC (S)	Chemical pollutants showed up in drain water collected below liner	Leak monitor	Apparent blockage of leachate collection drain; backup of leachate	Poor bonding at seams, appurtenance (?). Poor control of installation practices; used "Honor Camp" youth to install FML. Undersized collection drain (?); due to poor design (?).

Continued . . .

TABLE 6-26. (CONTINUED)

Site ID	FML ^a	Nature of "failure"	How detected	Apparent cause	Other contributing factors
V3-4	Bentonite (S)	Pollutants showed up in monitoring wells around site	Monitoring well	Unknown; possible break-up of soil sealant liner	Unknown; possible failure to fully test soil sealant for this type of application. Process for selecting liner unclear. No way to physically test liner once in use.
V5-1	CPE/UMAB ^b (3D,1S)	Liquids found in leak detector	Leak detector	Probable failure of sealing of concrete joints with PVC strips and spray-on UMA	Concrete installer, against explicit instructions, used curing compound that inhibited proper bonding of UMAB ^b to concrete. Poor design; improper information supplied on UMAB ^b ; owner suggested use of UMAB ^b . Poor installation; lack of knowledgeable supervision.
V5-2	CPE/PVC (S)	Physical damage to liner prior to being put into service	Visual	Unknown, but suspect carelessness	Questionable cooperation between contractors. Job awarded to low bidder (speculative). High winds and cold temperatures during construction (took 11 months).
V5-4	PVC (D)	Fluid intrusion into monitoring well	Monitoring well	Membrane rupture at five, uniformly-spaced positions; tears probably by D-4 cat tractor used to spread soil cover over liner	Operator of tractor let soil cover get too thin. Poor control of installation.

^aS = Single liner; D = Double liner.

^bUrethane-modified asphalt membrane.

Source: Bass et al, 1985, pp 27-28.

- Poor or inadequate communication and cooperation between companies working on an installation job.
- Using untrained and/or poorly supervised installers.
- Failure to conduct (or adequately conduct) waste-liner compatibility tests.
- Adverse weather conditions during installation.
- Using an old dump site, with contaminated soil, as a site for a lined unit.
- Using processes for selecting a lining material and an installation contractor that did not help ensure that good materials and workmanship would result.
- Selecting a liner material by a process not involving detailed bid specifications; specifications should be prepared by a design engineer, and not by an FML manufacturer.
- The age of the unit; more failures were associated with the older units.

Success was defined in this study as the converse of failure, i.e. non-routine corrective measures were not required, and the liner system was not breached. Bass et al (1985) considered the two main factors that contributed to success at a lined containment unit to be:

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

Key elements of this approach are:

- Assuming that there will be problems.
- Examining the possible consequences of those problems.
- Taking appropriate steps (e.g. design changes, quality control plans) to avoid or minimize the problems.

Success is also more likely to result if the general approach described above is applied to all stages or facets of a liner system including design, material and contractor selection, site preparation, liner installation, unit operation, and closure. Within each of these areas, the generalized approach needs to be applied within the framework of a formal quality assurance program. It is worth noting that at least 23 of the 27 sites in this study had some form of a quality assurance program for one or more critical operations (primarily liner manufacture, fabrication, and installation),

although the quality of these programs could not be assessed from the data submitted by the experts.

Other factors that Bass et al (1985) noted as contributing to success included:

- Overdesign of system.
- Presence of a knowledgeable customer.
- Bidding to specifications.
- Selecting qualified companies for construction, installation, and FML manufacture.
- Cooperation among companies during construction and installation.
- Conducting waste-liner compatibility tests.
- Simplicity of design.
- Good weather at time of construction and installation of the FML.

6.6. FIELD STUDIES OF GEOTEXTILES

Two field studies of geotextiles were reported by Christopher (1982); even though neither of the geotextiles studied was exposed in surface impoundments or landfills, these studies do provide information on geotextiles that were in service for 10 years. The two studies are summarized in the following subsections.

6.6.1 Field Study No. 1

The first field study inspected the condition of a geotextile used in the 79th Street Causeway in Miami Beach, Florida. The causeway was constructed using a monofilament woven polypropylene geotextile as a reverse filter in a stone riprap revetment-type seawall to protect one of the bridge abutments and a section of the causeway. In this design, the geotextile replaced a conventional granular filter as a means of preventing erosion of subgrade soils through the riprap. The protected section was designed for 3-ft waves and a 3-ft tidal variation.

When the project was inspected in October, 1979, the seawall appeared to have been functioning as designed, as no erosion problems were observed. Other areas of the causeway were also inspected where erosion control systems other than geotextiles were in use. In one area, concrete with very little aggregate had been poured against the abutment and over the exposed soil. Large voids were present (up to 1 ft in diameter) both in the concrete mat and underneath the mat where the soil and concrete had eroded. Inspection of

other areas indicated that using riprap without a filter layer (e.g. a geotextile) did not prevent areas from washing out, and that the minimum amount of erosion control was not successful.

Four areas along the length of the seawall with the geotextile filter were selected for further examination of the soil-geotextile system. Site 1 was selected due to the smaller size of riprap covering, its location in relation to protection of the bridge abutment, and its relatively flat slope. Site 2 was selected because it appeared to be exposed to more direct wave action than the other areas of the causeway. Site 3 was selected in an area where the fabric had been improperly placed and exposed to the sun. Excavation of the fourth site indicated that no geotextile had been placed.

At Site 1 the fabric appeared to be in excellent condition, and no large tears or punctures were observed. Small perforations and punctures (two to three 0.1-0.25-in. diameter holes per sq ft) were present which probably resulted from the placement of the riprap during construction. At Site 2 only one small tear was noted in the fabric, and the same magnitude and size of small perforations that were encountered at Site 1 were present. At Site 3 observations of the fabric indicated several tears and punctures where the fabric was exposed.

Samples of the geotextile were tested in the laboratory for strength, permeability, and particle retention. Grab strength was determined in accordance with ASTM D1682. Permeability of the geotextile specimens was determined using a U-tube geotextile permeameter, which is presented schematically in Figure 6-18. A falling head technique, from a head of 10 cm to a head of 3.7 cm, was used. (Note: since this testing was performed, ASTM has developed D4491-85, which is the preferred method). The particle retention of the fabric was evaluated in accordance with the Corps of Engineers, Army Engineers Waterways Experiment Station AD-745-085 procedure for determining the "open" area of the geotextile.

Grab strength results are summarized in Table 6-27. The grab strength of the sample from Site 2, where there was more wave action, was 30% less than that of the Site 1 sample. Figure 6-19, which was developed for Site 1, relates strength variations to location along the slope. In general, the grab strength appears to increase with location in the downslope direction. Section 4 of the Site 1 sample, which was probably under water during most of its 10-year service, had the greatest strength.

The results of determining the permeability and particle retention of the fabric are presented in Table 6-28. A slight reduction in the permeability of the excavated geotextile in comparison with the unexposed geotextile was found. Percent of open area is defined as the area of the openings (multiplied by 100) divided by the total surface area of the unit of fabric and is equivalent to the porosity of soil. The net results indicate a decrease of less than 10% in open area of the fabric.

The study indicated that the geotextile showed good long-term stability during exposure and retained a significant amount of strength after ten years

of service. There are some indications that the strength of the fabric may be affected by cyclic wetting and drying or repeated loading from wave action.

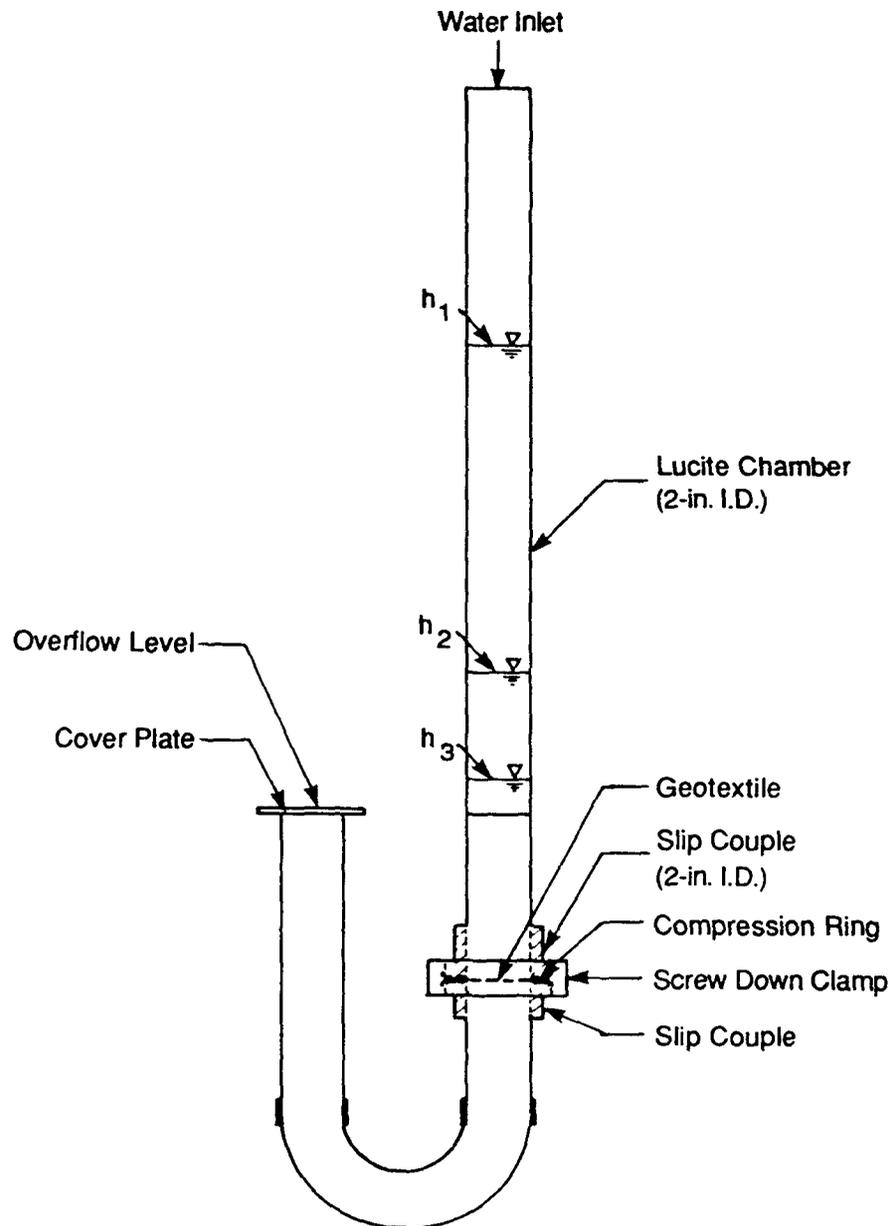


Figure 6-18. Geotextile permeameter. (Based on Christopher, 1982).

6.6.2 Field Study No. 2

The second study reviewed the condition of a geotextile which was of the same type that was studied in the previous case study (Section 6.6.1).

The monofilament polypropylene geotextile was used in the construction of the abutments for the Bahia Honda Bridge in Florida as a protective filter beneath sand-cement riprap constructed abutment slopes, drains, and seawalls. In this system, the fabric acted as a filter between the erosion control armoring and the underlying soil to prevent loss of soil through cracks or holes in the riprap as a result of weathering or wave action.

TABLE 6-27. GRAB STRENGTH OF A MONOFILAMENT WOVEN POLYPROPYLENE GEOTEXTILE THAT HAD BEEN IN SERVICE FOR 10 YEARS

Sample	Test in weaker principal direction			Test in stronger principal direction		
	Strength, kg	Apparent elongation at failure, %	Retention of original strength ^a , %	Strength, kg	Apparent elongation at failure, %	Retention of original strength ^b , %
New:						
Sample 1	97	50	...	171	30	...
Sample 2	101	43	...	163	35	...
Site 1:						
Section 1	89	37	89	130	38	76
Section 2	96	40	96	144	38	84
Section 3	100	40	100	136	39	80
Section 4	96	37	96	161	38	95
Site 2	67	38	67	104	25	61
Site 3	51	25	51	111	47	65

^aOriginal grab tensile strength = 100 kg used to calculate retention values.

^bOriginal grab tensile strength = 170 kg used to calculate retention values.

Source: Christopher, 1982.

A site investigation indicated good long-term stability of the sand-cement constructed facilities after 10 years of service. No erosion problems were apparent at any of the drains, slopes, or seawalls protected by the sand-cement armoring system, which indicated that the installation was functioning as designed. Geotextile could be seen protruding from beneath the riprap at the edge of the structures in several sections of the abutments, drains and seawall. In all cases, the geotextile appeared to be in good condition.

Samples of the exposed geotextile were collected and tested for strength, permeability, and the particle retention in accordance with the same test procedures used in the first field study. The grab strength of the exposed geotextile was 167 kg in the stronger principal direction and 111 kg in the weaker principal direction. These results indicate good retention of strength in both directions, the values for which were 170 kg and 100 kg, respectively, for new fabric. The apparent elongation at failure of the exposed sample was approximately 10% greater than the elongation at failure of the unexposed geotextile. The sample from between the sand bags had an average permeability of 1.2×10^{-2} cm s⁻¹, and the sample from directly beneath the sand bags had a permeability of 5.7×10^{-3} cm s⁻¹ indicating a loss in permeability. (The permeability of geotextile when new ranged from 3 to 4×10^{-2} cm s⁻¹. The sample from between the sand bags

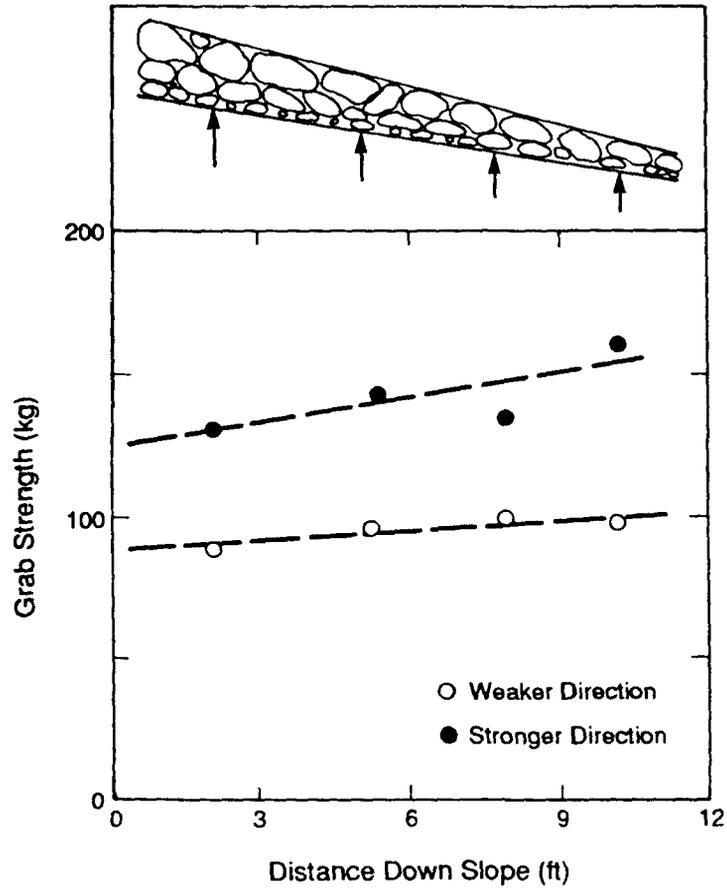


Figure 6-19. Strength of fabric versus position on slope at Site 1. (Based on Christopher, 1982).

TABLE 6-28. PROPERTIES OF A MONOFILAMENT WOVEN POLYPROPYLENE GEOTEXTILE THAT HAD BEEN IN SERVICE FOR 10 YEARS

Sample	Permeability, cm s^{-1}	Open area, %	Openings containing particles, %	Open area completely closed, %
New	$3 \text{ to } 4 \times 10^{-2}$	6	...	...
Site 1:				
Section 1	2.6×10^{-2}	5.5	29	6
Section 2	2.2×10^{-2}	5.7	20 (19.5) ^a	6
Section 3	1.8×10^{-2}	5.4	29	6
Section 4	1.9×10^{-2}	4.8	44 (44) ^a	9
Site 2	2.3×10^{-2}	5.0 5.1	40 to 48 (35 to 42) ^a	8 to 10

^aWashed with 3-ft head of water.

Source: Christopher, 1982.

had less than 10% of the openings closed by sand particles; however, the sample from beneath the sand bags had up to 50% of the space closed by sand particles. It appears that the large amount of clogging found in the sample from beneath the sand bags resulted from construction of the armoring system.

6.7 FIELD STUDIES OF LEACHATE COLLECTION AND REMOVAL SYSTEMS

Leachate collection and removal systems (LCRSs) must maintain flow capacity over the expected service life and post-closure care period of the containment unit in order to function either as a system for controlling liquid head on a liner or as a leak detection, collection, and removal system.

Clogging of LCRSs that has have resulted in significant loss of drainage and collection capacity has been observed. Some examples of clogging mechanisms include:

- Calcium carbonate encrustation.
- Iron deposition.
- Formation of biological slimes.
- Physical mechanisms.

Calcium carbonate encrustation occurs by a mechanism similar to that seen in the natural formation of stalactites.

Iron oxide deposition can occur from a number of complex processes; they can restrict leachate flow by clogging the inside of pipes or causing cementation or clogging of the materials surrounding the pipes.

The formation of biological slimes can occur when slime-producing bacteria or organisms are present under favorable conditions. In general, the formation of biological slimes is dependent on the presence of bacteria together with the appropriate nutrients, presence of oxygen, growth conditions and energy sources.

Examples of physical mechanisms for clogging include collapse of a system due to excessive loading of the waste above, damage to the system related to construction of the lining system (e.g. compaction of an overlying soil layer), and mechanical intrusion into the drainage layer by the layers above and/or below when under a static load, including intrusion by soils, FMLs, and/or geotextiles. Collapse of a pipe in the drainage system can result in a localized subsidence, which in time can cause a breach in an overlying FML and ultimately cause failure of the unit.

Ramke (1987), in an investigation of the construction and maintenance of granular-based LCRSs, reported examples of damage to these systems in MSW landfills. Of the seven he described, the drainage material of five were

clogged by encrustation. This damage resulted in the build up of as much as 33 ft of liquid on a liner. Flushing, dissolving, and grinding were partially successful in most cases in repairing the damage. In the other two LCRSs, the damage was mechanical due to improper selection of pipe and inadequate dimensioning of the collection pipes which collapsed.

Ramke (1987) concluded that damages have occurred repeatedly in LCRSs and pipelines in MSW landfills due to encrustation. Repair measures were only partly successful. Analyses of the encrustations showed that iron and calcium were the major components. The causes were considered to be bio-chemical and physical-chemically controlled precipitation processes.

Bass (1986) discussed the results of interviewing 16 individuals in 1983 from companies that design, construct, operate, and/or regulate landfills equipped with LCRSs. The objective of the survey was to determine various types of failure mechanisms that might occur in an LCRS. The experience with these systems is summarized in Table 6-29.

No detailed study was available on the field performance of LCRSs designed with synthetic drainage media.

6.8 OBSERVATIONS AND LIMITED CONCLUSIONS FROM STUDIES OF THE IN-SERVICE PERFORMANCE OF FMLS AND ANCILLARY MATERIALS IN CONTAINMENT APPLICATIONS

6.8.1 Introduction

The information that is reported in this chapter on in-service performance of materials and containment units is basically of the following two types:

- Quantitative information on the effects of various exposures on the properties of FMLs obtained by sampling and testing specific materials that had been in service in containment units.
- Qualitative information from the experience and field observations of experts relating to the condition of the containment units as a whole. Much of this information is descriptive and was not obtained in a uniform manner by the different experts for the various case studies, nor were the purpose and scope of the inspections the same.

The reader should be aware of the limitations of the information presented in this chapter and of the generalities that can be derived and applied to liner systems being installed in containment units. These limitations include the following:

- The objectives of the studies varied with the observer and reporter and, therefore, cannot be considered a statistically valid sample of

TABLE 6-29. EXPERIENCE WITH LEACHATE COLLECTION AND REMOVAL SYSTEMS

Failure mechanism	Facility type	Cause ^a	Comments
Sedimentation	NS ^b	C	No filter installed
Sedimentation	NS	U	General experience
Sedimentation	Co-disposal	U	In 1-year old system
Sedimentation	Co-disposal	U	Of gravel layer and pipe
Sedimentation	Municipal	U	General experience
Sedimentation	NS	C	General experience
Biological growth	Industrial	D	100-ft long biological growth flushed out under high pressure
Biological growth	Municipal	U	Reduction in flow every 2 years; flushed out
Biological growth	Municipal	U	Of filter fabric
Biological growth	Co-disposal	U	On 0.75-in. stone, not clogged
Chemical precipitation	Municipal	O	EPA test cell, not clogged
Chemical precipitation	Co-disposal	U	Iron oxide, not clogged
Chemical precipitation	Co-disposal	O	Attributed to waste characteristics
Biochemical precipitation	Co-disposal	U	In leachate collection wells
Pipe breakage	NS	O	By clean-out equipment if bends greater than 22°, general experience
Pipe breakage	Municipal	D	Differential settling, improper bedding
Pipe separation	Municipal	C	Joints not glued
Pipe deterioration	NS	D	Problems with ABS pipe, general experience
Pipe deterioration	Hazardous	O	From acid or solvent disposed of in wrong cell
Tank failure	Co-disposal	D	Leachate holding tank
Capacity exceeded	Co-disposal	D	Under-design, other problems noted
Capacity exceeded	Hazardous	O	Periodic rather than automatic pumping of sump
Outlet inadequate	Co-disposal	D	Caused leachate buildup

^aO = operation related; D = design related; C = construction related; U = undetermined.

^bNS = not specified.

Source: Bass (1986)

all in-place liner systems; also, there is likely to be some disproportionate representation of key variables.

- The types of units and the types of wastes that were contained at these units varied widely. The types of liquids or wastes that were contained included municipal and industrial wastewaters, oil field brines, municipal solid waste, power plant ash, and water being conveyed for irrigation, in addition to hazardous chemical wastes.
- The amount of information for each study is highly variable due to limitations on the amount and the quality of the information made available to the observer and/or the reporter and to the time available for performing each field study or survey.

Any conclusions drawn from the information presented in this chapter need to be consistent with these limitations.

The observations and limited conclusions regarding in-service performance of materials are made first on the performance of individual components of a containment unit. These include the liner system, the leachate collection and removal system, and the supporting structures and earthworks. Factors that contribute to the success or failure of a containment unit are the correlation of field performance and laboratory assessment of FMLs and the need for in-service performance information on waste containment units are also discussed.

6.8.2 Performance of Components

6.8.2.1 Liner System--

Except for FMLs that are sensitive to ultraviolet light and plasticizer loss and are exposed without a protective soil cover on the berms and slopes of surface impoundments, there is little indication from the field studies of polymeric deterioration during exposure. The PVC FMLs have shown the greatest need to be protected. Without protection by a soil cover, plasticized FML compositions exhibited loss of plasticizer, shrinkage, and loss of elongation, resulting in brittleness and breaches in the liner. On the other hand, buried PVC FMLs have shown relatively good retention of properties and have successfully controlled seepage from irrigation canals for up to 19 years (Morrison and Starbuck, 1984).

Incompatibility of the FML with the waste was observed in several cases. Incompatibility was indicated by the opening of seams, the swelling of the FML, delamination of fabric-reinforced FMLs, and the loss in values of some properties such as tensile strength, elongation at break, tear strength, and puncture resistance, all of which are properties of importance in the performance of FMLs. In a major fraction of these cases, the swelling was a result of uncontrolled chemicals being placed in the containment unit.

Increasing permeability of FMLs was not observed in any of the field investigations, which is indicated by the relatively low swelling of the recovered samples. On the other hand, neither the composition nor the

concentration of the volatile constituents immediately below an FML appear to have been determined. Increased permeation would be indicated by high swelling of the FML. Thus, what chemical incompatibility was observed did not appear to affect the FML's permeability.

Chemical incompatibility does not appear to have been a primary factor in the formation of breaches in the FML except in causing the opening of seams; however, it probably has a secondary influence on the FMLs, causing changes in their properties such as lower modulus, lower mechanical properties, such as tensile strength, tear resistance, and an increased tendency toward creep. In all of these cases, the FML would have to be under a tensile or torque stress to result in a breach.

In the results there was no indication that biodegradation of the polymers had taken place, except for the possible loss of plasticizer when the FML was buried (Morrison and Starbuck, 1984). Biocides are presently being incorporated in PVC FMLs to reduce this effect. On the other hand, there was an observation of bacterial effects on the surface of FMLs by algae formation followed by subsequent drying which caused the top coating of a fabric-reinforced FML to crack (Giroud 1984a, Case 26).

Failure of the seams was reported in several instances due to inadequate seaming, quality control, and improper selection of the FML for the particular application. For example, a butyl rubber reinforced with nylon was exposed without a cover (Giroud, 1984a, Case 11). The FML tended to shrink due to shrinkage of the nylon when heated (e.g. by sunlight), and the seams were pulled open.

Many of the breaches that have been observed in FMLs appear to be related to improper design and/or inadequate construction and quality control of other components of the containment unit.

6.8.2.2 Leachate Collection and Removal Systems--

The various materials that are involved in an LCRS include drainage soils and gravels, geotextiles, geonets, geocomposites, and pipe. The observations that were reported on these materials are very limited. Two sets of observations on LCRSs were those of Ramke (1987) and Bass (1986). In these cases, clogging of LCRSs was observed as a function of biological growth and inorganic deposits and carbonates and higher minerals. Pipe failures due to inadequate dimensioning, to overburden pressure, or perhaps to damage during construction were also observed. There were no indications in any of the cases of actual chemical incompatibility of the pipe with the leachate.

6.8.2.3 Supporting Structures and Earthworks--

Several cases were reported where the soil on which a surface impoundment was placed was incompatible with the waste liquid being contained; for example, problems resulted from the leakage of acidic waste liquid into underlying soil that contained carbonates. In one case, leakage of the waste

liquid resulted in gases being generated underneath the FML and the formation of "whales" which eventually caused failure of the FML (Ghassemi et al, 1984, Case Study 4). In another case, the acidic waste caused formation of cavities below the FML resulting in eventual failure of the FML (Giroud, 1984a, Case Study 1).

In another case, the wave action against a slope caused sloughing and formation of cavities behind an FML, which resulted in failure of the FML (Giroud, 1984a, Case Study 2).

6.8.3 Correlation of Field Performance and Laboratory Assessment of FMLs

Overall liner-waste compatibility observed in the field indicated by the effects on the properties of the FMLs in contact with waste streams appeared to compare well with laboratory results obtained with similar waste streams. It would thus appear possible to predict through compatibility tests the effects of the contained liquid on the properties of FMLs, at least for short-term service. Also, the weatherability of FMLs in-service was predictable from laboratory tests.

Whereas the laboratory studies and in-service performance related to the effects of weathering and swelling can be correlated, the field studies indicated that many problems resulting in physical damage to FMLs in surface impoundments have not been simulated in laboratory or pilot-scale tests. Examples of these include:

- "Whale" formation (trapped gas beneath the FML).
- Seam failures resulting from various stresses in the seam (e.g. shrinkage, and stresses caused by subsidence).
- Erosion of slopes from wave action and sloughing of the protective cover.
- Puncture and mechanical damage from operations.

These types of damage can be related to inadequate design, construction, and/or management during the operations of the containment unit.

Another phenomenon that was observed in a field study and had not been predicted in laboratory or simulated-service-type testing is the damage that can occur to some liners exposed to wastewaters that can sustain algae growth. A CPE FML was severely affected at the water line of a municipal wastewater storage facility. The top ply of the CPE FML split and delaminated as a result of algae drying out on its surface (Giroud 1984a - Case Study 26).

6.8.4 Factors That Affect the Performance of a Containment Unit

Based on the information presented in this chapter, it would appear that poor performance of containment units can be attributed to factors such as the following:

- Lack of good project planning during design and construction phases.
- Failure to execute proper quality assurance/quality control (QA/QC).
- Deviations from original and/or desired liner specifications.
- Inadequate liner-waste compatibility testing.
- Lack of rigorous site-specific investigations to develop the proper basis for design and construction.

The information presented in this chapter also indicates that four factors appear important for a successful FML installation:

- Selection of qualified companies for design, manufacturing, fabrication, installation, and quality control.
- Proper design including evaluating needs for chemical compatibility testing, selection of materials and specifications, and strict adherence to specifications.
- Quality control, quality assurance, and good communications during all phases of construction and installation.
- Controlling operations at the site during the service life of the facility.

6.8.5 Need for In-Service Performance Information on Waste Containment Units

Much of the information contained in this chapter relates to materials that are no longer being used in waste containment. Little information is available on the performance of polyethylene FMLs and the other geosynthetics that are presently used in the construction of liner systems and LCRSs. In addition, most of the field studies describe single-lined units that would not adequately meet the RCRA requirements for hazardous waste containment units. Over and above the monitoring programs required by regulation, it is highly desirable to assess the performance of the materials of construction used in constructing containment units from the time they are designed through post-closure monitoring in order to assess the type and magnitude of changes in properties of the construction materials. Only in this way can a correlation be established between properties and performance which can then be used to develop criteria for predicting chemical compatibility and

long-term serviceability of an FML and other geosynthetics with a particular leachate or waste liquid.

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CHAPTER 7

DESIGN OF LINED WASTE STORAGE AND DISPOSAL UNITS

7.1 INTRODUCTION

Containment units are lined for two basic reasons:

- To control the escape of constituents of the impounded material and thereby protect the groundwater environment.
- To store material, e.g. for resource recovery or recycling.

Types of lined containment units include surface impoundments, hazardous waste landfills, MSW landfills, waste piles, and heap leach pads. Because the range of variables involved in designing a containment unit and the high level of confidence that is required to meet statutory requirements for controlling the migration of constituents of materials contained in the unit (e.g. hazardous wastes), the planning and design of a lined containment unit can become highly complex.

Designing of waste containment units is guided by two separate, but equally important, sets of requirements. The first is meeting statutory and regulatory requirements; the second is the exercise of sound engineering judgment. Regulations promulgated under the Resource Conservation and Recovery Act (RCRA) state minimum performance requirements for the design and operation of storage and disposal units for the containment of solid wastes (40 CFR 257). The Hazardous and Solid Waste Amendments (HSWA) of 1984 to RCRA stated minimum technological requirements for hazardous waste landfills and surface impoundments. Regulations based on these requirements have been published in 40 CFR 264. Draft guidance documents for meeting RCRA and HSWA requirements for the containment of hazardous wastes have been released by the EPA for public comment and use (EPA, 1985; EPA, 1987a). These documents detail minimum technological guidance for the critical components of both lining and cover systems. This guidance is based on engineering judgment and is subject to change as changes in the relevant technologies change and improvements occur. Further proposed rules detailing minimum technological requirements for meeting RCRA and HSWA requirements have also been published (EPA, 1986a; EPA, 1987b). At the present time (May 1988), the EPA is in the process of developing a final rule on the minimum technological requirements for hazardous waste treatment, storage, or disposal facilities

(TSDFs) for publication in the near future. At present, the EPA has not developed minimum technology requirements for nonhazardous waste TSDFs. It should be noted that, in addition to the statutory requirements for waste TSDFs promulgated by the EPA, individual state and local authorities may have codified various requirements.

In addition to meeting regulatory requirements, the designer of a waste containment unit must also exercise sound engineering judgment. In designing a containment unit, meeting minimum technological requirements as set forth by RCRA regulations may appear to be relatively straightforward. However, due to the evolving nature of waste containment technology, the number and complexity of the operational variables encountered in the field environment, and the interactive nature of many of these variables, exercise of sound engineering judgment is complex. For example, insofar as all design decisions should be made through the exercise of engineering judgment, certain site-specific factors may require that regulatory minimums be exceeded.

This chapter discusses the minimum performance and technological requirements for the design of lined waste containment units and reviews engineering options available to the designer, with particular emphasis on the design of hazardous waste TSDFs. This information can be used by site owners and operators, permit writers, and those responsible for preparing permit applications to aid them in gaining a comprehensive understanding of the numerous elements involved in the design and construction of waste containment units. This chapter can also be used by researchers and materials and component suppliers as a source of information on the design of various types of waste containment units.

7.2 TYPES OF CONSTRUCTED CONTAINMENT UNITS

From a construction point of view, the three major types of containment units are as follows:

- Totally excavated.
- Diked (i.e. totally aboveground).
- Combination.

Figures 7-1 through 7-3 schematically illustrate excavated, diked, and combination surface impoundments. Excavated units are dug from a surface such that the major portion of the capacity is below the grade of the surrounding land surface (Figure 7-1). Diked units are built up above grade such that the major portion of the capacity is elevated higher than the immediate surroundings (Figure 7-2). Combination units result when material is both excavated and filled (Figure 7-3). The construction of a particular type of unit at a specific site depends on economic, hydrogeologic, regulatory, and other site-specific factors.

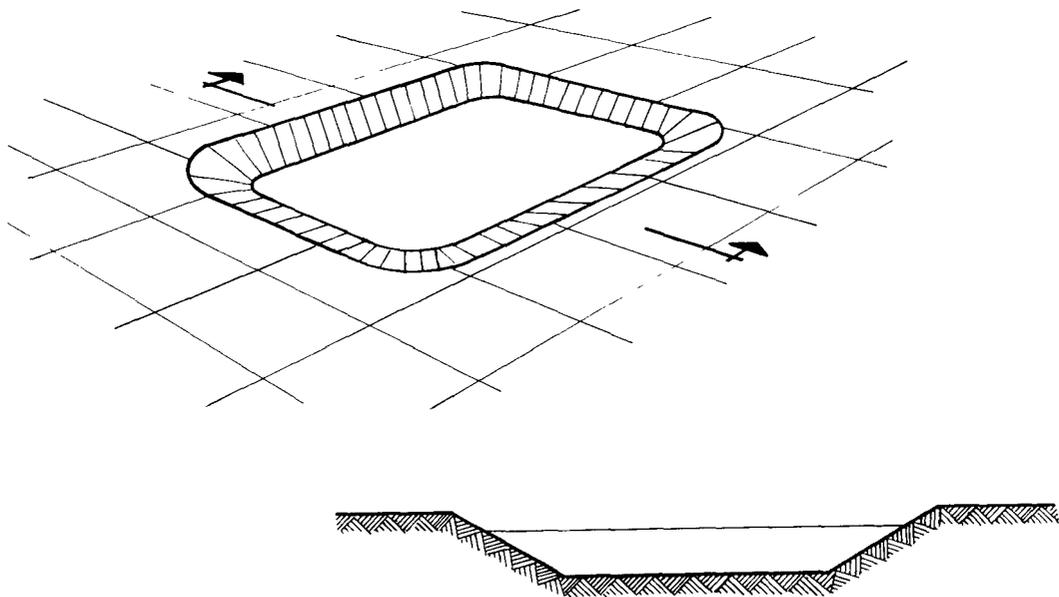


Figure 7-1. An excavated surface impoundment (Source: EPRI, 1980, p 8-6).

Excavated units are generally found in relatively flat areas where excavatable soil of a suitable nature exists (e.g. alluvium). As soil is excavated, some may be left at the perimeter of the excavation to be used for berm construction and levelling. The remainder of the material may be used for daily cover (if the unit is a landfill), for general grading, or for fill in other construction activities.

Diked, or aboveground, units are generally constructed at sites with bedrock near or at the surface because the cost of blasting and excavating precludes excavated units. This type of unit is becoming more common as waste disposal becomes more expensive. Where local geologic considerations preclude the economical construction of excavated units, the desirable earth materials (sand, silt, or clay) for berm and bottom construction are often hauled in from off-site locations. Diked units are also constructed at sites with a high water table and capillary zones.

A special type of diked unit can be built in an existing valley. An earthen dike is constructed between the valley walls and across the valley floor (Figure 7-4). Earth materials are used to prepare the sides and bottoms of the unit prior to liner installation. In designing valley span

7-4

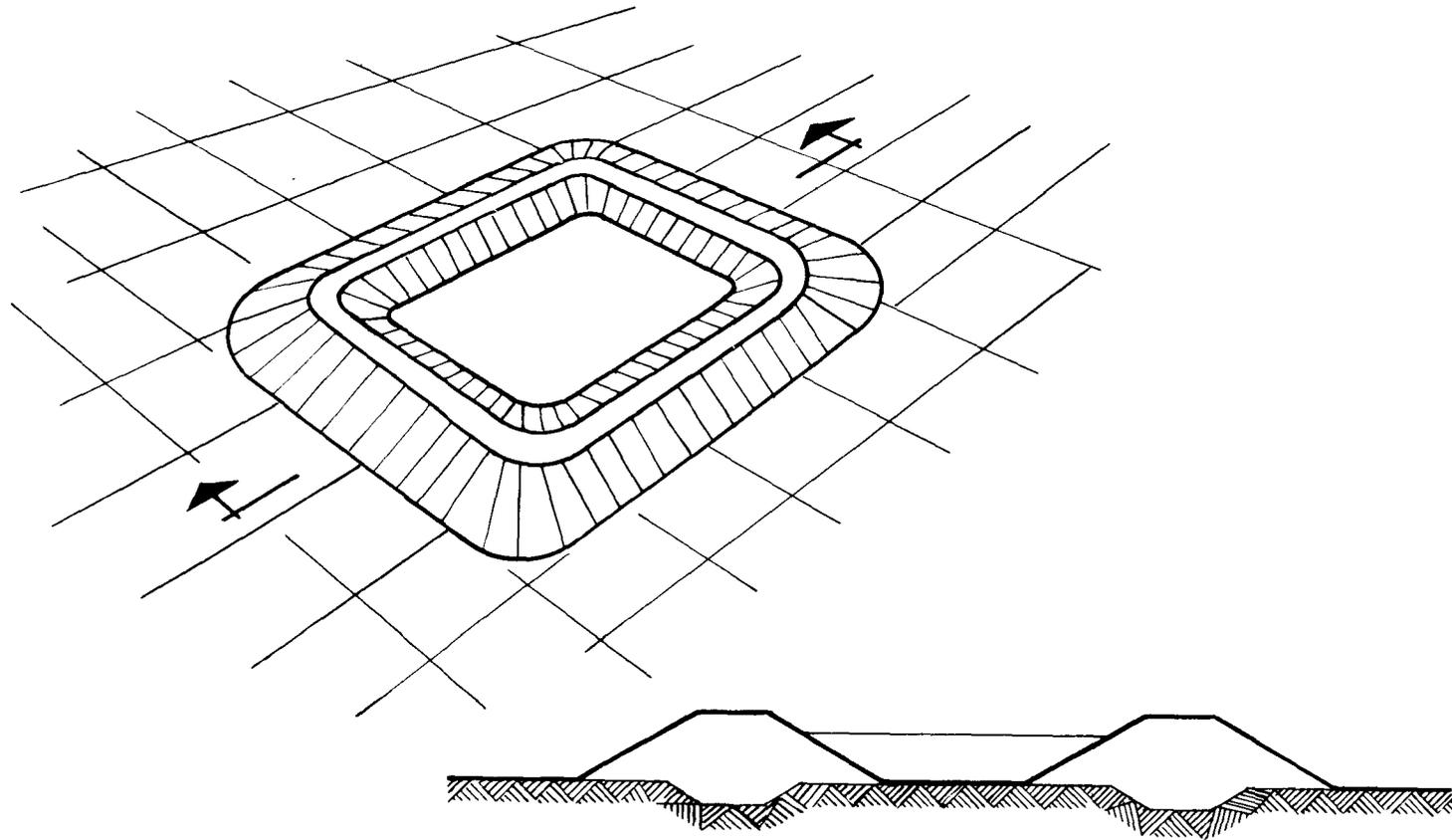


Figure 7-2. Diked surface impoundment constructed above-grade (Source: EPRI, 1980, p 8-5).

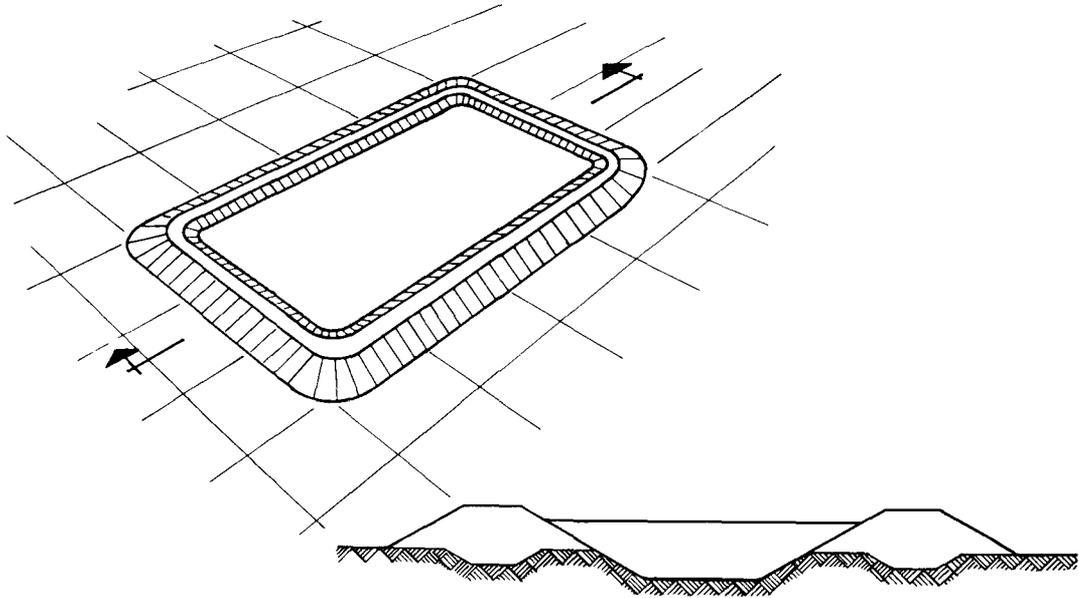


Figure 7-3. Diked surface impoundment partially excavated below grade (Source: EPRI, 1980, p 8-4).

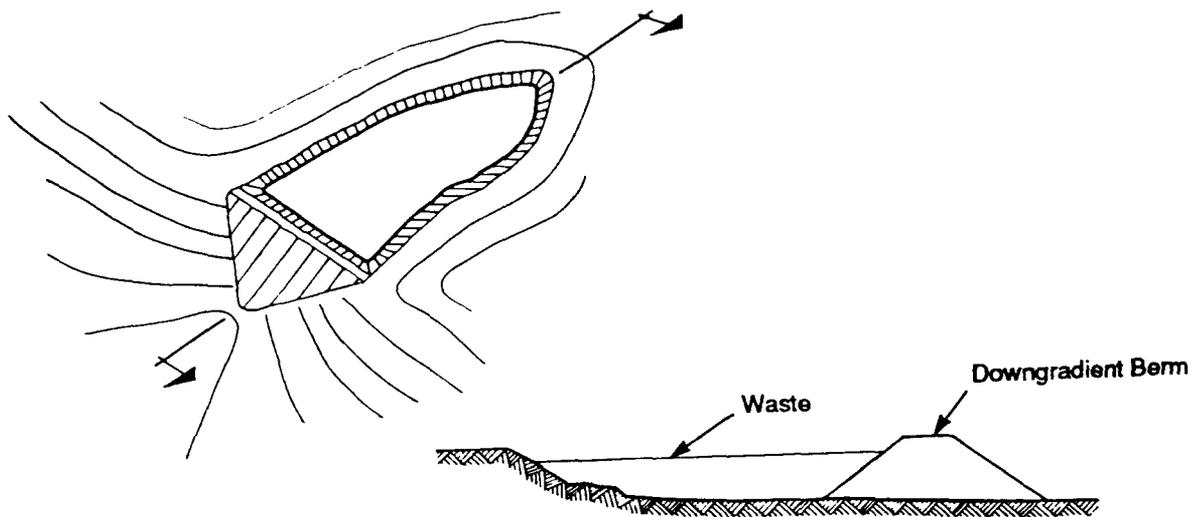


Figure 7-4. A cross-valley surface impoundment configuration (Source: EPRI, 1980).

units, special consideration is given to managing the waste placement along with the flow of surface and subsurface runoff. The downgradient berm should be in place at the time waste is placed in the unit in order to provide passive restraint against gravitational and/or dynamic forces of the mass.

Most storage and disposal units can be classified as combination excavation-fill impoundments because a balanced cut-fill project generally results in the best economics.

7.3 FACTORS IN DESIGNING A LINED CONTAINMENT UNIT

This section discusses some key factors that must be considered in designing a waste containment unit, including:

- Site-specific factors.
- Regulatory requirements and minimum guidance developed by the EPA.

7.3.1 Site-Specific Factors in Designing a Waste Containment Unit

The design of a waste containment unit can be greatly influenced by various site-specific factors. These factors can be separated into operational factors, hydrogeological factors, climatic factors, locational factors, and biological factors. Table 7-1 lists factors that need to be considered in designing various types of waste containment units. Many of these factors and their effect on unit design are discussed in the following subsections.

7.3.1.1 Operational Factors--

7.3.1.1.1 Purpose of the unit--The purpose of the unit significantly affects the design and the type of operational factors that need to be considered in the design. For example, settling ponds can require significantly different designs from hazardous waste landfills. Important differences can include the necessity of collecting leachate in a landfill, the probable necessity of conveying supernatant liquid out of a settling pond, different regulatory requirements, etc.

7.3.1.1.2 Characteristics of the waste to be contained--In designing a waste containment unit it is important to consider the possible interaction between constituents of the waste to be contained and components of the lining system. For example, the organic constituents that may be present in a hazardous waste landfill or surface impoundment may have a significant effect on the polymeric components of the lining system. Some of the organics may be volatile and be able to migrate throughout the landfill. These organics may permeate the FML and be absorbed by the other components of the lining system, such as geotextiles and geonets, which are not in direct contact with the leachate. Depending on the organic, this absorption can

TABLE 7-1. SITE-SPECIFIC FACTORS TO BE CONSIDERED
IN DESIGNING A WASTE CONTAINMENT UNIT

Operational Factors:

- Purpose of the unit, i.e. whether the unit is for temporary storage or permanent disposal and whether the waste to be contained is hazardous.
- Characteristics of the waste to be contained, including unusual variations, e.g. composition, concentration, temperature.
- Desired service life of the unit.
- Pre-existing operational systems for conveyance of wastes into and/or out of a unit, e.g. from mining operations.
- Acceptable seepage rate out of unit.
- Projected use of closed facility.
- Desired dimensions and capacity of unit.
- Estimated leachate volume during the active life of a landfill (dependent on climatological factors).
- Harvesting or recycling/recovery programs, e.g. in settling ponds.
- Waste flow variation and discharge velocity, e.g. for a settling pond.
- Groundwater monitoring requirements.
- Berm width requirements.
- Requirements for monitoring conditions of lining system, e.g. coupon testing.

Hydrogeological Factors:

- Characteristics of in-place soils at facility site.
- Subgrade characteristics as determined by soil borings.
- Location and type of bedrock.
- Competency of bedrock.
- Location of uppermost aquifer and other hydraulically interconnected aquifers beneath facility property.
- Groundwater flow direction and rate.

continued . . .

TABLE 7-1 (CONTINUED)

-
-
- Location of capillary zones.
 - Seismic history of area.
 - Proximity to faults.
 - Floodplain level.
 - Presence of surface waters including intermittent streams.
 - Site topography.

Climatological Factors:

- Ambient temperature, including average and range.
- Prevailing wind speed and direction.
- Precipitation.
- Solar radiation.
- Evapotranspiration.
- Underground temperature (i.e. predicted service temperature of buried lining system).

Locational Factors:

- Public relations.
- Adequacy of buffer zones.
- Surrounding land uses (commercial, residential, agricultural).
- Proximity to major waste generators.
- Regulations regarding locations of containment facilities.
- Regulations regarding design and operation at specific location.

Biological Factors:

- Local vegetation.
 - Presence of indigenous burrowing animals.
 - Presence of microorganisms.
 - Potential for gas production underneath lined unit.
-
-

soften polymeric drainage materials (e.g. geonets and geocomposites) and thus, in conjunction with the overburden placed on a drainage system, can reduce the drainage capacity of a system that depends on a polymeric drainage medium. In addition, dissolved organics may interact with an FML to alter its initially low permeability and change its mechanical properties. Knowledge about the composition of a waste liquid or leachate is important in making an initial judgment about the compatibility of the waste liquid and different components of the lining system.

The types of wastes that may be placed in a lined containment unit are discussed in Chapter 2. Chapter 5 presents data from studies investigating the interaction between actual waste liquids, leachates, or test liquids and various types of lining materials, particularly FMLs. Goldman et al (1985) summarize the results of selected studies investigating the effect of interactions between chemicals and clays on soil liner hydraulic conductivity.

7.3.1.1.3 Configuration and dimensions of the unit--The most economical shape for a containment unit is a rectangle with straight sides. Curved sides and irregular shapes usually add to the grading and installation costs and increase the number of structural failure points that can occur. The construction of circular containment units result in significantly higher grading costs, installation costs for liner materials, and overall construction costs.

7.3.1.1.4 Recycling/recovery operations--Some surface impoundments functioning as settling ponds for the recovery of water can require sludge removal or other dredging operations. Because of the potential for damage to a liner during these operations, the design should include measures to protect the liner. Where mechanical equipment is used, the EPA presently recommends a minimum of 18 in. of protective soil, or the equivalent, covering the top liner except in cases in which it is known that the FML will not be damaged by the sludge removal practices (EPA, 1985).

7.3.1.1.5 Berm width requirements--The width of the top of the containment embankments will be determined by their height and the design side slope. Thus, the berm must be sufficiently wide to provide adequate strength to the embankments. From an operational point of view, the minimum suggested top width is 10 ft in order to allow sufficient room for equipment and personnel to operate during liner installation, to provide enough room so that anchor trenches can be efficiently installed, and to facilitate maintenance and repairs throughout the unit's active life, particularly in the case of surface impoundments.

7.3.1.1.6 Inflow/outflow/overflow conveyances--The fewer penetrations in a lined containment unit, the lower the potential for breaches in the liner system; thus, in the case of the surface impoundments, inflow/outflow piping designed to go "over the top" is generally preferred. If inflow/outflow penetrations through a liner are required, pipes made of materials that are compatible with the liner type and the waste liquid need to be used.

During construction of the unit, soil around the pipes should be well compacted to ensure that voids and loosening of the structures (e.g. an inflow pipe) due to variable subsidence of the soil base are eliminated to prevent breakage. In some cases, it may be desirable to construct a concrete base below the penetration. If an "over the top" inflow pipe is used, a splash pad may be needed to prevent damage to the liner. In the case of landfills, construction of the sump system outside the unit may be desirable under some circumstances.

7.3.1.1.7 Estimated leachate volume in a landfill--The volume of leachate produced in a landfill unit is primarily a function of the amount of water that flows through the solid waste. Precipitation is a key factor affecting the volume of leachate produced; thus, in regions of moderate-to-heavy rainfall, leachate generation can be significant. The estimated amount of leachate produced by a unit is important for designing the leachate collection and removal systems which need to be designed to handle a maximum expected volume, e.g. the leachate volume predicted from a 24-hour, 25-year storm, while ensuring that the leachate depth over the liner does not exceed 30 cm (1 ft).

A tool for predicting with a reasonable degree of accuracy the quantity of leachate that a given landfill can be expected to produce under a number of different scenarios has been developed, based on the water balance method of Thornthwaite and Mather (1955) in the soil and water conservation field. Computer models has been developed to simulate hydrologic characteristics of landfill operations (Perrier and Gibson, 1982; Schroeder et al, 1984a and 1984b).

The water balance method is a mathematical accounting process which considers precipitation, evapotranspiration, surface run-off, and soil moisture storage, all of which have a bearing on the extent to which infiltration can be expected to occur after a rain. Since infiltration is the major contributor to leachate generation, knowing how much can be expected under a given set of site conditions will provide the designer with valuable information on which to base the design, particularly for the leachate collection and removal system (LCRS) above a top liner. Figure 7-5 schematically illustrates, for an unlined MSW landfill, some of the factors that can affect the volume of leachate produced.

The Hydrologic Evaluation of Landfill Performance (HELP) model is the most recent computer simulation tool that has been developed to assist landfill designers and regulators (Schroeder et al, 1984a and 1984b). This program simulates the performance of alternative designs using climatological, soil, and design data to produce estimates of water movement across, into, through, and out of a landfill.

In designing a trial landfill configuration, four types of layers can be arranged into a profile with up to nine layers. These four types of layers include:

- Vertical percolation layers (e.g. the daily cover or the vegetative cover on a closed landfill).

- Lateral drainage layers (e.g. a leachate collection and removal system).
- Waste layers.
- Barrier layers (i.e. a soil liner with or without an FML).

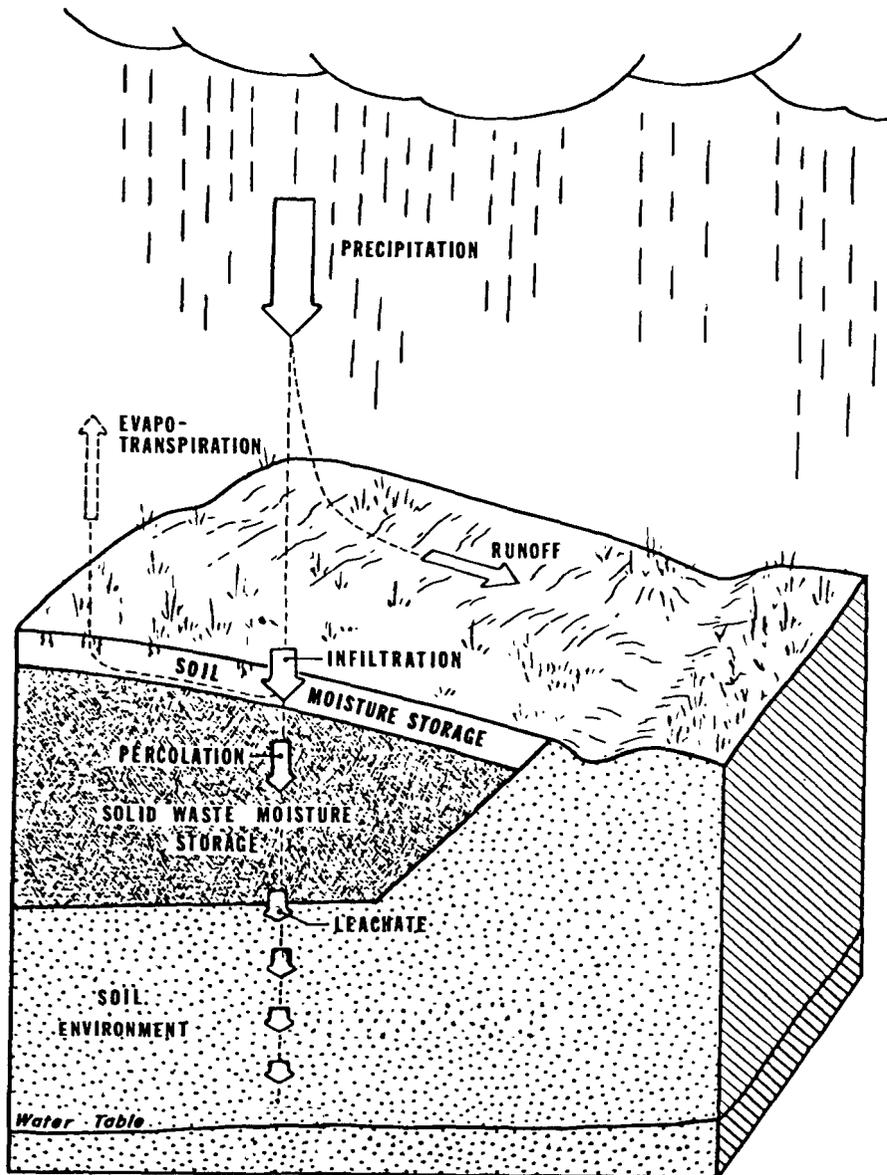


Figure 7-5. Percolation through a closed MSW landfill and movement of the leachate into the soil environment.

Variables for each layer need to be defined, including:

- Thickness.
- Porosity (i.e. the ratio of the volume of voids to the total volume occupied by a soil).

- Field capacity (i.e. the ratio of the volume of water that a soil retains after gravity drainage stops to the total volume occupied by a soil).
- Wilting point (i.e. the ratio of the volume of water that a soil retains after plants can no longer extract water (thus, the plants remain wilted) to the total volume occupied by a soil).
- Saturated hydraulic conductivity.
- Evaporation coefficient (i.e. a value that indicates the relative ease by which water is transmitted through soil in response to capillary suction).
- Whether or not the layer was compacted.

In addition, the total surface area of the landfill and the drainage slope and the maximum drainage distance in the drainage layers need to be defined. Default data for various types of soils are available in the program.

In simulating the performance of the trial landfill design, various climatological factors are taken into consideration, including:

- Daily precipitation.
- Mean monthly temperatures.
- Mean monthly insolation (i.e. solar radiation).
- Leaf area indexes (i.e. a dimensionless ratio of leaf area of actively-transpiring vegetation to the nominal surface area of land).
- Winter cover factors, which account for the insulating effect of dormant vegetation on the rate of evaporation from the soil.
- The evaporative zone depth (i.e. the maximum depth from which water may be removed from the landfill by evapotranspiration).

Default climatological data for 102 cities are available in the program.

Simulations representing between 2 and 5 years of landfill performance can be performed, generating values for precipitation, surface runoff, evapotranspiration, percolation through the base of each subprofile, and lateral drainage from each subprofile. These values can be reported on a daily, monthly, or yearly basis. Thus, the program can be used to estimate the magnitudes of various components of the water budget, including the volume of leachate produced by the fill and the thickness of the water-saturated layer (i.e. the hydraulic head) above the barrier layers (i.e. the liner or the cover system). These results can be used to compare the leachate production potential of alternative designs, select and size appropriate leachate collection and removal systems, and size leachate treatment facilities. Two

verification studies of the HELP model have been performed (Schroeder and Peyton, 1987a and 1987b). Version 2 of the model is now available in a draft form for public comment.

7.3.1.2 Hydrogeological Factors--

7.3.1.2.1 Characteristics of in situ soils--The characteristics of the in situ soil materials are important because of their use in the foundation and their potential use in soil liner and embankment construction. If the native soils are found to be unsuitable for use in constructing the liner or the embankments, borrow sources need to be identified and investigated. Soil characteristics are also a necessary element in analyzing slope stability and determining whether special design measures are necessary for controlling settlement. The classification, relative homogeneity, and relevant physical, mechanical, and chemical characteristics of the in situ soils need to be determined. During the site investigation, the soils need to be tested for Atterberg limits and grain size relative to "shrink/swell" moisture, density, strength, consolidation, permeability, organic material content, clay mineralogy, cation-exchange capacity, and solubility in accordance with appropriate soils engineering test methods. These tests are described by Spigolon and Kelley (1984) and Goldman et al (1985). Chapman (1965) presents a method for measuring cation-exchange capacity. Other methods include those developed by the EPA [Methods 9080 and 9081 (EPA, 1986c)]. Elements of a site investigation are discussed in Section 7.4.

Soil materials used in the construction of waste containment units should have stable characteristics under different loading and climatic/meteorological conditions and over a range of moisture contents. Soils which have high "shrink/swell" characteristics are generally avoided. The changes that occur in soils that experience excessive expansion when wet and contraction when allowed to dry may act to weaken an earthen structure, both at the bottom and on the sidewalls/berm structures, if the structure is allowed to be alternately wet and dry. Unwanted voids may be generated by repeated "shrink/swell" cycles and may compromise the integrity of the liner system.

The presence of decomposing organic material in a soil below a lining system can result in gas generation and subsidence problems. These problems and their effects on the design of a containment unit are discussed in Section 7.3.1.4.2. The presence of soluble material in the soil beneath an FML can also result in similar problems. Any acid leakage, however minimal, which could reach a carbonate rich soil, might produce quantities of gas resulting in a catastrophic liner failure. The dissolution of the carbonate in the soil by the acid might also cause cavities below the liner and loss of liner support. Giroud (1984) reports how leakage of an acidic liquid through small holes in a liner dissolved the underlying acid-sensitive soil, eventually resulting in the rupture of the FML (see Section 6.4.2.1).

7.3.1.2.2 Subgrade characteristics--The subgrade serves as the foundation by providing a relatively firm and unyielding support for the entire lining system. In this sense, the subgrade includes all soil below what is

excavated, all engineered fill, and all trench backfill. The performance of the subgrade is dependent on:

- The loading it is subjected to by the combined weight of the lining system and the waste.
- The characteristics of the subgrade soils.
- The uniformity of compaction during construction of the foundation.
- Slope stability.
- Changes in the groundwater.
- The performance of the liner.
- Seismic activity.

The main characteristics of relevance for subgrade materials are immediate settlement (stress-strain relationship), long-term settlement or consolidation (stress-strain-time relationship), strength, and acid solubility. These parameters are readily determinable by field and laboratory tests. Simpler, less expensive tests which have been previously correlated with these tests can be performed during construction as part of the construction QC/QA programs. These simpler tests include Atterberg limits, grain size, and compaction tests. Strength, permeability, and consolidation tests may also be performed on the subgrade earthwork, if deemed necessary.

7.3.1.2.3 Presence of hydrologic pathways--The presence of hydrologic pathways such as fractures and sand seams can contribute to rapid migration of wastes from a containment unit if liner failure occurs. In addition, if a liner system intersects these pathways, pressures can build against the outside of the system, possibly resulting in heaving, slope failure, and liner rupture. Provisions for sealing these pathways need to be incorporated into the unit design.

7.3.1.2.4 Location and type of bedrock--The location of bedrock underneath a site may require rock removal (through blasting and other procedures) and rock shaping in order to construct an excavated unit. However, the cost of working in intact rock is many times greater than construction activity in weathered rock or soils. In addition, the potential for large angular particles and irregular surfaces is much greater. It may be more economical under such circumstances to construct a diked unit.

The in situ rock quality is also important for assessing the presence of hydrologic pathways and the potential for leakage from a site. The higher the rock quality (i.e. the larger the percentage of intact rock), the greater the ability of the site to contain whatever leakage occurs through the lining system. In situ rock quality can be estimated by a modified core recovery

ratio known as the rock quality designation (RQD) (Deere, 1963). RQD is determined by measuring the total length of the pieces recovered in the core that measure 10 cm (4 in.) in length or longer and dividing this length by the total length of the core. The resulting value is reported as a percentage.

7.3.1.2.5 Seismic history of area and proximity to faults--Current (as of 1986) EPA regulations require new hazardous waste TSDf units to be constructed at least 61 meters (200 ft) from a fault which has had displacement in Holocene time (40 CFR 264.18). Proximity to faults can affect decisions regarding penetrating the lining (if penetrations are being considered) and embankment design.

7.3.1.2.6 Location of uppermost aquifer--In designing a facility it is important to know the location of the uppermost aquifer, including seasonal groundwater level variations, from both a design standpoint and a regulatory standpoint. Depending on the type of waste being contained and the geographical location of the facility, a specific distance between the unit base and the water table may be required. For sites with high water tables, this may necessitate aboveground unit design. Present EPA guidance for the design and construction of hazardous waste TSDf's require the lining system to be constructed completely above the seasonal high water table (EPA, 1985). If the base of the unit is allowed to extend below the water table, special intragradient (below water table) design provisions will be required.

7.3.1.2.7 Surface and groundwater drainage considerations--If the containment unit is in the natural pathway of either surface or subsurface drainage (including intermittent streams), diversion drainage systems, overflow structures, and subterranean diversion systems must be designed as required to handle the water excesses in order to minimize potential damage to the unit structure and prevent washout of the waste. Outside grades or drainage ditches may be required to prevent run-off from entering the unit, or an underdrain system may be required to remove groundwater which may accumulate beneath the installed liner with time. In addition, the directions of groundwater flow will determine the placement of the monitoring wells. Infiltrating water beneath units is particularly common in areas with high subsurface flow, or high groundwater table; the problem needs to be recognized in advance so that design accommodations can be made if the integrity of both the containment unit and the liner is to be maintained throughout its projected life. Areas subject to flooding and areas with high water tables must receive special design, construction, operations, and maintenance concern.

7.3.1.2.8 Floodplain level--Except for those cases that qualify for statutory exemption, current (as of 1986) EPA regulations require hazardous waste TSDf units located in a 100-year floodplain to be designed, constructed, and maintained to prevent washout of any waste by a 100-year flood (40 CFR 264.18).

7.3.1.2.9 Site topography--The site's topography can influence unit configuration and the run-on/run-off control drainage system design. For

example, special cut-off trenches may be necessary in mountainous regions to prevent large quantities of surface run-off from entering the unit and to protect the integrity of the unit's structure.

7.3.1.3 Climatological Factors--

7.3.1.3.1 Prevailing wind speed and direction--The design of a surface impoundment needs to consider the prevailing winds. Winds can adversely affect an FML in two ways: first, in the form of wave action as the wind impinges on the liner or cover, and secondly, in the form of lifting action on the slopes. Proper venting of an FML at the top of the slope can mitigate or negate the airfoil effect created by the slope. The placement of weighted tubes (e.g. sand bags) on the slopes also helps to break up the flow of air across the unit in addition to providing ballast to hold an FML on the slope. Dedrick (1974 and 1975) has developed models for analyzing air pressure over surfaces exposed to wind for water harvesting catchments and reservoirs. Wayne and Koerner (1988) apply the information developed by Dedrick (1974 and 1975) to solid waste land disposal units and surface impoundments during construction and prior to filling and develop a design methodology which can be used in determining the magnitude and distribution of tractive (uplift) forces on FML systems.

7.3.1.3.2 Ambient temperature--The temperature characteristics of the environment can be a factor in the liner selection process. Of particular significance are temperature extremes and the duration of those extremes. Materials that exhibit superior low temperature resistance to cracking may not be able to withstand the effects of high temperatures. Low temperatures along with strong winds can result in a flex fatigue type failure of an FML. Freeze-thaw cycling can affect the integrity of the subgrade. Materials that creep at high temperatures may elongate to failure during cycles of high temperature (Small, 1980). Workmanship for installing a liner may suffer if performed during a period of extreme temperatures.

7.3.1.4 Biological Factors--

7.3.1.4.1 Local vegetation--Vegetation can jeopardize liner integrity as a result of growth. Although there is no evidence of roots penetrating FMLs, certain grasses have been known to penetrate FMLs from underneath, particularly on the slopes and berms of surface impoundments where no soil cover has been placed on the liner. Use of thicker sheeting or sheeting with a high puncture resistance may prevent such damage. Where certain woody vegetation or grasses are evident, soil sterilization with an appropriate nonpolluting herbicide may be required to prevent damage to the liner. Salt grass, nut grass, and quackgrass are examples of vegetation that require soil sterilization before installation of the liner. The top-soil layer containing this vegetation should be removed as a part of subgrade preparation. If these grasses are present, soil sterilization should also be automatically included in the construction process. If a soil sterilant is used, FMLs should not be placed immediately after application. Time should

be allowed for the sterilant to be absorbed by the soil or to lose its volatile components so that it will not react with the liner.

7.3.1.4.2 Presence of indigenous burrowing animals--The presence of burrowing animals at a site demands special design considerations, particularly for embankments or the final cover of a closed landfill (Johnson and Dudderar, 1988). Animals of concern can include woodchucks, muskrats, ground squirrels, moles, chipmunks, termites, etc. Compacted clay liners (e.g. the cover for an MSW landfill) appear to be effective protection against burrowing animals. However, FMLs used in covers may require extra protection, including:

- Rip-rapping above the FML. Johnson and Dudderar (1988) recommend the use of rock of about 6 in. in diameter to minimize the size of the gaps between rocks and also to be large enough to resist excavation.
- Matting (e.g. Kevlar or Mylar), provided the matting is of sufficient strength and durability.
- An anti-animal layer such as a biocide, irritant (e.g. cinders), or repellent.
- The use of vegetation that is not attractive to burrowing animals.

In the case of embankments, a special vertical rock zone may be constructed to prevent animals from burrowing into the unit.

7.3.1.4.3 Presence of microorganisms--The presence of microorganisms such as bacteria and fungi in an LCRS can eventually result in clogging of the drainage media either because of sedimentation of the system with biological by-products or because of growths which attach themselves to the media and close off the drainage voids. Ramke (1986) describes mechanisms related to biological activity which could result in clogging. Further information is also presented by Bass (1986). Clogging of an LCRS above a top liner in a landfill or a waste pile would allow the hydraulic head to increase and could contribute to rupture of the FML; clogging of an LCRS between the two liners of a double-liner system would prevent detection of a leak in the top liner and prevent removal of the liquids entering the system.

An engineer needs to consider the potential for biological clogging in designing an LCRS for a containment unit. The design should include features that allow inspection of the drainage system. In addition, in case clogging does eventually develop, procedures for remedial action should be explored, and procedures compatible with the design need to be described. Flushing the system periodically with biocides is one method that may prevent biological clogging; however, the biocide needs to be environmentally safe, and it should be demonstrated that the biocide does not adversely affect the FML and the other polymeric components of the lining system, including synthetic drainage materials if they have been included in the design. Design considerations for avoiding clogging are discussed by Ramke (1986) and Bass (1986).

7.3.1.4.4 Presence of organic material in the subgrade soil--The presence of decomposing organic material in a soil below a lining system can cause a variety of problems. Organic material, unless it has already degraded to terminal products, can generate gases (principally methane and carbon dioxide) through natural decay processes. In addition, tree trunks and extensive root systems can create voids beneath the liner. If gases are generated beneath a liner, they may collect to the extent that the liner is pushed upward from the subgrade. In the case of a surface impoundment, FML displacement by gases can result in the "whale back" effect where large portions of liner rise up and out of the liquid being impounded (like a balloon), eventually rupturing or requiring puncturing to release the trapped gases. In addition, the development of "whale backs" can substantially reduce the capacity of the impoundment. The decay of organic material can also create voids which lead to slumping of the foundation, subsequent liner shifting, and potential liner failure.

The installation of a gas venting system in conjunction with the removal of organic material may be necessary if the soil contains organic material, or if other gas problems are known for the particular site. In order to encourage gas movement out from underneath a containment unit, the underside of the unit needs to slope upwards with a minimum grade of 2% from a low point. Since the venting system must contain porous materials with sufficient transmissivity to allow gases to move underneath the entire unit and provide a way of conveying collected gases to the atmosphere, it may also serve as an underdrain. The designer may decide to provide for the collection and removal of liquids (e.g. perched groundwater) as well as the safe discharge of the vented gases.

7.3.2 Statutory and Regulatory Requirements and EPA Guidance for Waste Containment Units

The designer of a waste containment unit must be aware of the current statutory and regulatory minimum design and operating requirements for waste containment units. RCRA, which was passed in 1976, mandated that the EPA promulgate regulations establishing performance standards and requirements for the location, design, construction, and operation of solid waste TSDFs. In response to this requirement, the EPA has codified performance standards for solid waste TSDFs, set minimum technological requirements for hazardous waste TSDFs, and developed draft minimum technology guidance documents on the design, construction, and operation of hazardous waste TSDFs for comment and use. In 1984, passage of HSWA established the double-liner requirement for new hazardous waste landfills and surface impoundments, except under those conditions that meet criteria for statutory variance.

This section reviews present (as of May 1988) statutory requirements, EPA regulations, and EPA guidance concerning the design of hazardous and nonhazardous solid waste TSDFs. It should be noted that these regulations are under continuous review; it should also be noted that, in addition to EPA regulations, state and local regulations may apply to the design of waste containment units at a particular site.

7.3.2.1 Performance Criteria for Solid Waste TSDFs--

The EPA regulations describing performance criteria for the design and operation of solid waste TSDFs are presented in 40 CFR 257. These criteria state general performance standards for determining whether a solid waste TSDF poses a reasonable probability of adverse effects on health or the environment in relation to:

- Performance within a floodplain.
- The effect of the unit or practice on endangered species.
- The effect of the unit or practice on surface water.
- The effect of the unit or practice on groundwater.
- The application of wastes containing cadmium or polychlorinated biphenyls (PCBs) to land used for the production of food-chain crops.
- The potential for disease propagation resulting from the unit or practice (e.g. by disease vectors such as rodents, flies, and mosquitoes capable of transmitting diseases to humans and by the handling of sewage sludge and septic tank pumpings).
- The effect of the unit or practice on air quality (with particular reference to the open burning of wastes).
- The safety of the unit or practice (with particular reference to the concentration of explosive gases, potential for fire hazard, bird hazards to aircraft, and uncontrolled public access so as to expose the public to potential health and safety hazards at the disposal site).

At present (May 1988), the criteria set forth by EPA in 40 CFR 257 are the only Federal regulatory requirements for the design of containment units for managing wastes subject to regulation under RCRA Subtitle D (i.e. non-hazardous wastes). Further proposed rules relating to the design, construction, and operation of Subtitle D waste containment units are due to be released by the EPA for public comment in the near future.

7.3.2.2 Statutory and Regulatory Requirements for the Design of Hazardous Waste TSDFs--

As knowledge about the environmental effects of the land disposal of hazardous wastes increased, Congress amended RCRA in 1984 with HSWA, which established minimum technological requirements for the design and construction of new hazardous waste landfills or surface impoundments, except in cases where the conditions for statutory variance are met. These minimum requirements include [Sec. 3004(o)(1)(A)]:

- The installation of two or more liners and a leachate collection system above (in the case of a landfill) and between such liners.
- Groundwater monitoring around the landfill or surface impoundment.

HSWA also required the EPA to promulgate regulations or issue guidance documents regarding the implementation of the minimum technology requirements. Since then, the EPA has promulgated regulations detailing operation and design requirements for hazardous waste TDSFs (40 CFR 264). The EPA has also issued a draft minimum technology guidance document on double liner systems for landfills and surface impoundments (EPA, 1985) and a similar document on final covers for landfills and surface impoundments (EPA, 1987a). Both the minimum technology requirement regulations and the technology guidance documents are presently under review. EPA eventually will formalize technology guidelines by incorporating them into the Agency's regulations.

A proposed rule was issued in March 1986 (EPA, 1986a), and a second notice presenting additional information on the performance of bottom liners in double-lined landfills and surface impoundments was issued in October 1986 (EPA, 1986b). Further proposed minimum technology requirements, particularly with reference to the leachate detection, collection, and removal systems, were published in another proposed rule issued in May 1987 (EPA, 1987b). The EPA is in the process of developing a final rule for double liner and leachate detection, collection, and removal systems, which is scheduled for May 1989 publication.

This section describes the present EPA regulations (as of May 1988) concerning the lining system design requirements for new hazardous waste piles, surface impoundments, and landfills. Section 7.3.2.3 discusses the double liner and final cover systems described in the draft minimum guidance technology documents.

7.3.2.2.1 Design Requirements for Hazardous Waste Piles--Except for those units exempted by regulation, a regional administrator of the EPA, or some other regulatory agency, EPA regulations state that a waste pile must have [40 CFR 264.251 (1986 ed.)]:

- (a)(1) A liner that is designed, constructed, and installed to prevent any migration of wastes out of the pile into the adjacent subsurface soil or groundwater or surface water at any time during the active life (including the closure period) of the waste pile. The liner may be constructed of materials that may allow waste to migrate into the liner itself (but not into the adjacent subsurface soil or groundwater or surface water) during the active life of the facility. The liner must be:
 - (i) Constructed of materials that have appropriate chemical properties and sufficient strength and thickness to prevent failure due to pressure gradients (including static head and external hydrogeologic forces), physical contact with

the waste or leachate to which they are exposed, climatic conditions, the stress of installation, and the stress of daily operation;

- (ii) Placed upon a foundation or base capable of providing support to the liner and resistance to pressure gradients above and below the liner to prevent failure of the liner due to settlement, compression, or uplift; and
 - (iii) Installed to cover all surrounding earth likely to be in contact with the waste or leachate.
- (2) A leachate collection and removal system immediately above the liner that is designed, constructed, maintained, and operated to collect and remove leachate from the pile....The leachate depth over the liner [must] not exceed 30 cm (1 ft). The leachate collection and removal system must be:

- (i) Constructed of materials that are:
 - (A) Chemically resistant to the waste managed in the pile and the leachate expected to be generated; and
 - (B) Of sufficient strength and thickness to prevent collapse under the pressures exerted by overlaying wastes, waste cover materials, and by any equipment used at the pile; and
- (ii) Designed and operated to function without clogging through the scheduled closure of the waste pile.

The regulations also require a waste pile to have a run-on control system which prevents flow onto the active portion of the pile during peak discharge from at least a 24-hour, 25-year storm and a run-off management system to collect and control at least the water volume resulting from a 24-hour, 25-year storm. If the pile contains any particulate matter that may be subject to wind dispersal, the pile must be covered or otherwise managed to prevent dispersal.

In essence, these regulations were written so as to allow the use of a single soil or FML liner. However, ultimate design specifications for new facilities still need the approval of a regulatory agency, i.e. either the EPA or a state agency. Regulations extending the double-liner requirements to new hazardous waste piles have been proposed (EPA, 1987b).

7.3.2.2.2 Design Requirements for Hazardous Waste Surface Impoundments--Except for those units exempted by regulation, a regional administrator of the EPA, or some other regulatory agency, EPA regulations state that all new surface impoundments must have [40 CFR 264.221 (1986 ed.)]:

...Two or more liners and a leachate collection system between such liners. The liners and leachate collection system must protect human health and the environment....The requirement for the installation of two or more liners...may be satisfied by the installation of a top liner designed, operated and constructed of materials to prevent the migration of any constituent into such liner during the period such facility remains in operation (including any post-closure monitoring period), and a lower liner designed, operated, and constructed to prevent the migration of any constituent through such liner during such period. For the purpose of the preceding sentence, a lower liner shall be deemed to satisfy such requirement if it is constructed of at least a 3-ft thick layer of recompacted clay or other natural material with a permeability of no more than 1×10^{-7} centimeter per second.

The regulation concerning the top liner of the double liner system was written so as to require the use of an FML. The regulations also require that a surface impoundment must function without overtopping and that the embankments for an impoundment must maintain their structural integrity and that their structural integrity must be ensured without assuming that the liner system will not leak during the active life of the unit. Requirements for the structural integrity in the service environment, placement, and coverage of the liners and the requirements for the leachate collection system parallel those for waste piles.

7.3.2.2.3 Design Requirements for Hazardous Waste Landfills--Except for those landfills exempted by regulation, a regional administrator of the EPA, or some other regulatory agency, the EPA requirements for lining a new hazardous waste landfill parallel those for surface impoundments except that a leachate collection system is required above as well as between the two liners [40 CFR 264.301 (1986 ed.)]. The requirements for a run-on control system, a run off management system, and control of particulate matter to prevent wind dispersal are the same as those for waste piles.

7.3.2.3 Draft EPA Guidance on Hazardous Waste Containment Units--

The present regulations promulgated by the EPA often represent design goals rather than actual technological requirements for the design of hazardous waste containment units; one example is the clause that "the liners and leachate collection system must protect human health and the environment," which applies to both new surface impoundments and landfills. In order to clarify implementation of the regulations and to allow for public review of this guidance, the EPA released draft Minimum Technology Guidance (MTG) documents on double liner and final cover systems for landfills and surface

impoundments, including guidance on design, construction, and operation (EPA, 1985; EPA, 1987a). These documents were prepared as part of the process of writing minimum technology regulations for the design, construction, and closure of hazardous waste containment units and facilities.

This section discusses the double liner and final cover systems described in the draft MTG documents. The minimum requirements for each component of these systems are discussed in more detail in Section 7.5.

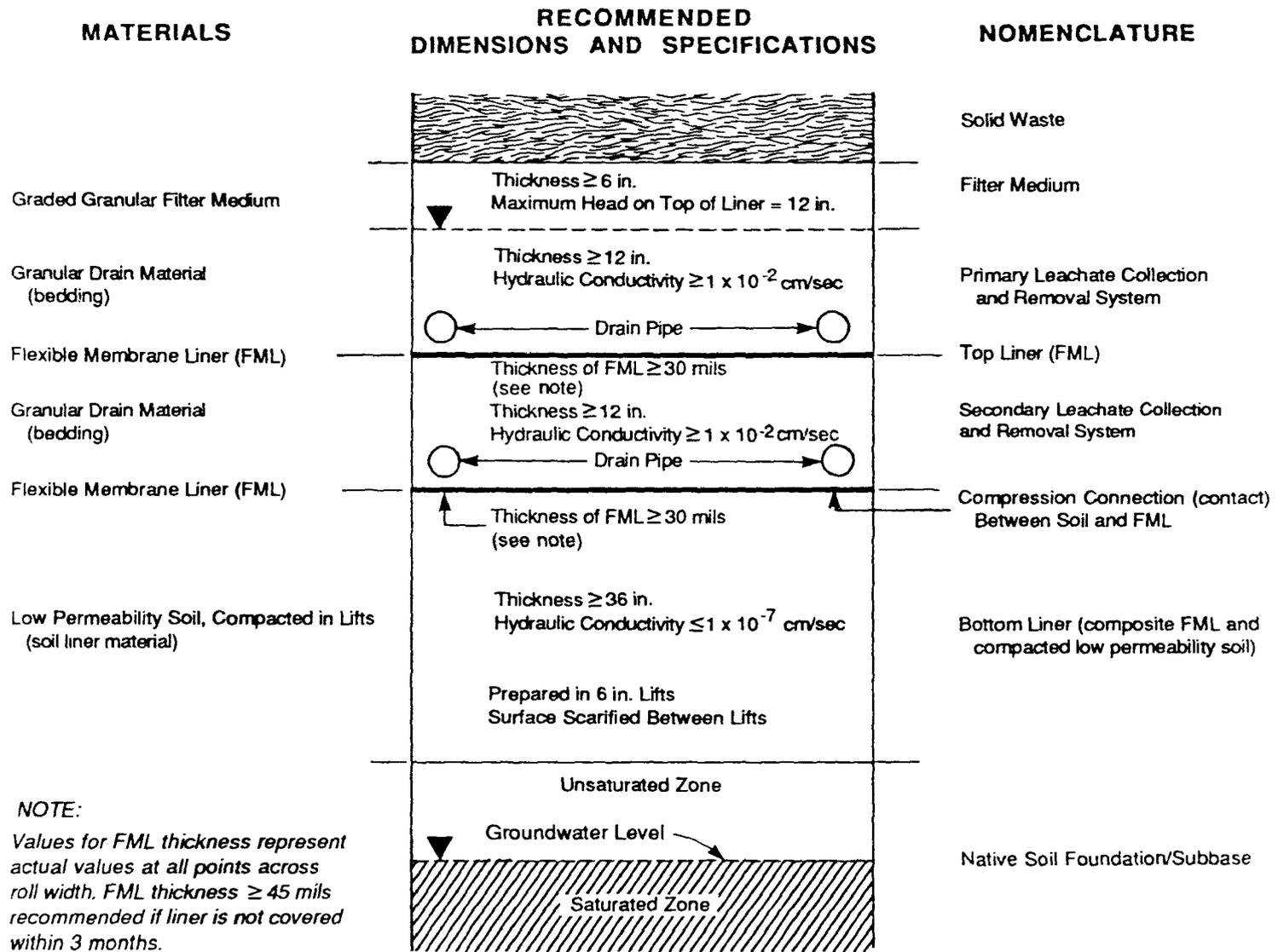
7.3.2.3.1 Draft EPA Guidance on Double Liner Systems--In the draft minimum technology guidance document on double liner systems for hazardous waste landfills and surface impoundments, two double liner systems are described: an FML/composite double liner system and an FML/compacted soil double liner system (EPA, 1985). Insofar as concern has arisen with respect to the latter system, only the FML/composite double liner is described in this section.

The FML/composite double liner system for a hazardous waste landfill consists, at a minimum, of a primary leachate collection and removal system (LCRS), a top FML liner, a secondary LCRS, and a bottom composite FML/low-permeability soil liner. The secondary LCRS is also referred to as the leak detection, collection and removal system (LDCRS). The lining system for a surface impoundment is the same except that there is no primary LCRS. A schematic cross section showing the basic components of the FML/composite double liner system for landfill and surface impoundment units is presented in Figure 7-6, which also presents the basic requirements for each component. The thickness requirements for the LCRSs only apply if granular media are used. LCRSs based on synthetic polymeric materials (e.g. geonets, geocomposites, synthetic filters) may also be used if it is demonstrated that they are equivalent to "conventional" granular systems with pipes, i.e. if they meet the design requirements for drainage, ability to withstand expected overburden pressures while maintaining their drainage capabilities, chemical resistance, etc.

Each component of the lining system is intended to fulfill a specific function and should meet the stated design requirements. The function of the primary LCRS at a landfill is to minimize the head (depth) of leachate on the top liner during the active life of the landfill unit and to remove liquids through the post-closure care period, which for design purposes is nominally assumed to be 30 years. The primary LCRS must be capable of maintaining a leachate head of less than 1 foot. The recommended thickness for a graded granular filter medium is greater than or equal to 6 inches. A granular drainage medium is recommended to have a thickness of 12 in. or greater and a hydraulic conductivity greater than or equal to 1×10^{-2} cm s⁻¹.

The top liner should be designed, constructed, operated, and maintained to control the escape of waste constituents during operation of the unit including the post-closure care period. At a minimum, this liner should consist of an FML with a minimum actual (not nominal) thickness of 30 mils. The draft guidance document also suggested a requirement that the FML should

7-24



NOTE:
 Values for FML thickness represent actual values at all points across roll width. FML thickness ≥ 45 mils recommended if liner is not covered within 3 months.

Figure 7-6. Schematic profile of an FML/composite double-liner system for a hazardous waste landfill presenting EPA draft guidance. Synthetic drainage media and synthetic filter media can be used instead of granular media if equivalency performance is demonstrated. (Based on EPA, 1985).

allow no more than de minimis leakage of all polluting species through the liner itself. The concept of de minimis comes from the legal principle, "de minimis non curat lex" (i.e. the law does not concern itself with trifles). De minimis leakage is considered to be that amount which is of no threat to human health or the environment. The allowance for de minimis leakage was in recognition of the fact that FMLs, since they are not impermeable, will allow some transmission of waste constituents, e.g. via vapor transmission or very small imperfections.

The EPA is presently (June, 1988) reevaluating the use of the term de minimis and the requirement that an installed FML allow no more than de minimis leakage. In recently proposed regulations, the EPA discusses leakage through a top liner in terms of an action leakage rate (ALR) (EPA, 1987b). The ALR constitutes a trigger for initiating interactions between the owner/operator and the EPA and the implementation of a predetermined response action plan (RAP). The EPA has proposed an ALR of 5 to 20 gpad, which the EPA believes is representative of a high level of construction quality assurance at surface impoundments, or alternatively a site-specific ALR. In the proposed regulations, RAPs are required for at least two leakage rates:

- Rapid and extremely large leakage (RLL), which is defined as the maximum design leakage rate that the secondary LCRS can remove under gravity flow conditions.
- Leaks less than rapid and extremely large but greater than the ALR.

For leaks that exceed the ALR but are less than rapid and large, the EPA considers acceptable responses to include:

- Terminating receipt of waste and closing the unit.
- Repairing any leaks expeditiously.
- Instituting operational changes to reduce leakage into the LCRS between the liners.
- Collecting and removing leachate, and, in addition, accelerating groundwater monitoring.
- Maintaining current operating procedures (including the collection and removal of leachate).

The secondary LCRS between the two liners should be designed, constructed, operated, monitored, and maintained to rapidly detect, collect, and remove liquids entering the the collection system for treatment through the post-closure care period. The recommendations for thickness and hydraulic conductivity are the same as those for the drain material component of the primary LCRS.

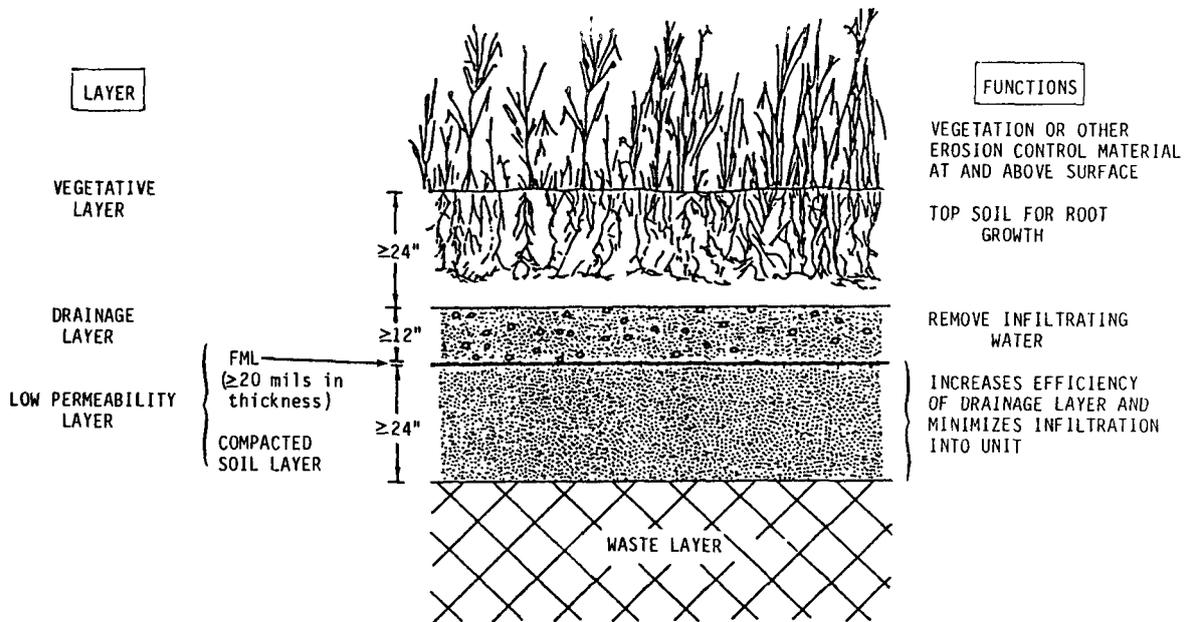
The bottom liner consists of two components, an FML and a low-permeability soil liner, which are intended to function as one system; hence, the term "composite" liner. Like the top liner, the upper (FML) component of the bottom liner should be designed, operated, and constructed to prevent migration of any constituent of the waste liquid into the liner during the period of facility operation, including the post-closure care period. The recommended minimum thickness is 30 mils. The lower (soil) component of the bottom liner should be designed, operated, and constructed to minimize migration of any constituent of the waste liquid or leachate through the upper component if a breach in the upper component were to occur prior to the end of facility operation, including the post-closure care period. The recommended thickness and hydraulic conductivity of the soil component reflect the regulatory requirements (Section 7.3.2.2). The EPA believes that this design is effective in protecting human health and the environment because the combination of the two components in the bottom liner system provides for virtually complete removal of waste or leachate by the secondary LCRS if a leak were to occur in the top liner.

The guidance on the minimum requirements is described in more detail in Section 7.5, which describes design options for components of a complete liner system. Also described in that section is the double composite liner option in which the top liner consists of a composite liner such as has been suggested by Buranek and Pacey (1987), Buranek (1987), and other designers.

7.3.2.3.2 Draft EPA Guidance on Final Cover Systems--The draft document presenting the EPA's minimum technology guidance on final covers for hazardous waste landfills (EPA, 1987a) recommends a multilayer design (Figure 7-7) consisting of the following layers from top to bottom:

- A vegetative layer consisting of an erosion control component (vegetation, gravel, etc.) and a 24-in. (60-cm) minimum thickness top soil component. The top of the layer should have a final slope, after allowance for settling and subsidence, of between 3 and 5%, including side slopes to prevent pooling due to irregularities of the surface and or vegetation, and excessive erosion. Erosion for any part of the cover should not exceed 2.0 ton/acre/year, using the U.S. Department of Agriculture Universal Soil Loss Equation (USLE).
- A drainage layer. If composed of sand, it should have a 12-in. (30-cm) minimum thickness to prevent ponding on the underlying low-permeability layer and to remove water that infiltrates through the top layer of the cover. This layer also serves as a protective bedding for the FML. The drainage media should have a minimum hydraulic conductivity of $1 \times 10^{-2} \text{ cm s}^{-1}$, and the final bottom slope after allowance for settlement should be at least 2%. A drainage system based on synthetic materials can also be used if it is demonstrated that the synthetic system is equivalent to the recommended granular system.

- A low-permeability layer which includes an FML with a minimum thickness of 20 mils, and a minimum of 24 in. (60 cm) of compacted soil which should have an in-place saturated hydraulic conductivity of $1 \times 10^{-7} \text{ cm s}^{-1}$ or less. This layer serves to increase liquid removal efficiency in the drainage layer and provides added backup for minimizing liquid infiltration.



NOTE: GRANULAR OR GEOTEXTILE FILTERS AS APPROPRIATE ARE TO BE INSTALLED BETWEEN LAYERS.

Figure 7-7. Cover system design recommended by EPA guidance (Source: EPA, 1987a).

The EPA recognizes that there may be specific cases where an alternative design (e.g. fewer layers or optional layers) may be applicable. For instance, in extremely arid regions, a gravel mulch may be needed over the topsoil to compensate for lower vegetative coverage or the drainage layer may not be required. In areas where burrowing animals may damage the low-permeability layer, it may be necessary to place a stone layer above the FML component. At a unit that is expected to produce gases, a gas-venting layer between the waste and the low-permeability layer would be needed.

7.4 SITE INVESTIGATION

As with any earthwork project, a waste containment unit must be designed for the geological conditions at the specific site because of the subsurface

heterogeneity and spatial variability that is the rule in most geologic settings. In addition, because the particular site may have been selected for reasons other than its technical suitability for a containment unit, a thorough site investigation is necessary in order to reveal conditions that may require special design considerations. It is assumed that a preliminary site investigation was performed as part of the site selection process and that this investigation showed the suitability of constructing a waste containment unit at the particular site.

Site investigations are conducted to delineate a site's topography, subsurface geology, and hydrogeology. Ways in which these factors can affect a design are discussed in Section 7.3. Steps of a site investigation include the following:

- Compilation and review of existing data and information.
- A site reconnaissance.
- Indirect subsurface investigation.
- Direct subsurface investigation.
- Field tests to determine soil characteristics.
- Groundwater studies.
- Laboratory tests to determine soil characteristics.

Site investigations usually begin with compilation and review of existing information that pertain to the site. Sources of information include Soil Conservation Service County Soil Surveys, U.S. Geological Survey topographic and surficial geology maps, aerial photographs, published literature, state geological survey information, and county records of geotechnical tests associated with previous construction projects. This information can be very useful for planning the scope and approach of further site investigation activities. The compilation and review should include data on the geohydrologic regime of the region surrounding the site.

The design team visits the site to confirm how existing recorded data and information correspond to conditions at the site. The reconnaissance involves a complete walk-through of the site and observation of vegetation, soil cover, soil types, rock outcrops, and any other conditions that could affect the facility design. Observation of soil properties is based largely on visual classification.

Indirect subsurface investigations, which are also known as geophysical or nondestructive test evaluations, study the materials below the ground surface without actual penetration into the subsurface materials. Indirect subsurface investigative techniques include electrical resistivity and inductance methods, electro-magnetic survey methods, seismic refraction, and ground-penetrating radar. The use of a particular investigative technique

can depend to a large degree on the geologic setting (White and Brandwein, 1982). Electrical resistivity and/or inductance surveying can be used to locate the water table as well as the presence of subsurface layers or lenses of different permeability that have contrasting resistivities (EPA, 1978; Freeze and Cherry, 1979). Seismic refraction surveys can provide information on the depth to bedrock, topography of the bedrock, and some physical properties of the subsurface soil (Cichowicz et al, 1981; Dobrin, 1960). Ground-penetrating radar can be used to locate buried structures and pipes, and for indicating depth to shallow bedrock (White and Brandwein, 1982). Proton precession magnetometry, metal detectors, and electrical inductance devices have also been used with varying degrees of success (Lord and Koerner, 1987). These indirect techniques can be used to reduce the cost of direct investigative techniques, such as drilling and laboratory testing, by providing a large amount of information at a relatively low cost. This information can also be used in planning direct site investigations which can then be carried out as economically and as efficiently as possible. Unfortunately, most of these methods require a good deal of skill to interpret the test results.

Direct methods of investigating the subsurface include drilling boreholes and wells and excavating pits and trenches. The purpose of these methods is to expose subsurface material so that the physical conditions can be directly observed and measured (e.g. faults, slickensides, sand seams, depth to bedrock and to the water table, penetration tests, and in situ permeability) and to obtain samples of surface material for laboratory testing of engineering properties. Exploratory methods are described by the Bureau of Reclamation (1974). Methods of testing the soils are described by the Bureau of Reclamation (1974) and in ASTM Part 4.08. Methods of testing soils are also discussed by Goldman et al (1985) and by Spigolon and Kelley (1984). Detailed discussions of techniques for general geotechnical site investigations may also be found in Winterkorn and Fang (1975) and Hunt (1984).

Geohydrologic site investigations are necessary for planning the groundwater monitoring system and for estimating hydraulic stresses that can act on the unit so that they can be properly considered during unit design. In conjunction with existing data, these investigations are used to define:

- The location and extent of aquifers underlying the site. These investigations define not only the "uppermost" aquifer, but at a minimum the next aquifer below and all underground sources of drinking water.
- The direction and rate of flow in and between the aquifers.
- The nature of the aquitards, i.e. the geologic barriers to flow between the aquifers, and their effectiveness in preventing flow.
- Geochemistry of the groundwater in the different aquifers. Knowledge of the chemistry of the groundwater in the different aquifers prior to construction of the TSD unit is necessary to properly evaluate the results of monitoring the aquifers once the unit is in service.

Further information on conducting hydrogeologic investigations and on installing monitoring wells and piezometers may be found in U.S. Environmental Protection Agency (1983), Fenn et al (1977), Johnson Division (1975), Lutton et al (1983), EPRI (1985), and Dunicliff (1988).

7.5 DESIGN OF COMPONENTS OF A LINING SYSTEM

The lining system for waste containment units is made up of a number of different components. In the context of this document, the term "lining system" includes the lining materials and all of the materials and components that comprise the leachate collection systems. For example, the "lining system" for a new hazardous waste landfill or the lateral extension of an existing landfill must have:

- A foundation.
- Sidewalls.
- A bottom composite liner.
- A leak-detection system between the top and bottom liners.
- A top liner.
- A leachate collection system on top of the top liner.

Depending on the containment design, a protective soil cover may be placed above the leachate collection system on top of the top liner. In addition, various ancillary components, including anchor trenches, sumps associated with the leachate collection and leak-detection systems, etc., are also a part of the whole system. Finally, when a landfill is closed, a cover system needs to be placed over the whole landfill which is also constructed with a number of different components, including a cap drainage and collection system, cover soil, and venting systems (Lutton, 1986).

This section describes approaches to the design of the various components of a lining system with particular reference to the design of a hazardous waste landfill. It should be noted that the components of a lining system for a hazardous waste surface impoundment are the same as those for a hazardous waste landfill except that there is no leachate collection and removal system above the top liner. This section also discusses ways in which a choice in designing one component may affect the design of the other components. The design requirements for hazardous waste containment units proposed in the draft Minimum Technology Guidance documents (EPA, 1985; EPA 1987a) are discussed in detail. Even though most of the information presented in this section refers to the design of hazardous waste containment units, much of this information is also applicable to the design of non-hazardous waste units. Engineering equations for many design problems dealing with polymeric components and their interaction with various components of the lining system have been developed by Richardson and Koerner (1987).

7.5.1 Foundation Design

A foundation should provide a structurally stable subgrade for the overlying components and wastes. Thus, a foundation should resist consolidation, differential settlement, and uplift resulting from pressures inside or outside the containment unit, thereby preventing distortion of overlying components. In addition, the foundation should provide complete and integral contact with the overlying liner or other component of the lining system.

The exact design for the foundation will depend on the geologic, hydrologic, and hydrogeologic conditions that exist at the specific site. In particular, the design is a response to the conditions at the site which may require special design considerations. The presence of any soil heterogeneities should have been observed as part of the site investigation. Settlement analyses may have revealed soils which have significantly different settlement characteristics which may require removal of some soil or homogenization, e.g. collapsible soils which are unsaturated soils that can experience large settlements when wetted and loaded. The site investigation may also have revealed soil heterogeneities such as large cracks, sand seams, sand lenses, and slickensides which may also require special design considerations. The construction of units below the water table (intragradient facilities) presents problems due to seepage and hydraulic forces on the liner system.

Goldman et al (1985) report that, given that site topography is fairly uniform and significant soil heterogeneities are not present, settlement is usually not a problem for the foundations of a clay liner, e.g. the soil component of the bottom liner, because most clay liners are sufficiently thick and elastic to withstand some differential settlement of the foundation soils. The greater the thickness and elasticity of the clay liner the greater the tolerance range for differential settlement. However, Goldman et al (1985) also report that several design engineers recommend excavating and recompacting the upper 1 to 2 ft of foundation soil to control local settlement and seepage before installing a clay liner. Some facility components, such as footings for pile-type structures used to gain access to sumps, and underdrain systems which may be required for some facilities, will require special design considerations to prevent localized settlement under load.

Seepage into the unit, which can occur in intragradient facilities, must be controlled. Potential problems associated with the construction of intragradient facilities are discussed by Goldman et al (1985). An underdrain system may be necessary where there is a high groundwater table or a source of water infiltration. Underdrain systems may serve the purpose of transmitting fluids beneath and through the impoundment site without interaction with any contaminants from the containment unit. In addition, an underdrain (or venting) system may be used to prevent the buildup of gases underneath a containment unit (see Section 7.3.1.4.3). In the design of units other than hazardous waste containment units, the underdrain system may function as a leak-detection system.

The basic design of an underdrain or a pressure relief system, which is similar to that of a leachate collection and removal system, depends on the intended purpose of the system. For example, a pressure relief system built underneath a landfill may only be used during construction until the fill placed on top is capable of counterbalancing uplift forces acting on the base of the lining system. Thus, no system may be required for collecting and removing liquids present in the underdrain. The subcomponents of an underdrain generally include the following:

- A drainage system that allows rapid movement of liquids and/or gases.
- A collection system for conveying what is present in the drainage medium to points for collection and removal from the underdrain system, e.g. a sump.
- A system for conveying what is collected by the underdrain system out from underneath the containment unit, e.g. pumps and closed pipes.
- A system for disposing of what is collected by the underdrain system.

Depending on the function of the underdrain system, the drainage system will intercept any liquids resulting from leakage or natural drainage or gases pushing up on the base of the lining system. The drainage system may underlie the entire unit, including the sidewalls, or it may underlie one particular section of the unit, e.g. if the underdrain system is designed to handle a specific spring, etc. If the underdrain system is intended to remove liquids that are flowing downwards into the drainage system, the underdrain system needs to have a base layer of low permeability to allow the drainage system to collect liquids efficiently. In addition, the drainage system needs to be sloped to promote the movement of gases (to a venting system at a high point) and/or liquids (to a sump at a low point). Materials used in underdrain drainage systems have included select gravel and open-graded asphalt (Kays, 1986). Measures to prevent the interaction of the layers immediately above and below the drainage system need to be considered. For example, a covering layer may be required to protect the overlying liner (e.g. an FML in a design for a pond for containing nonhazardous liquids) from penetration by the drainage materials. Materials that have been used include geotextiles, geonets, graded earth, and coarse sand.

Filters are required where there is a danger of the lining material fines (i.e. of a clay soil liner) or of the soil underneath the underdrain working into the drainage system. Granular filters constructed in the field or geotextile filters can be used. The purpose of the filter is to stop the migration of particles within the system and simultaneously allow the uninhibited flow of liquids. The movement of particles into any part of the underdrain system can, and will, eventually inhibit the acceptable operation of an underdrain system. Any sign of turbidity in liquid issuing through the underdrain system could be a sign that the filtering system may be failing.

The function of the drainage system is to convey seeping fluids to collectors, which are generally located in blankets or trenches underneath the unit. The number of feeding collectors is dependent on the size of the unit and the basic design of the collection system. Underdrain tile and perforated pipe have been used for the collection system.

The underdrain monitoring system feeds into a closed pipe system which needs to be sized to handle more than the expected maximum flow, as any back-up within the system can cause serious repercussions (e.g. instability of the embankment). Kays (1986) advised that pipes should terminate in sumps, channels, drains, or concrete exit structures.

Depending on the function of the underdrain and the containment unit as a whole, the underdrain monitoring system may be designed to allow any leakage from the unit to be detected and managed. Some units have pumping arrangements whereby leakage and underflow are pumped and returned directly into the unit, while others collect the liquids that are present and dispose of them off site.

A critical need for an adequate drainage system may exist if groundwater is present immediately below the unit. A well-designed underdrain system would minimize or eliminate (1) reverse hydrostatic pressure and (2) removal of soil from beneath the liner due to groundwater flow. Reverse hydrostatic pressure occurs when the groundwater level exceeds the operating water level in the unit. This could occur, for example, during normal level fluctuations in a drinking water reservoir. The groundwater reverse pressure can then push on the back side of the lining system, causing liner failure. Soil may be removed by groundwater flow below a liner, eventually causing the liner to rupture. If possible, sites where high groundwater exists should be avoided.

7.5.2 Design of Embankments

The purpose of an embankment in a waste containment unit is to function as a sloped retaining wall that provides passive restraint to resist the lateral forces of the stored wastes and to provide support to the overlying facility components. Embankments can be either aboveground extensions of the foundation or separate earthwork constructions placed above the foundation. They must be designed, constructed, and maintained with sufficient structural stability to prevent their failure. If the overall facility design calls for a number of units within the facility either to separate different wastes or to limit the size of an individual unit, embankments can also be used as walls between the units, thereby creating "cells" within the facility.

Embankments can be constructed of soil material that is compacted as necessary to a specified strength, unlike soil liner materials which are compacted for low permeability. Embankments can also be constructed simultaneously with the soil liner component in a series of horizontal lifts, as is shown in Figure 7-8. Materials other than soils can be used to construct embankments, provided that the embankment design accommodates the properties of the particular material being used and proper construction procedures are

followed. Even though seepage through the embankment should be prevented by the overlying lining system, drainage layers and structures can be included in the embankment design because the embankments must be designed to maintain their integrity even if the lining system fails and seepage occurs.

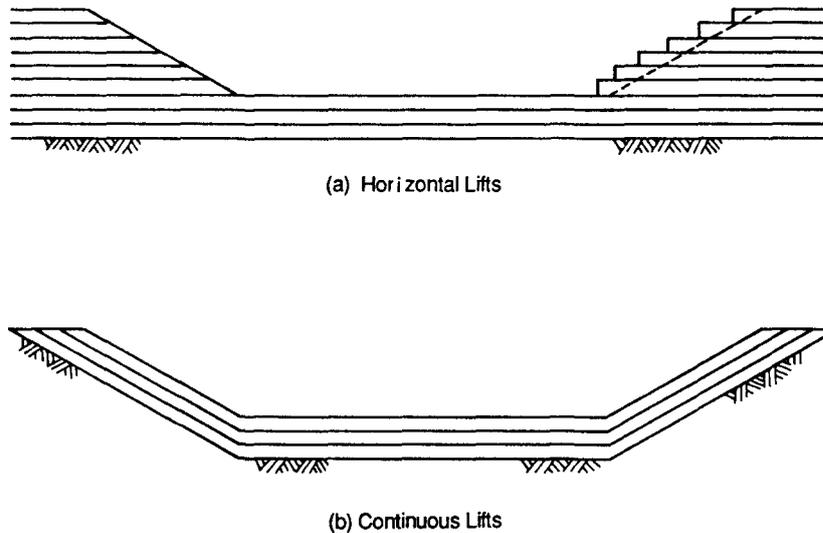


Figure 7-8. Methods of liner and sidewall compaction. (Source: Goldman et al, 1985, p 5-20).

The use of embankments in a containment unit will depend on whether the unit is constructed above grade, excavated, or a combination of the two. Above-grade units may be preferred if the costs for constructing embankments is less expensive than excavation and in cases where the location of the water table may limit the depth of excavation. In addition, there is less uncertainty in the design and construction of embankments than there is for cut slopes because properties of engineered embankments can be more closely controlled by limiting variations in material type and by uniform compaction efforts. The natural soil variations that can be present in cut slopes can result in uncontrolled differential settlement or other problems.

In designing embankments for waste containment units to be lined with FMLs, the designer must make decisions concerning the following:

- Whether the embankment should be constructed as part of the soil liner, i.e. in horizontal lifts. Construction in horizontal lifts results in more stable slopes and allows steeper slopes than construction in continuous lifts. However, many engineers feel that continuous lift construction results in soil liners of lower permeability (Goldman et al, 1985).
- Whether to include a drainage layer or structure into the embankment, and if so, what type. Two types include rockfill toes and horizontal drainage blankets.

- How the embankment will be keyed into the foundation.
- Preparation of the foundation so that it has adequate bearing capacity to support the embankment and the overlying system components.
- Whether the embankment should be zoned or homogeneous (Figure 7-9). The requirement for both strong and low permeability material in a homogeneous embankment can result in a compromise in selecting the material. Embankments are often designed with zones of materials that each serve a separate function, e.g. one zone is for the structural stability of the embankment and another zone is compacted for low permeability to prevent flow through the embankment.

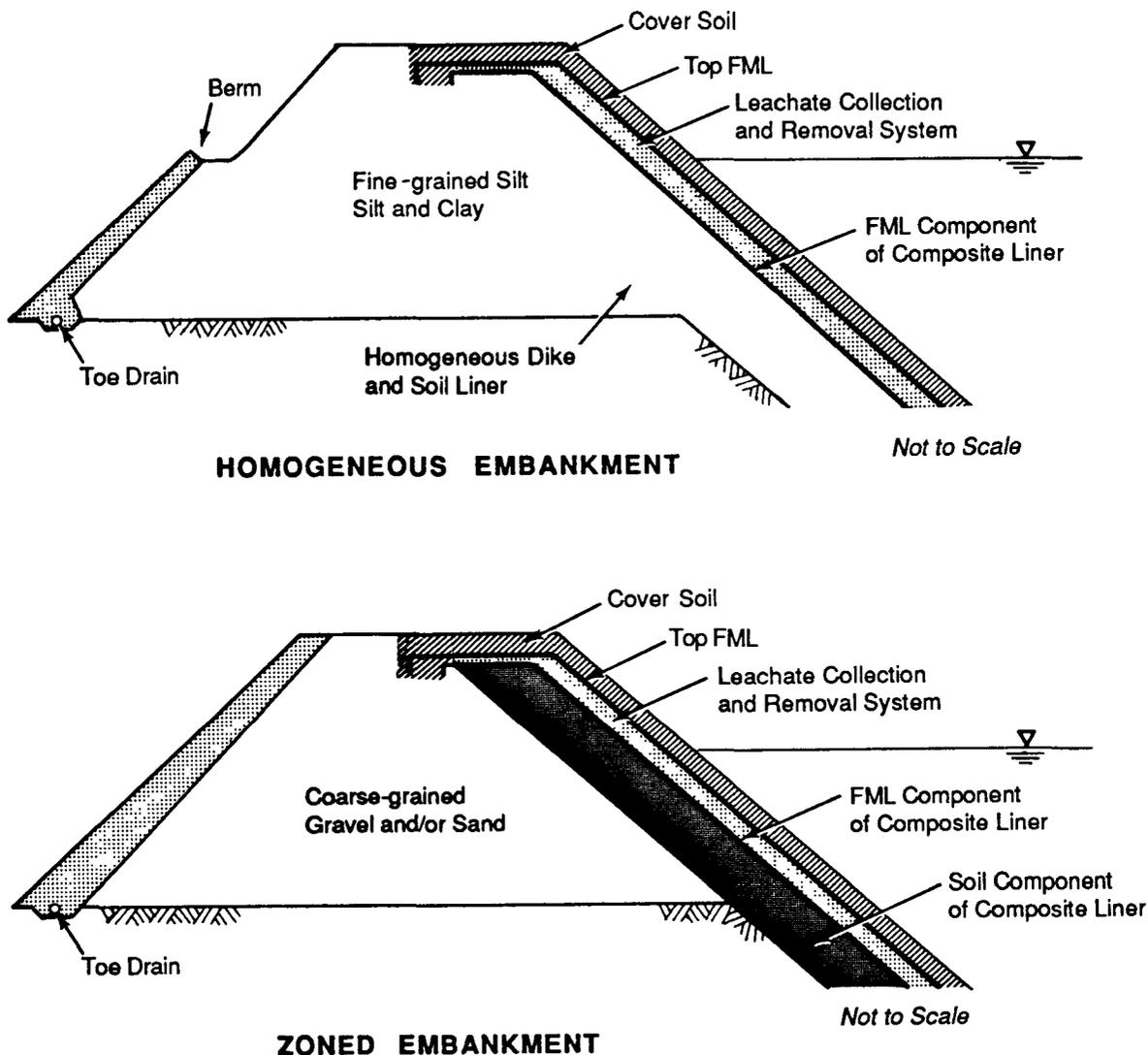


Figure 7-9. Schematic of homogeneous and zoned embankments for surface impoundments lined with FML/composite double liners. Slopes of actual embankments will be less steep.

- Selection of the materials for embankment construction. Potential fill materials for use in the construction of embankments should be evaluated for several engineering properties, including shear strength, permeability, settlement behavior, shrink/swell characteristics, and compaction characteristics.
- Slope of the embankments.
- Compaction requirements for the fill material. Actual requirements depend on the properties of the selected fill material and the use of the material in the embankment design. Design specifications usually specify minimum relative compaction effort (specified in percent of Standard or Modified Proctor maximum dry density) and compaction water content. Soils compacted for strength are usually compacted dry of optimum. The designer may also specify compaction equipment, number of passes, and/or load energy.
- Runoff diversion to prevent flow into the containment unit. In the case of a surface impoundment, run-off diversion helps prevent overflow, and in a landfill reduces the amount of leachate generated.
- Erosion protection of the outer slopes using berms or vegetation.
- Control of desiccation. In arid regions special designs incorporating gravel-filled troughs in the embankment crest have been used to prevent desiccation cracking. If the trough is kept filled with water, the exposed upper portion of the embankment can be kept moist (Goldman et al, 1985).

Designing the slopes of embankments and their relation to the design of the units are discussed in the following paragraphs.

The selection of a specific slope can depend on a combination of factors including the design limitations set by the use of specific construction materials including both the fill materials and any materials used to reinforce the slopes and limitations set by the effect a specific slope will have on the construction, installation, or performance of the overlying layers. The use of geogrids and geotextiles to reinforce slopes and intermediate berms has allowed designers to think in terms of steeper slopes which can allow for more efficient land use by increasing the capacity of the containment unit.

Because the friction angle of an FML to a specific soil is lower than the friction angle of the soil to itself, particularly for HDPE (see Section 4.2.2.5.5), the use of steeper slope angles will affect anchoring of the FML. In addition, if a soil cover is required to protect the FML, the slope angle is limited by the angle at which the soil cover begins to slough. If a granular drainage media, such as sand, is being used in leachate collection or leak-detection systems that extend up the slopes, the slope angle will be limited by the angle required to maintain the integrity of the drainage layer. Synthetic drainage layers on the slopes may require special anchoring.

The steepness of the embankment slopes can also affect the ability to install the various components of a lining system. In installing soil liners in continuous lifts, Boutwell and Donald (1982) report that a maximum slope of 2.5 to 1 (horizontal to vertical) is recommended for bulldozer operation and 2.8 to 1 when sheepsfoot rollers are used. The ability to install an FML on the slopes will depend on the liner type, the seaming technique, and the amount of seaming that needs to be performed on the slopes. Relatively heavy hand-held equipment, such as that used in extrusion fillet welding, may be difficult to control. The installation of a soil cover on top of an FML can also be affected. Morrison et al (1981) reports that FML manufacturers indicated that embankment slopes should be no steeper than 3 to 1 because, in cases where tracked vehicles were used to push soil cover material up slopes steeper than 3 to 1, the vehicles had begun to stall, spun their tracks through the soil cover, and damaged the FML. In the draft Minimum Technology Guidance document, the EPA suggests that slopes should be no steeper than 3 to 1 (EPA, 1985).

Once a trial slope angle has been selected, slope stability analyses are performed. A number of computational models are available for analyzing the stability of embankment slopes. Every slope contains numerous potential failure surfaces. The end product of an analysis of a given potential failure surface is the factor of safety (FS), defined as the summation of driving moments or forces tending to resist failure divided by the summation of moments or force tending to produce failure. It is necessary to make a trial and error search for the potential failure surface in the slope having the smallest FS. The more rigorous methods include the Simplified Bishop, Spencer, Janbu Simplified, Janbu Generalized, and Morgenstern-Price Methods, among others. Details of some of the various methods can be found in Lambe and Whitman (1979), Morgenstern and Price (1965), and Winterkorn and Fang (1975). In all of these methods, the body of soil within the failure mass is divided into a number of vertical slices that interact by means of forces transmitted along the sides of the slices. The methods vary principally in the assumptions regarding the location and inclination of the side forces necessary to solve the equations derived for the statically indeterminate system (Vick, 1983). The greatest source of uncertainty in slope stability analysis is in obtaining the laboratory-generated shear strength data. Meyers et al (1986) have developed, under the sponsorship of the EPA, a computer program for the stability analysis of embankments. It is a generalized program that includes dead loads, live loads, hydrostatic loads, etc., but not the use of reinforcement "inclusions."

If analysis of the desired slope indicates the need for slope reinforcement, the designer can explore the use of geotextiles and geogrids. Various schemes for the deployment of geotextiles or geogrids in the reinforcement of embankments are shown in Figure 7-10. The design process for reinforcing embankments with geotextiles and geogrids is a direct extension of soil slope stability analysis using plastic equilibrium concepts common to geotechnical engineering practice. Consider the soil slope shown in Figure 7-11a without reinforcement, and then the same slope, as shown in Figure 7-11b, reinforced with four layers of geogrid or geotextile. The design for

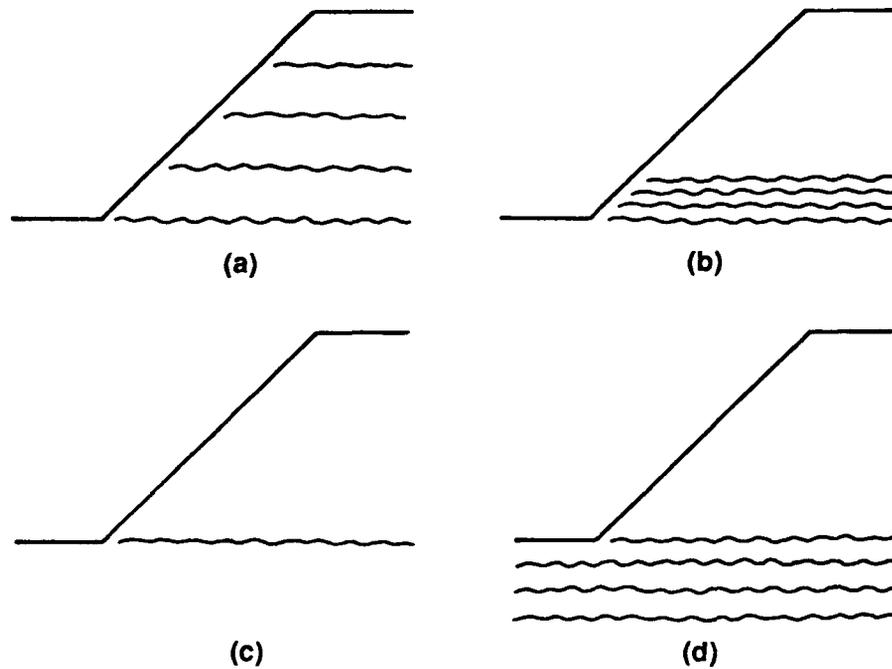


Figure 7-10. Various geotextile or geogrid deployment schemes for stabilizing embankments: (a) multiple even-spaced layers in embankments; (b) multiple concentrated layers in embankments; (c) single layer on top of foundation soil; (d) multiple layers within foundation soil. (Based on Koerner, 1986, p 109).

each case revolves around taking moments about a hypothetical center of rotation and forming a factor of safety equation:

- Without reinforcement:

$$FS = \frac{\tau R}{WX} , \quad (7-1)$$

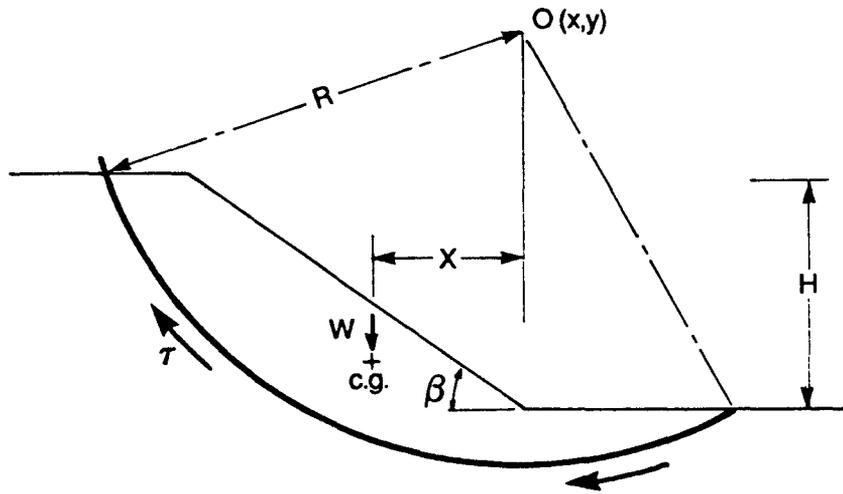
- With reinforcement:

$$FS = \frac{\tau R + \sum_{i=1}^n T_i Y_i}{WX} , \quad (7-2)$$

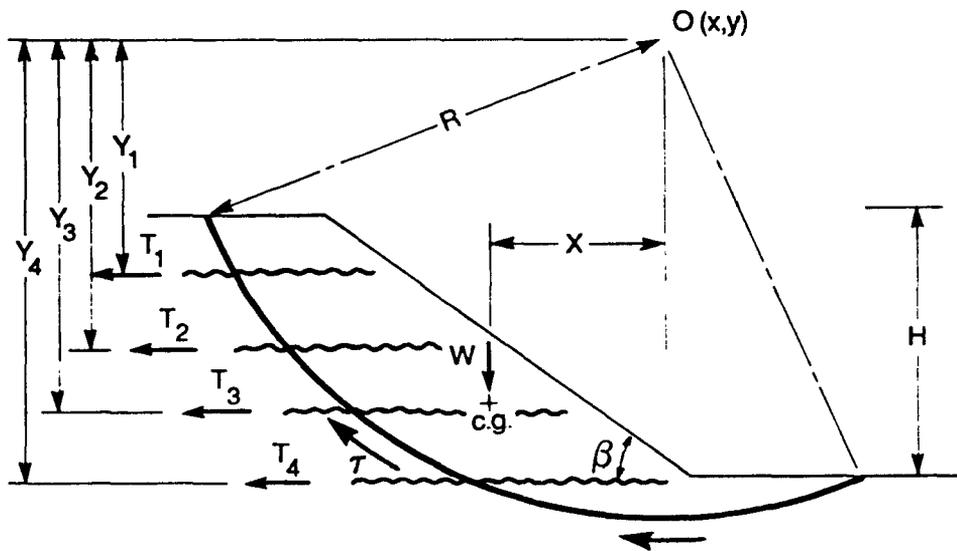
where

- FS = factory of safety,
- τ = shear strength of the soil,
- R = radius of failure arc,
- W = weight of failure zone,
- X = moment arm to center of gravity of failure zone,

T_i = allowable strength of geogrid or geotextile,
 Y_i = moment arms to each level of geogrid or geotextile,
 and
 n = number of reinforcement layers.



(a) UNREINFORCED SOIL SLOPE



(b) SOIL SLOPE REINFORCED WITH GEOGRIDS OR GEOTEXTILES

Figure 7-11. Design approach toward soil slope reinforcement using geogrids and geotextiles; β = slope angle; H = height.

It can easily be seen that the " $T_i Y_i$ " term can be increased by more layers, higher strength geogrids or geotextiles, or different positioning, such that the slope angle (β) or height (H) can be increased drastically over the soil working by itself. This process is discussed in more detail by Koerner (1986).

A final comment on the above design should be mentioned as to the allowable strength value " T_i ". Current practice is to determine the ultimate strength of the product (geogrid or geotextile) in a wide-width tension test. ASTM D4595 recommends testing a 8-in. wide test specimen with a 4-in. gage length. The strength value resulting from a wide-width tension test is then reduced by a factor of safety against creep and subsequent stress relaxation. This factor of safety is quite undecided on at this time. Literature gives recommendations ranging from 2.0 to 5.0 depending on polymer type, manufacturing style, and intended application (den Hoedt, 1986). It is felt, however, that for temporary waste containment facilities the lower end of the above range is appropriate. Thus values of 2.0 to 3.0 are recommended.

Further discussion on the use of geotextiles in slope reinforcement can be found in Koerner (1986), Fowler (1982), and Rowe and Soderman (1985). The use of geogrids to reinforce slopes is discussed by Schmertmann et al (1987) and Wallace and Fluett (1987).

7.5.3 Design of the Bottom Composite Liner

Section 3004(o)(5)(B) of HSWA established Interim Minimum Technological Requirements until EPA regulations codifying minimum technology requirements promulgated under Section (o)(1)(A) take effect or the EPA publishes a guidance document. This section of HSWA states that a liner consisting of at least a 3-ft layer of recompacted clay or other natural material with an hydraulic conductivity no greater than $1 \times 10^{-7} \text{ cm s}^{-1}$ is deemed to satisfy the Interim Minimum Technology requirements for the bottom liner of a double liner system for hazardous waste landfills and surface impoundments. In the draft Minimum Technology Guidance document on double liner systems for hazardous waste landfills and surface impoundments, the EPA requires that soil bottom liners have a minimum 3-ft thickness and be sufficiently thick so as to prevent any constituent from migrating through the bottom of the compacted soil liner for the combined active life and 30-year post-closure care period of a containment unit, usually a total of 40-50 years (EPA, 1985). Current EPA regulations (as of May 1988) reflect these requirements (40 CFR 264). However, it is stated in the draft guidance document that the EPA has "strong reservations" concerning the likelihood that the construction of a soil-only bottom liner which meets the requirement for preventing migration is either economically or technically feasible. In addition, in comparison with an FML/soil composite bottom liner a clay-only bottom liner can result in a significantly less efficient leachate collection and removal system between the top and bottom liners and a potentially higher level of escape from the containment unit (EPA, 1987c; EPA 1987d).

The other alternative for the bottom liner of a double liner system for hazardous waste containment units is a composite liner consisting of two

components, an upper FML component and a lower component of compacted low-permeability soil. The FML component is required to be compatible with the waste or leachate to be contained and have a minimum 30-mil thickness. The soil component of the composite liner is required to be at least 90 cm (36 in.) of emplaced (i.e. in situ soils used to construct a liner must be excavated and then placed back in lifts with a maximum thickness of 6 in. after compaction), compacted, low-permeability soil with an in-place saturated hydraulic conductivity of 1×10^{-7} cm s⁻¹ or less.

This section discusses design considerations for the soil and FML components and also discusses requirements for the interface between the two components.

7.5.3.1 Design of the Soil Component--

Soil liners are constructed of compacted soils and are installed in a series of lifts of specified thicknesses. The compacted liner must have sufficient thickness and strength to provide structural support to overlying facility components. In the case of soil liners used as the lower component of a composite liner, the soil component serves as a protective bedding material for the FML upper component and minimizes the rate of leakage through any breaches in the FML upper component. The present draft of the Minimum Technology Guidance document on double liners for hazardous waste landfills and surface impoundments requires soil liners used as the lower component in the bottom liner of a double liner to be at least 90 cm (36 in.) thick and have an in-place saturated hydraulic conductivity of 1×10^{-7} cm s⁻¹ or less (EPA, 1985). Soil liners associated with the management of nonhazardous materials may have different thickness and permeability requirements; for the purposes of this discussion, a maximum saturated hydraulic conductivity requirement of 1×10^{-7} cm s⁻¹ is assumed.

In considering a particular soil as a lining material, the most important characteristic is low permeability to water and to dissolved inorganic and organic species. Other characteristics include the tendency of the soil to interact with constituents of the waste liquid to be contained, the ability of the soil to attenuate constituents of the waste liquid, and the strength of the soil liner before and after contact with constituents of the waste liquid, the amount and type of compactive effort required to achieve the density associated with the required permeability, and the range of moisture contents at which the soil can be compacted to achieve the required permeability.

This subsection briefly discusses some aspects of the design of a soil liner with particular reference to permeability and the relationship between soil properties and permeability. Also discussed are some aspects of selecting a soil for use as a lining material, the specifications of a soil liner, and the importance of inspecting construction and verifying design specifications by performing field permeability testing, e.g. on a constructed test fill. Goldman et al (1985) discuss the design of clay liners in more detail.

7.5.3.1.1 Soil permeability--The permeability coefficient of a soil is a measure of the ability of a soil to transmit a particular liquid and is one of the most important geotechnical characteristics of a soil, particularly of a clay soil. This coefficient represents a rate movement for a unit volume of fluid per unit cross-sectional area perpendicular to the flow direction and normalized per unit gradient. For systems in which water is the permeating liquid, the permeability coefficient is usually called hydraulic conductivity. This coefficient is derived from Darcy's equation. Most of the technical information that has been developed, particularly by engineers, to describe saturated flow through porous media, i.e. through soils, uses Darcy's equation. As is discussed in Section 3.3.2, Darcy's equation states that the flow rate, Q , is proportional to the hydraulic gradient, i , (i.e. the difference in hydraulic head divided by length) as follows:

$$Q = kiA \quad , \quad (7-3)$$

where

Q = the rate of flow ($\text{cm}^3 \text{ cm}^{-2} \text{ s}^{-1}$),

k = a constant, also known as Darcy's coefficient of permeability (cm s^{-1}),

A = the total cross-sectional area normal to the flow (cm^2), and

i = the hydraulic gradient (cm cm^{-1}).

Darcy's equation reflects the idealizations that the gradient is so significant in determining the flux Q that it masks the importance of other influences (such as diffusion) and that flow is proportional to total cross-sectional area of flow, which includes both solid particles and voids. The principal postulate is that the permeability coefficient k is constant; that is to say, there is a linear relationship between gradient and flux, which has been shown to exist for many soils. The validity of Darcy's equation, however, has been questioned for some clay soils, where it is believed that the physical properties of the pore liquid can be altered by proximity of the liquid and the soil matrix. In addition, the permeability coefficient k of some clay soils can be changed by a sufficient increase of gradient to cause separation and migration of clay particles, which subsequently plug some pores that might conduct flux.

Despite its limitations, Darcy's equation is the relationship most frequently used to describe the water flow in soils, particularly for firm soil structures, i.e. those that are neither affected by the magnitude of the pore-water pressure and the gradient, nor affected by osmotic and swelling effects. Qualitatively, Darcy's equation is always applicable, since the flux increases with hydraulic gradient.

7.5.3.1.2 Relationship between soil properties, compactive behavior, and permeability--The permeability of a compacted soil depends on two groups of factors. The first group includes all the intrinsic properties of the particular soil that determine its potential for remolding and compaction, such as clay proportion, clay particle-size distribution, clay mineralogy and physical chemistry, and soil gradation. These intrinsic properties control the relationship between compactive effort and density at different moisture contents, i.e. the compactibility of a soil. The second group includes the various conditions during compaction (e.g. moisture content, load size, mode of application, and thickness of the lift) which also affect the permeability of the resulting soil liner.

Clay Content and Hydraulic Conductivity--Clay soil particles are flat, platelike shapes varying in thickness from 10 to 500 Å, while their length and widths are significantly larger. The flat surfaces of the particles are highly negatively charged by virtue of their geologic formation processes. This negative charge attracts water molecules (and also partially hydrated cations) to form an adsorbed water layer around the particle itself. Collectively this adsorbed water on all of the clay particles gives it its plasticity or slippery feel. The adsorbed water layer is actually many layers thick and extends well into the soil's voids rendering the clay soil itself quite poor in its ability to conduct water.

The hydraulic conductivity of most undisturbed soils ranges from 10^{-7} cm s⁻¹ to 10^{-3} cm s⁻¹. The particle-size distribution seems to be the most significant characteristic over the whole range of conductivity values of undisturbed soil. Soils with more than 25-30% clay-size particles are concentrated in the lower range of conductivities, i.e. 10^{-7} cm s⁻¹ to 10^{-5} cm s⁻¹. If, however, k is correlated with the percentage of clay-size particles over this range of values, the relationship between particle size and hydraulic conductivity becomes less significant.

Given a relatively high percentage of clay-size particles in a specific soil, properties other than the percent clay content are more significant determinants of its flow properties: the types of clay minerals in the clay fraction, the interlayer chemistry of the crystal-unit, the susceptibility of the particles to disperse or flocculate upon hydration and/or mechanical remolding, and the average size of a typical tactoid (an agglomerate of clay particles).

The three groups of clay minerals, in order of decreasing permeability, are:

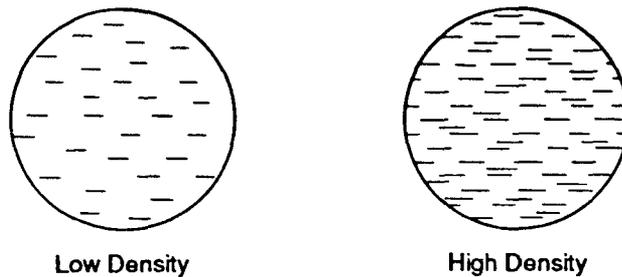
- Kaolinites.
- Illites.
- Montomorillonites (including smectites and bentonites).

The predominance of one or the other of these minerals in the clay fraction will affect soil-water flow characteristics and interaction of the soil with

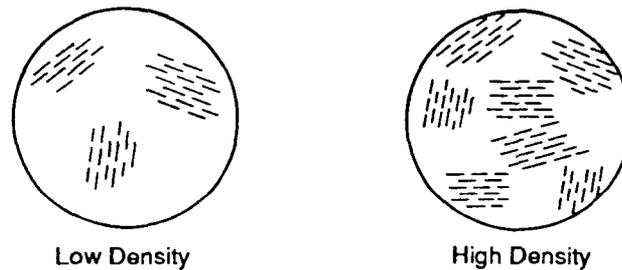
the permeating liquid. All of these variables have great effects on soil-water flow characteristics, and can cause permeability to vary by up to two orders of magnitude for soils that are otherwise apparently similar.

Clay Soil Structural Arrangements--The structural arrangement of soil particles is important in determining the density and thus also the permeability of a given soil. Figure 7-12 presents three types of clay particle arrangements which are significant in understanding their behavior. These types include:

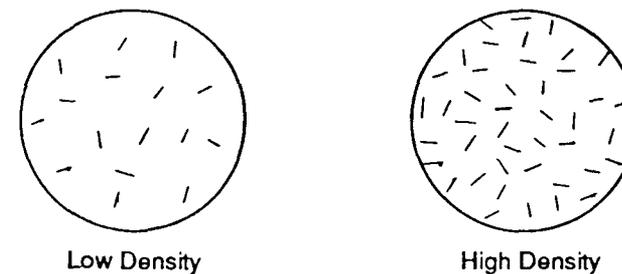
- Dispersed or parallel arrangements. In this type of arrangement, the clay particles are parallel to one another and their relative closeness gives rise to their density. Note that given this type of arrangement, the soil is anisotropic, i.e. that the hydraulic conductivity will be very different in different directions.



(a) Dispersed, or Parallel, Type



(b) Flocculated Type



(c) Random, or Cardhouse, Type

Figure 7-12. Types of clay particle arrangements.

- Flocculated arrangements. In this type, numerous dispersed particle groups gain sufficiently in mass and arrange themselves in flocs which settle collectively.
- Random or cardhouse arrangements. The clay particles in this type are arranged edge to face in a random fashion. Note that given this type of arrangement, the soil is isotropic, i.e. that there is no preferential direction for the conductivity of water.

Dispersed and random arrangements are seen in field compacted (hence remolded) clay soils, whereas flocculated arrangements are not.

Compacted Behavior of Clay Soils--As originated by Proctor in the 1930's and standardized by ASTM as D698, laboratory compaction tests compact the target soil in a standardized mold in a prescribed number of layers at a given compactive effort. The compactive effort is determined by the weight of the hammer, the number of layers, and the number of blows per layer. The soil is at a given water content and results in a measured unit weight (or wet density). The test is repeated at a number of different water contents (usually starting low and successively going higher) which results in a set of water contents and wet densities. Using the formula,

$$\gamma_d = \gamma_t / (1 + w), \quad (7-4)$$

where

γ_d = dry density,

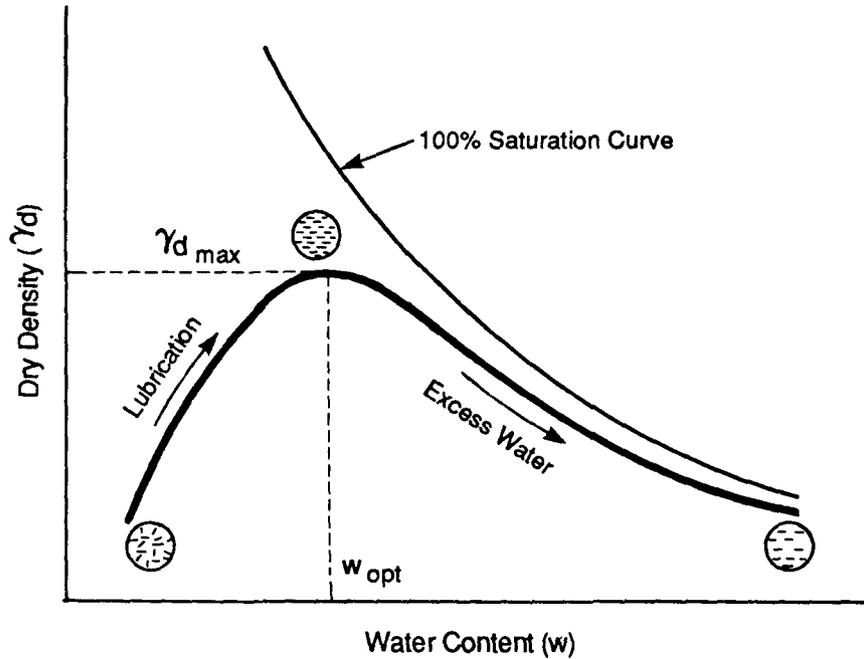
γ_t = total (or wet) density,

w = water content, and

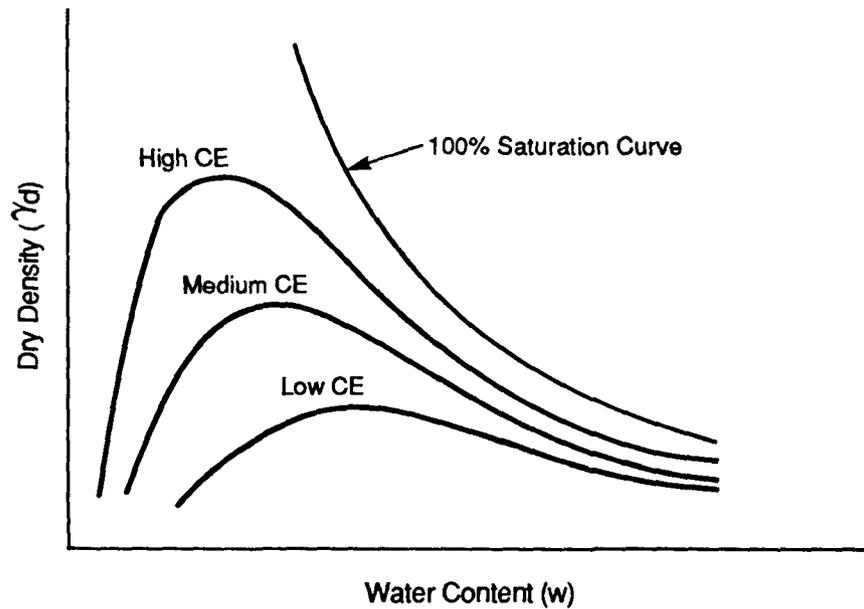
the corresponding dry densities are calculated and plotted versus water content. Figure 7-13a presents typical relationship between density and water content resulting from a compaction test. The "optimum water content" is the water content at which the maximum density is achieved, given a specific compactive effort. Note that the soil only approaches 100% saturation but never meets it, since some air is usually trapped in the soil during placement. Also note that the structure of the clay goes from random (due to lack of water), to dispersed (at the maximum density), to a low-density dispersed (due to excessive water). Figure 7-13b shows how the relationship between density and water content shifts with different compactive efforts.

Moisture Content and Field Placement of Clay Soils--Specifications for compaction of clay soils in various earthwork projects revolves around achieving a minimum dry density which is a percentage of the maximum dry density ($\gamma_{d_{max}}$). Often 90 to 95% of a given method, e.g. Standard or Modified Proctor, will be stated as the required value. As can be seen in Figure 7-14, for a particular compactive effort (e.g. Standard Proctor), the

water content at which the required density can be achieved now becomes a range. The soil described in Figure 7-14 has a maximum density of 115 lb/cu ft. Given a required density of 90% maximum density, which is equal to 103.5 lb/cu ft, the required water content ranges from 10 to 28%.



(a) BASIC COMPACTION RESPONSE OF CLAY SOIL



(b) EFFECT OF COMPACTIVE EFFORT (CE)

Figure 7-13. Compaction response of clay soils.

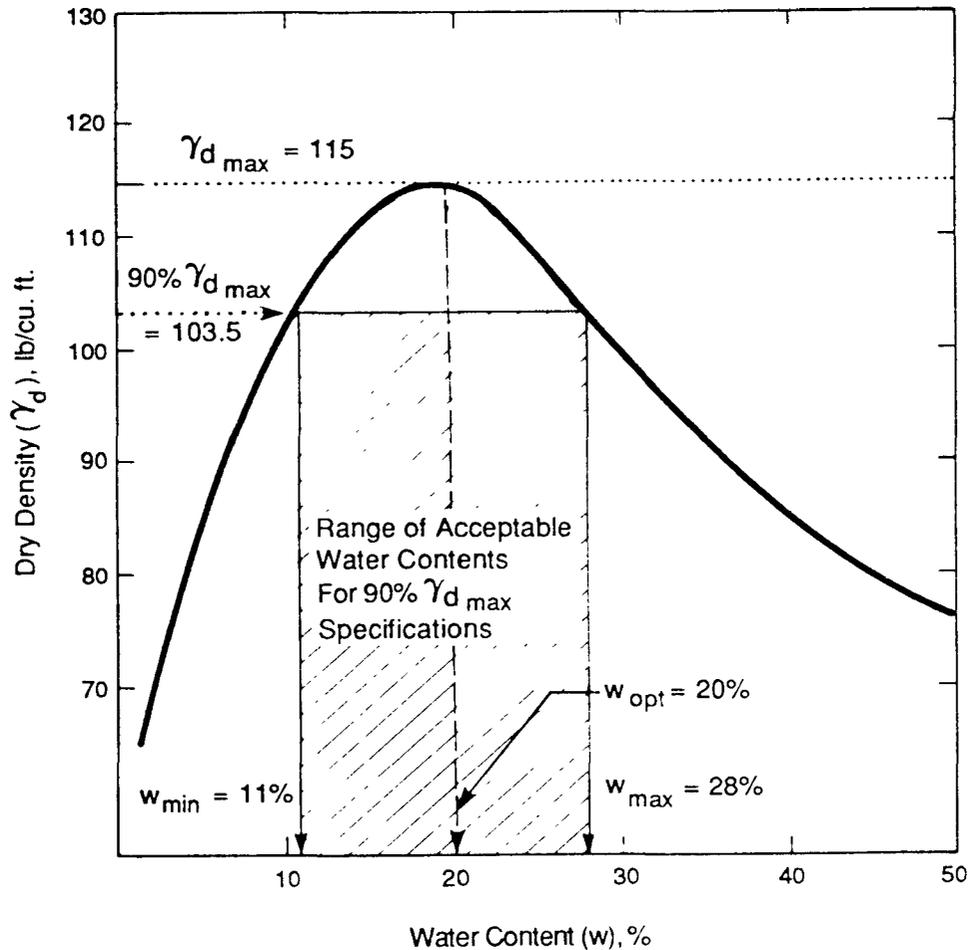


Figure 7-14. Water content range for achieving a density value related to considerations depending on the compaction response of a soil.

From a contractor's point of view, it is less problematic to compact clay soil at the lower end of the required water content range because it is easier to add water to a fill than it is to remove it. Thus, if precipitation occurs during construction of a site which is being placed at the lower end of the required water content range, the additional water may not result in a soil water content greater than the required range. Conversely, if the site is being placed at the upper end of the range, e.g. at 25%, any additional moisture will be excessive, resulting in a water content over 28% and making the 90% $\gamma_{d\max}$ unattainable. Under such conditions, the contractor must wait, aerate the soil with disc harrows and road graders, and hope for sun, all of which result in scheduling delays and increased costs. Nevertheless, it should be noted that this discussion has focused on density and not on hydraulic conductivity, which is the most important property of soil liners for waste containment units.

There are numerous studies on the influence of clay type, clay structure, and density on hydraulic conductivity. For the purpose of this discussion it can be said that the higher the dry density for a given soil, the lower the permeability coefficient. Figure 7-15, shows the relationship between the void ratio (which is the ratio of the volume of void space to the volume of solid particles in a given soil mass and, hence, inversely related to density) and permeability, which changes by orders of magnitude depending on the void ratio. It can also be seen that, for two clay soils, the response curves are very different.

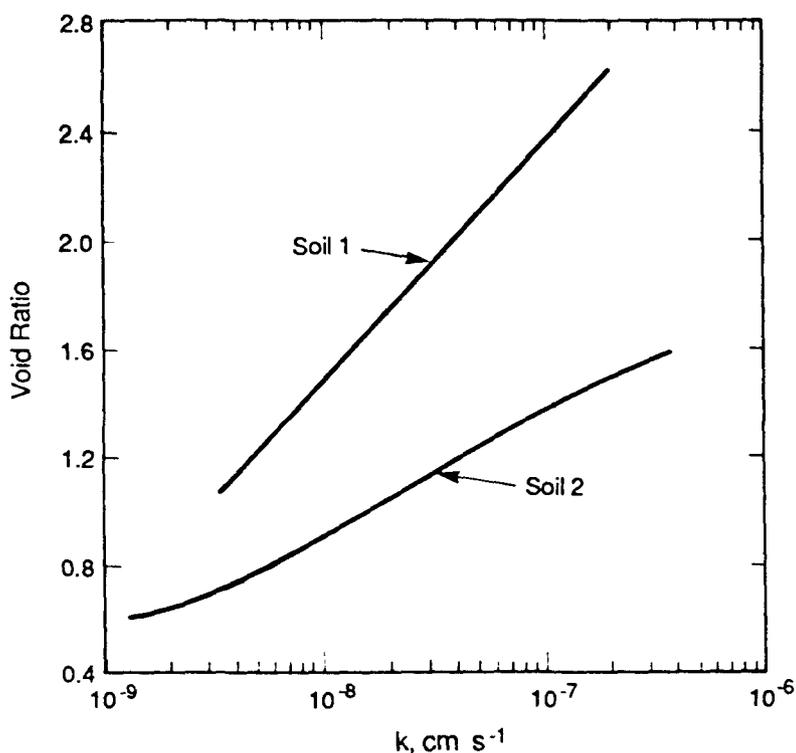


Figure 7-15. Relationship between hydraulic conductivity and the void ratio for two soils. (Based on Olsen and Daniel, 1981).

However, particle arrangement can also have a significant effect on permeability. It seems intuitively more advantageous for a soil liner to have a dispersed clay structure in order to retard vertical moving liquids; thus, given the relationship between water content and particle arrangement presented in Figure 7-13a, wet of optimum conditions are preferable to dry of optimum. When these permeability considerations are added to the difficulties presented by soil "clods" which appear when clay soils are placed dry of optimum, it seems that wet of optimum is a technically-sound approach to obtaining a low in situ hydraulic conductivity for a clay soil. Some engineers presently recommend compacting soils at a water content 3 to 6% wet of optimum. Note, however, that placement wet of optimum can pose problems and that the contractor will always be challenged by inclement weather.

7.5.3.1.3 Selection of soil for use as a lining material--One of the most important design activities associated with the construction of a soil liner is selecting a soil. During the site investigation, the on-site soils should have been tested for various properties including compactibility, chemical sensitivity (e.g. compatibility with the waste to be contained). Tests for these properties are discussed by Haxo et al (1987), Spigolon and Kelley (1984), and Goldman et al (1985). The results of these tests may indicate a range of soil moisture contents following a specific compaction procedure and a range of soil densities for which the corresponding soil permeability coefficient is below the required maximum hydraulic conductivity value, i.e. 1×10^{-7} cm s⁻¹ for the bottom component of a composite bottom liner for a hazardous waste landfill or surface impoundment. Examples of what the designer may face in comparing soil compaction data with soil permeability data include the following situations:

- Case 1: For an idealized soil, there is a broad range of moisture contents (w) and of soil dry density (γ_d) for which the permeability coefficient (k) is less than the maximum allowable (Figure 7-16). Moreover, the range of moisture contents which can result in the minimum dry density necessary to achieve required permeability coefficient corresponds to the range of the moisture contents which results in acceptable permeabilities. This is expressed by a unique relationship between γ_d and k . This situation is the safest possible because there should be no problems in optimizing the moisture content and corresponding density of the soil during compaction. In addition, over-compaction will not damage the permeability characteristics of the resultant soil liner.
- Case 2: For an idealized soil, there is a range of moisture contents (w) for which the permeability coefficient (k) is less than the maximum allowable (Figure 7-17). However, in this case, the corresponding range of densities is in absolute terms on the low side, and compaction to maximum density will not result in a liner that meets the requirement for hydraulic conductivity. The soil in this example achieved a state of low permeability, not because of densification, but because of shear deformation and particle orientation. Even though the soil may be compacted within the necessary moisture content range to achieve the required conductivity values, it would be risky to rely on the stability of this structure with time. Thus, this particular soil is probably not suitable for use as the clay component of the bottom composite liner in a double liner system.
- Case 3: The soil cannot be compacted so as to achieve the required conductivity value, indicating that this soil is not acceptable for use as the clay component of a bottom composite liner.

If the on-site soils are not acceptable for use in constructing a soil liner, borrow sources may need to be identified and investigated. The possibility of constructing a soil liner by blending the on-site soils with clay additives can also be explored.

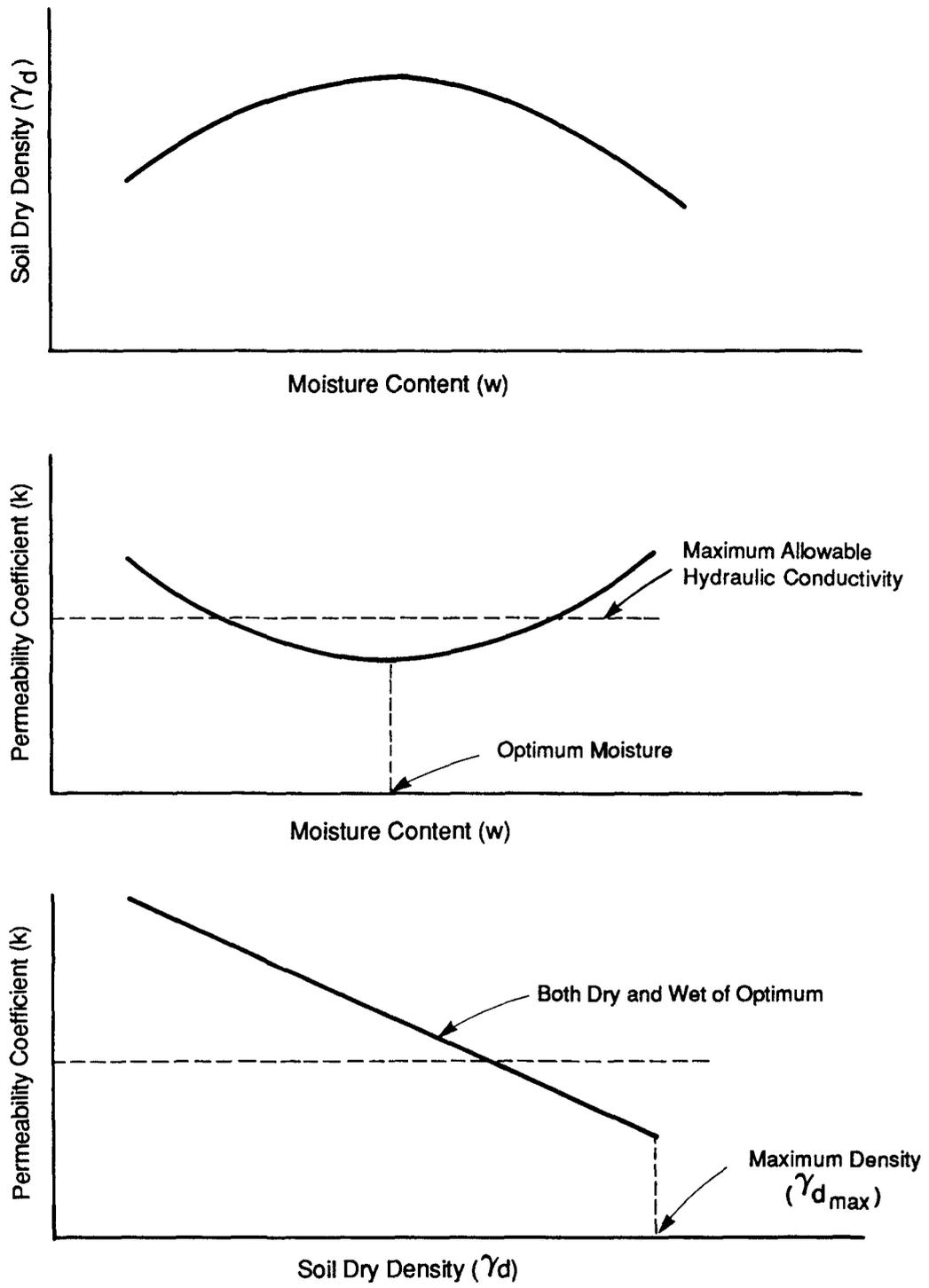


Figure 7-16. Schematic representation for Case 1 of the relationships between soil dry density, soil moisture content, and permeability coefficient for an idealized soil with no particle orientation when compacted at high compactive effort.

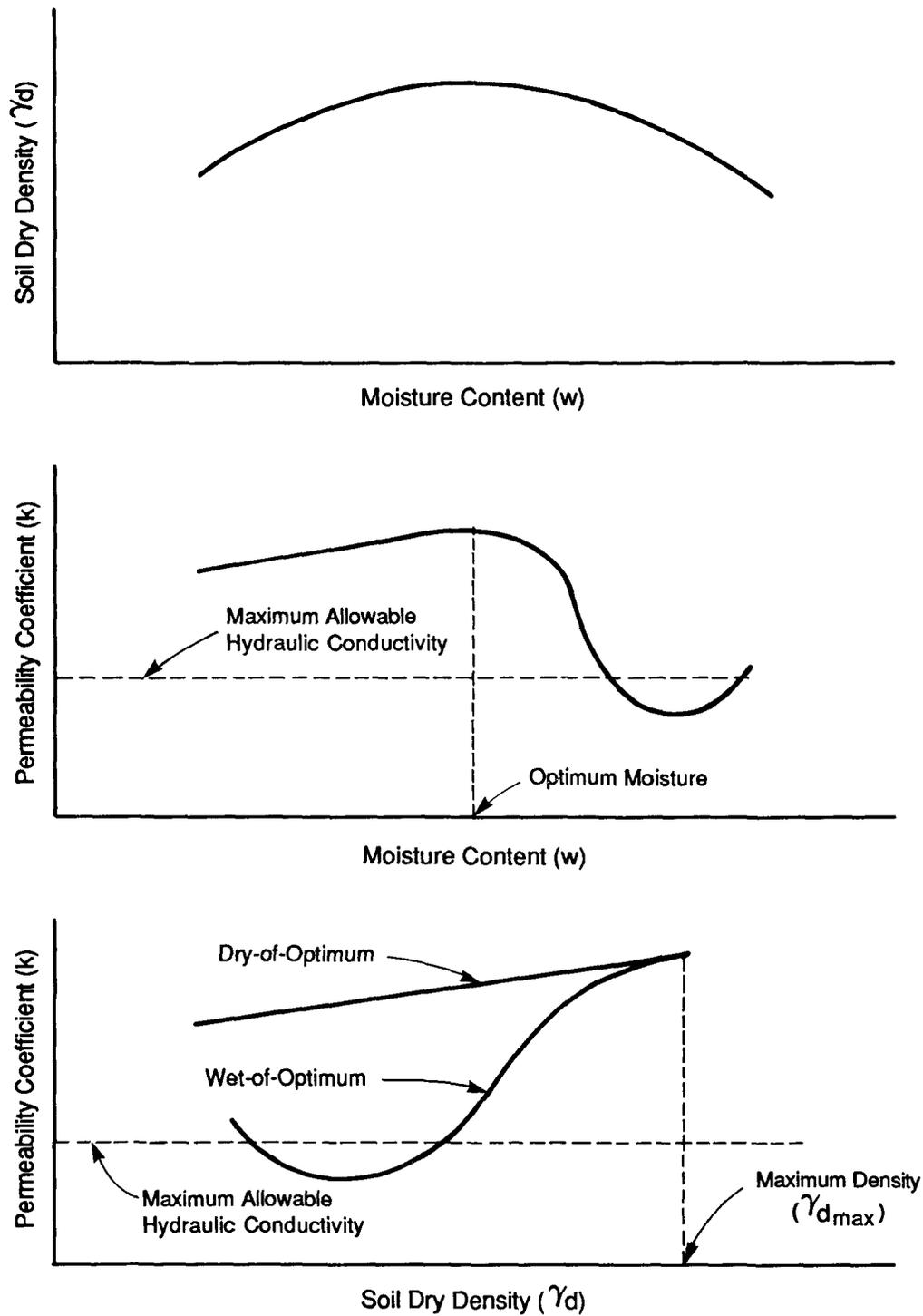


Figure 7-17. Schematic representation for Case 2 of the relationships between soil dry density, soil moisture content, and permeability coefficient for an idealized soil.

This discussion only indicates some of the factors involved in evaluating selecting of a soil for use as a soil liner. Other factors include the compatibility of the soil liner with constituents of the waste to be contained, shrink/swell behavior, etc. Present EPA policy requires assurance that the soil materials used in constructing a liner for a hazardous waste containment unit are compatible with the waste to be contained (EPA, 1986d). The test method recommended to verify compatibility is EPA Test Method 9100 (EPA, 1986c), which determines the effect of the leachate or waste liquid to be contained on the hydraulic conductivity of the compacted soil. It should be noted that Method 9100 is currently (June, 1988) under review. Further discussion on soils as liner materials can be found in Haxo et al (1987) and Goldman et al (1985).

7.5.3.1.4 Design and specifications for a soil liner--Once a soil has been selected for use in constructing a soil liner, the other important design activities are associated with specifying the parameters for construction. The design specifications, based on the information developed during the site investigation and in the process of selecting the soil, must provide the contractor who performs the construction with the information necessary for constructing a soil liner, including any special procedures for the different soils that may be present so that the end result will be a uniform soil liner. These specifications need to be stated in terms of the performance required from the soil liner and in terms of methods of achieving the required performance. The basic performance requirement is low hydraulic conductivity. Specifications for constructing a soil liner can include the following:

- Overall thickness of the soil liner. In the draft Minimum Technology Guidance document on double liner systems for hazardous waste landfills and surface impoundments, the EPA requires the soil component of a bottom liner to be at least 90 cm (36 in.) in thickness after compaction (EPA, 1985).
- Required density, usually expressed as a percentage of a maximum dry density obtained by a specific method, e.g. 90 or 95% Proctor.
- A soil moisture content necessary to achieve the required density, usually 2 to 3% wet of optimum; some engineers are presently recommending 3 to 6% wet of optimum.
- Maximum clod size.
- The depth of the unit-layer to be compacted at one time, i.e. lift thickness. In the draft Minimum Technology Guidance document on double liners systems for hazardous waste landfills and surface impoundments, the EPA recommends that the liner be compacted in lifts not exceeding 15 cm (6 in.) after compaction to maximize the effectiveness of compaction throughout the lift thickness (EPA, 1985).
- Measures to be taken for tying together the lifts, e.g. scarification.

- Number of passes of the compacting equipment over one unit-layer.
- Type of compacting equipment.
- Weight of the compacting equipment.
- Trade-name and model of the compacting equipment, if applicable.
- Method of constructing the sidewall. In the draft Minimum Technology Guidance document on double liners systems for hazardous waste landfills and surface impoundments, the EPA recommends constructing the liner in lifts parallel to the slope in order to minimize flow between the lifts (EPA, 1985). However, some design engineers feel that construction of the liner in horizontal lifts can result in an acceptable liner. In this method of construction, the sidewalls are overbuilt and trimmed back to the specified slope. Special care is required to ensure that adjacent lifts are tied together properly. In addition, some engineers who advocate sidewall construction in horizontal lifts also place a prefabricated bentonite liner on top of the soil liner.

Because of soil variability and the scale of the operation in designing and constructing a soil liner, some flexibility must be provided by the designer in the construction specifications. If it were the case that the top layer of soil used in constructing a liner had a uniform moisture content and density characterization in the undisturbed state, then the working procedures indicated in the design specifications for a particular soil unit normally would be easy to observe. In addition, heterogeneity of soil is the rule rather than the exception, and more than one soil unit may be used in constructing the soil liner. Thus, two important features of constructing a soil liner are inspection of both the workmanship and the soil material being used in construction and the ability to modify construction practices as the need arises. Inspection is performed to monitor the quality of the work being performed and to verify that the design requirements are being met (e.g. compaction at proper moisture content or to the specified density). Inspection is also performed to verify the accuracy of the results of the site investigation on which the design specifications are based. Often there can be soil heterogeneities that escaped observation during the site or borrow source investigations. Depending on the results of the QA/QC inspections, the designer may be required to modify the design specifications in order to achieve the required hydraulic conductivity.

7.5.3.1.5 Field verification of design specifications--Present EPA guidance on the construction of hazardous waste containment units recommends the construction of a test fill to verify that the specified soil density, moisture content, and permeability values can be achieved consistently in constructing the full-scale unit (EPA, 1985; Northeim and Truesdale, 1986). Constructing a test fill before constructing the actual soil liner can minimize the potential dangers and expense of constructing an unacceptable liner. The test fill is constructed using the same soil, equipment, and

procedures that are specified for the construction of the actual liner. The data resulting from constructing the test fill, including documentation of actual construction and the results of all QA/QC testing, need to be well documented in accordance with good engineering practice.

In particular, the test fill is a convenient method for evaluating the most critical requirement for a compacted soil liner--low hydraulic conductivity. Several studies have indicated that in-place measurements of hydraulic conductivity are more trustworthy than laboratory tests for determining the hydraulic conductivity of soil liners because the soil volume being tested can be quite large and because there is only minimal disturbance of the soil material during testing (Herzog and Morse, 1984; Gordon and Huebner, 1983; Daniel, 1984; Boutwell and Donald, 1982). Daniel (1984) reported a case in which the rate of leakage through a pond liner was approximately 1,000 times greater than that predicted from laboratory hydraulic conductivity measurements on both undisturbed and recompacted samples. A field hydraulic conductivity test which used an 8-ft diameter ring and which was run for four weeks resulted in a hydraulic conductivity value that was within the range calculated from the actual leakage rate. These results are summarized in Table 7-2. The large discrepancy between the laboratory and field generated data was felt to be caused by the presence of large clods in the compacted soil which allowed flow within the relatively large pathways. In general, reasons for a higher than expected hydraulic conductivity of a soil liner have been related to the presence of macrofeatures (such as desiccation cracks, weathering discontinuities, and root-holes), and the inadequate control of field compaction parameters, including density, water content, soil type, and placement procedures. The presence of these macrofeatures in a soil liner would tend to result in a higher quantity of liquid flow than would be predicted from laboratory tests.

TABLE 7-2. SUMMARY OF HYDRAULIC CONDUCTIVITY MEASUREMENTS AT SITE IN CENTRAL TEXAS

Type of Test	Hydraulic conductivity (cm s ⁻¹)
Laboratory hydraulic conductivity test	5 x 10 ⁻¹⁰ to 8 x 10 ⁻⁷
Field hydraulic conductivity test	4 x 10 ⁻⁵
Back-calculated from actual leakage rate	2 x 10 ⁻⁵ to 5 x 10 ⁻⁵

Source: Daniel, 1984.

The two types of tests that have been proposed as field hydraulic conductivity tests use either lysimeter pans or infiltrometers. The test fill design described by the EPA Technical Guidance document on the CQA for hazardous waste containment units includes a free-draining underdrain system

equipped with a lysimeter pan for collecting and quantifying seepage through the test fill liner (Northeim and Truesdale, 1986, pp 21-23). The major objection to this type of test as a CQA test is the length of time that would be required to verify an hydraulic conductivity of 1×10^{-7} cm s⁻¹ or less.

Several types of infiltrometers have been developed as methods of measuring in-place hydraulic conductivity, which is calculated from the infiltration rate. The infiltrometer that appears to have the most promise for verifying hydraulic conductivities less than or equal to 1×10^{-7} cm s⁻¹ is the sealed double-ring infiltrometer (SDRI) developed by Daniel and Trautwein (1986), which is a modified version of the infiltrometer used in ASTM D3385. Double-ring devices are designed to restrict the amount of lateral spreading of liquid originating from the inner ring, allowing seepage to be considered essentially one-dimensional. In comparison with the D3385 infiltrometer, which is unsealed, the SDRI allows greater precision in determining small changes in water level and has greater control over evaporative loss. To determine the hydraulic gradient, which is necessary for calculating the hydraulic conductivity of the liner from the infiltration rate, the test can continue until the wetting front reaches the base of the liner (assuming the water pressure is zero at the base of the liner) or tensiometers can be used if porous probes at different depths are attached to a differential pressure gauge or manometer.

In comparison with laboratory CQA tests, field hydraulic conductivity tests have several disadvantages including their duration, the effort involved in monitoring and maintaining test conditions, and concerns about the exact volume of soil being tested. The duration of field tests can result in substantial delays in construction. In addition, the use of infiltrometers has been criticized because of:

- Difficulties in achieving saturated flow conditions within the relatively limited time allotted to performing infiltrometer CQA tests.
- Concerns about the accuracy of gradient values used to calculate hydraulic conductivity, particularly at the beginning of tests when soil suction may cause a high rate of infiltration and result in a calculated hydraulic conductivity that is too high.
- Concerns about the effect of not confining the soil tested by the infiltrometer on the rate of infiltration, particularly for highly plastic soils. The normal stress on a test fill can be negligible in comparison with normal stress levels caused by waste loadings in actual landfills and surface impoundments.

If field hydraulic conductivity testing of the test fill is specified as the method of verifying that the construction and material specifications result in a liner with the required hydraulic conductivity, the results of the field hydraulic conductivity test need to be correlated with the construction parameters (e.g. compactive effort, maximum clod size) and the results of potential surrogate tests. Even though field permeability testing

could be performed on the full-scale liner, such testing would result not only in substantial construction delays but would probably result in damage to the liner as a whole due to prolonged exposure to natural weathering. Thus, tests need to be selected that can be applied to the full-scale liner as surrogates for field hydraulic conductivity tests. Surrogate tests are a group of tests that do not actually measure field permeability but whose results, when considered together, can be used to estimate field hydraulic conductivity and, hence, can be used to control this parameter during low-permeability soil liner construction. If surrogates for field hydraulic conductivity tests are to be used with a high degree of confidence, data obtained from a test fill evaluation need to show the relationships between the hydraulic conductivity as measured by the field test of areas and lifts across the test fill and the proposed surrogate test results. Examples of potential surrogate tests include hydraulic conductivity of laboratory compacted soil samples, hydraulic conductivity of undisturbed samples, Atterberg limits, particle-size distribution, compacted moisture content, compacted soil density, and penetrometer strength tests.

Guidelines for constructing a test fill are discussed by Northeim and Truesdale (1986).

7.5.3.2 Design of FML Component of Bottom Composite Liner--

The purpose of an FML in a waste containment unit is to control the migration of any mobile constituents out of the unit during the period that the unit is in operation and during the post-closure care period. In order to fulfill this function, the FML has to meet the following requirements:

- The FML must have sufficiently low permeability to the constituents of the waste to be contained so that escape from the unit is below a level that may pose a danger to human health or the environment.
- The FML must be chemically compatible with all constituents of the waste to be contained, i.e. the waste must affect neither the FML nor the seams in such a way that the FML is no longer able to fulfill its function.
- The FML must be mechanically compatible with its service conditions.
- The FML must be sufficiently durable to maintain its integrity in the service environment through the end of the post-closure care period.
- The FML must be capable of being installed under a sufficiently broad range of environmental conditions; in particular, the FML must be capable of being seamed in such a way that the seams approximate the strength and durability of the FML itself.

This section discusses these performance requirements, and describes the factors involved in selecting an FML and ways in which the choice of a particular FML may affect the unit design. Design of the FML layout and design considerations involved in attaching the FML to penetrations and appurtenances are also discussed.

7.5.3.2.1 Performance requirements of an FML--In order to function as a liner in a TSDf containment unit, an FML must meet performance requirements for a wide range of properties, including permeability, chemical compatibility, mechanical compatibility, and durability. These properties are discussed in Section 4.2.2.4. The mechanisms of transport through an FML are discussed in Chapter 3. The seaming of FMLs is discussed in Section 4.2.2.3. These performance requirements, various ways in which these requirements can affect selection of a particular FML, and the minimum technology requirements proposed in the draft Minimum Technology Guidance document on hazardous waste landfills and surface impoundments (EPA, 1985) as ways of meeting these performance requirements are discussed in this subsection.

7.5.3.2.1.1 Low Permeability. The primary function of an FML in a TSDf containment unit is to minimize or control the flow of mobile constituents out of the unit and prevent them from entering the environment, particularly the groundwater. In order to do this, the installed FML must have sufficiently low permeability to all constituents of the waste to be contained such that the level of transmission through the FML does not pose a threat to human health or the environment. It should be noted that transmission level for a particular constituent which can pose a threat to human health or the environment is specific to the site, the constituent's toxicity, and the mobility and biodegradability of the constituent.

Transmission of liquids and soluble waste constituents through an installed FML can occur because of permeation through the FML on a molecular basis or because of discontinuities (e.g. holes) in the sheeting or the seams. Thus, an FML should be free of pinholes, blisters, holes, contaminants, and any other imperfections that can result in a discontinuous membrane. It should also be noted that, in order to allow only the minimum level of transmission, an FML needs to be capable of being installed in such a way that there is 100% seam continuity, needs to be mechanically compatible with the other components of the lining system, and needs to have sufficient durability to continue to function after long-term exposure.

As is discussed in Chapter 4, continuous FMLs do not appear to be permeable by ions with the possible exception of hydrogen ions. In addition, flaw-free FMLs cannot be permeated by liquids per se; however they can be permeated by liquids, gases, and vapors on a molecular level, depending on the solubility of the permeating species and its diffusibility in the membrane. A concentration or partial pressure gradient across the FML is the driving force for the direction and rate of transport. The individual species migrate through the FML from higher to lower concentration. The permeation mechanism for transport through a nonporous membrane is discussed in Chapter 3, the transmission of organics through FMLs in Section 4.2.2.4.1, and the transmission of organic mixtures and of organics in aqueous solutions through FMLs in Section 5.4.1.6. The results of the studies reported in these sections indicate the following:

- The transmission of an individual species can vary from polymer to polymer.

- The transmission of several species through a single FML can vary over several orders of magnitude.
- The presence of other permeating species can affect the transmission of a species through an FML.
- The permeation rate through an FML of an organic in an aqueous solution can be substantially higher than what would be expected from the difference in concentration because of selective permeation.

The specification of a maximum transmission level through an FML can affect the choice of a generic FML type and a specific composition, particularly if organics are present in the waste liquid. The requirement can also affect the selected thickness because, given a specific composition, transmission rates are related to the thickness of the polymeric membrane. In the case of fabric-reinforced FMLs, it should be noted that transmission rates are related to the thickness of the membrane and not the overall thickness, which includes the thickness of the fabric reinforcement.

7.5.3.2.1.2 Chemical Compatibility. In order to function as a liner, the FML must be compatible with the waste to be contained, i.e. the FML must maintain its low permeability and mechanical properties after exposure to the waste so that it can continue to function as a liner. The seams also need to be compatible with the waste liquid. Chemical incompatibility of an FML with a waste liquid can result principally because of the following:

- Absorption of large amounts of waste constituents.
- Extraction of components of the original FML compound.

Chemical stresses are discussed in Section 5.3.1.

The EPA has developed Method 9090 (EPA, 1986c) as a method for assessing the chemical compatibility of waste liquids and FMLs. Method 9090 is presented in Appendix L. This test attempts to simulate some of the conditions that an FML may encounter in service and to determine the effects of contact with a waste liquid on an FML. In this test, slab samples of candidate FMLs are immersed for up to four months at 23° and 50°C in a representative sample of the waste liquid which will contact the in-service FML. Physical and analytical tests are performed on the unexposed FML for baseline data and on samples exposed to the waste liquid for 30, 60, 90, and 120 days. Thus, the test involves many steps including selecting representative samples of both the waste to be contained and an FML, exposing the FML samples to the waste under highly controlled conditions, testing the unexposed and exposed FML samples for physical and analytical properties, and interpreting the final results. Factors that can influence Method 9090 test results are discussed in Section 5.4.3.

The draft Minimum Technology Guidance document states that the EPA considers significant deterioration in any of the properties measured on samples exposed in a Method 9090 test to be evidence of incompatibility (EPA, 1985). Quantification of levels that indicate significant deterioration, however, are not available. At the present state-of-the-art of FML technology and the design and construction containment units for TSDFs, it is not possible to set minimum test values which correlate with ultimate performance. Thus, there are no established or accepted benchmarks of FML performance based on immersion tests, and professional judgment is still necessary for interpreting the significance of Method 9090 test results.

Computer programs based on expert systems are being developed by the EPA to assess data from Method 9090 compatibility tests (Rossman and Haxo, 1985). These systems are designed to provide assistance to those responsible for evaluating Method 9090 test results. One such system, called FLEX (which is an acronym for Flexible Liner Evaluation Expert) is available in a draft form from the Hazardous Waste Engineering Research Laboratory (HWERL) of the EPA. FLEX is intended as a screening tool geared for use by those familiar with FML testing and EPA Method 9090. The system can rapidly pinpoint inconsistencies in the test data and test results which suggest that the liner is substandard or incompatible. However, the recommendations resulting from an analysis by FLEX should not be considered absolute; they are to be used only as a guide by a permit reviewer.

The requirement for chemical compatibility affects the choice of FML type and composition more than any other consideration, particularly if organics are present in the waste to be contained.

7.5.3.2.1.3 Mechanical Compatibility. An FML used to line a TSDF unit must be able to maintain its integrity after exposure to mechanical stresses. Short-term mechanical stresses can include stresses during installation such as those caused by placement of a granular drainage layer and the traffic of heavy equipment, stresses caused by thermal shrinkage, and stresses related to the weight of the materials placed on top of the liner system. Long-term mechanical stresses are more often the result of the materials on top of the liner system or differential settlement of the subgrade. Tests that have been developed to simulate field mechanical stresses are discussed in Section 5.5.

At present, no correlations have been developed between properties measured by standardized methods (e.g. uniaxial tensile strength, biaxial burst strength, tear resistance, etc.) and the ability of an FML to function as a component of an engineered system. Thus, no minimum values for these properties have been established. Appendix K presents suggested specifications for selected FMLs. These specifications represent an index of the quality of the FML compound and/or construction and are similar to purchase specifications; however, they are not performance specifications.

There must be adequate friction between the FMLs on the slope and the soil and components of the leachate drainage and collection systems to ensure

that no slippage or sloughing may occur. The low friction angles of some FMLs with respect to soils and other materials must be taken into account in the design (Section 4.2.2.5.5). Friction angles are considered by Richardson and Koerner (1987) in design equations to evaluate:

- The ability of an FML to support its own weight on the side slopes.
- The ability of an FML to withstand shear stresses of the waste after filling.
- The anchor capacity of an FML placed in various anchorage configurations.
- The stability of a soil drainage layer or geonet on top of an FML.

Various textured FMLs are being developed by different manufacturers to increase the friction between the FML and soils. It should be noted that textured FMLs, specifically polyethylene, pose difficulties for specification, testing, installation, and seaming.

Considerations about mechanical compatibility can affect choice of FML type and construction. In addition, since in the case of unreinforced FMLs absolute mechanical properties are related to thickness, concerns about mechanical compatibility can also affect choice of a specific thickness.

7.5.3.2.1.4 Capability of Being Installed. An FML used to line a TSDF containment unit must be capable of being installed in such a way that it can form a continuous durable membrane. The ability to form a continuous durable membrane is dependent on the ability of the material to be seamed. A major reason for the tendency in recent years not to use crosslinked FMLs is the difficulty encountered in seaming these FMLs. In addition, if an FML tends to become brittle at colder temperatures and becomes particularly sensitive to damage caused by winds, this type of FML will be difficult to install. Some unreinforced thermoplastic FMLs (e.g. PVC or CPE) may become difficult to handle on hot sunny days due to softening and shrinkage caused by the increased surface temperature of the FML, which may get to 160°F and higher. Due to its high coefficient of linear expansion, HDPE tends to expand when warmed by sunlight, but contracts when cooled. This characteristic can cause severe stress in the sheeting if it is installed when warm without sufficient slack. Also, if seamed when warm, both sheetings should be at the same state of expansion.

7.5.3.2.1.5 Durability. FMLs used to line TSDF containment units must be durable, i.e. be able to maintain their integrity and performance characteristics over the operational life of the unit and the post-closure care period. Ultimately, the service life of a given FML will depend on the intrinsic durability of the material and on the conditions under which it is exposed. Differences in composition and construction will cause FMLs to vary

in their response to the exposure conditions which, even within a given facility, can differ greatly. In particular, the FML must be able to resist the combined effects of chemical, physical, and biological stresses. The procedures and test results that have been developed to assess the durability of FMLs are discussed in Chapter 5. Not adequately investigated, however, are the synergistic effects of combined stresses; these effects need to be studied through the further investigation of actual field performance.

7.5.3.2.2 Selection of the FML--In selecting a membrane that meets the performance requirements for an FML, the designer must make decisions concerning:

- Composition.
- Thickness.
- Construction (fabric-reinforced or unreinforced).
- Desired mechanical properties.

The decision about composition will be based primarily on chemical compatibility, although in the case of an FML that will be exposed without a soil cover on the slope of a surface impoundment, compatibility with service conditions is also an important consideration. The selection of an FML of a certain thickness, particularly of an unreinforced FML, will probably result from concerns about mechanical compatibility. Any decision needing to be made about the construction of an FML depends on the FML composition selected, i.e. whether that composition is available or a fabric-reinforced membrane, an unreinforced membrane, or both. In addition, as the mechanical properties of a fabric-reinforced FML are related to the mechanical properties of the fabric reinforcement, and since some compositions may be available with more than one type of fabric reinforcement, the designer must decide on the desired mechanical properties. Lastly, if more than one FML is found suitable for lining a particular containment unit, selection of a particular FML may depend on costs, which are discussed in Chapter 12.

7.5.3.2.3 Effect of FML selection on design--The selection of a specific FML for use in lining a treatment, storage, or disposal unit can affect the overall design and design specification in several ways. An FML is only a single component of a lining system which, in the containment of hazardous wastes, can include a soil liner, two FMLs, a leak-detection system between the two FMLs, a soil cover above the top FML, in the case of a surface impoundment, and a leachate collection system above the top FML, in the case of a landfill. These different elements must be compatible so that each can fulfill its own function. One way in which the selection of a particular FML can affect overall design is its friction angle. There must be sufficient friction between the soil liner and the FML combined with adequate anchorage to prevent slippage of the installed FML down the slope. The use of an FML with a relatively low friction angle, such as an untextured

HDPE, can affect the exact design for anchoring the FML. The design of anchor trenches is discussed later in this chapter.

The coefficient of thermal expansion of the FML can affect its installation and its performance in service. Ideally, the FML component of a composite liner should lay flat on top of the soil component. However, the difference between ambient temperature during installation and the service temperature may result in excessive waviness or tautness in the FML at the service temperature. The wrinkles resulting from the waviness may affect drainage in the leak-detection system or be the site of local stresses resulting in cracking of the FML. Excessive tautness may affect an FML's ability to resist puncture and localize stress on the seams. Provisions may need to be included in the design to allow for changes in dimensions resulting from thermal expansion or contraction. Residual stresses left in some FMLs from their manufacture can cause shrinkage when heated by sunlight. This shrinkage can also affect installation and result in tautness of the FML.

Depending on the order in which the bid package and the FML specifications are written and the FML is selected, the selection of either an FML type or a particular FML can affect the FML specifications because of the differences between the reference or purchase specifications of the different FML types. Specifications of FMLs are discussed in Chapter 8.

7.5.3.2.4 FML layout--One part of the fabricator's/installer's job is to create an FML sheet or panel layout, which is a drawing showing the way in which the FML will be installed at the unit. In addition to the site conditions, exact layout will depend on the width of the rolls in which the FML is manufactured and whether or not the FML is fabricated into panels. An example of an FML layout with sheets that are 33-ft wide and have a maximum length of 650 ft is presented in Figure 7-18. An example of an FML panel layout is presented in Figure 7-19. In an FML layout, horizontal seams on slopes and seams at the toe of slopes are avoided because such seams are often likely to be subjected to excessive stresses.

7.5.3.2.5 Attachment to penetrations and appurtenances--In general, the fewer penetrations through a lining system, the better. An excessive number of protrusions or penetrations makes it difficult to install the lining system and increases the number of locations where stress concentrations are likely to be generated in an FML or where FML movements are likely to be restrained. When penetrations are necessary, the seal between the structure and the FML needs to be liquid-tight. The designer needs to consider the methods of attaching the FML to these structures. An FML can be attached to a structure with a mechanical-type seal supplemented by chemically compatible caulking, adhesives, or heat fusion to effect a liquid-tight seal. Sharp edges on the structure should not contact the FML. Design for attaching different types of penetrations and appurtenances are discussed in Section 7.5.7.

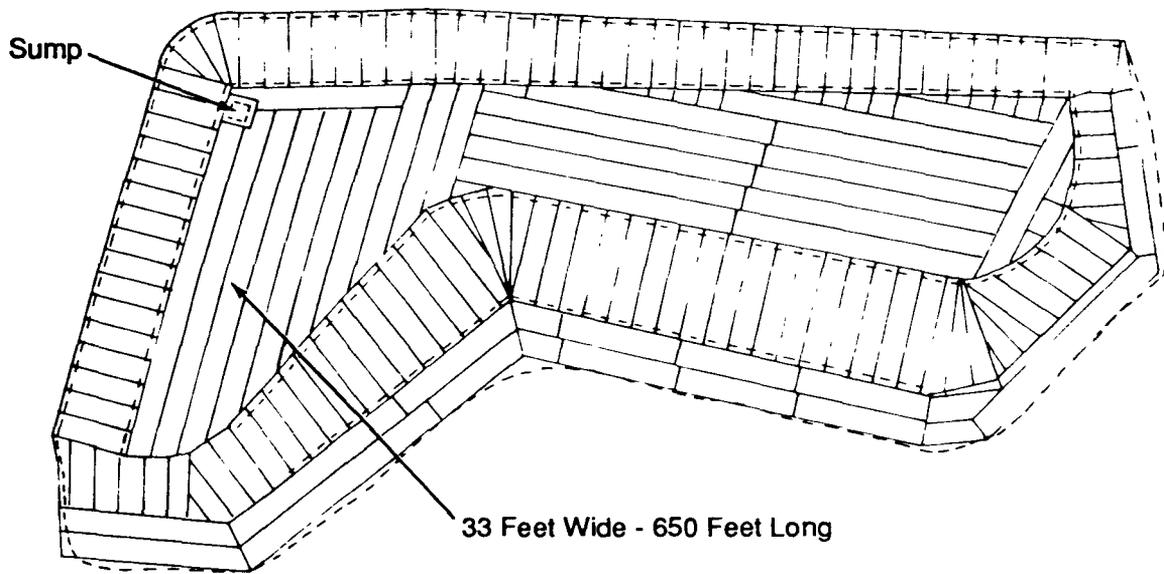


Figure 7-18. FML sheet layout for a surface impoundment. Total lined area equals approximately 861,000 ft². (Source: Schlegel, n.d.)

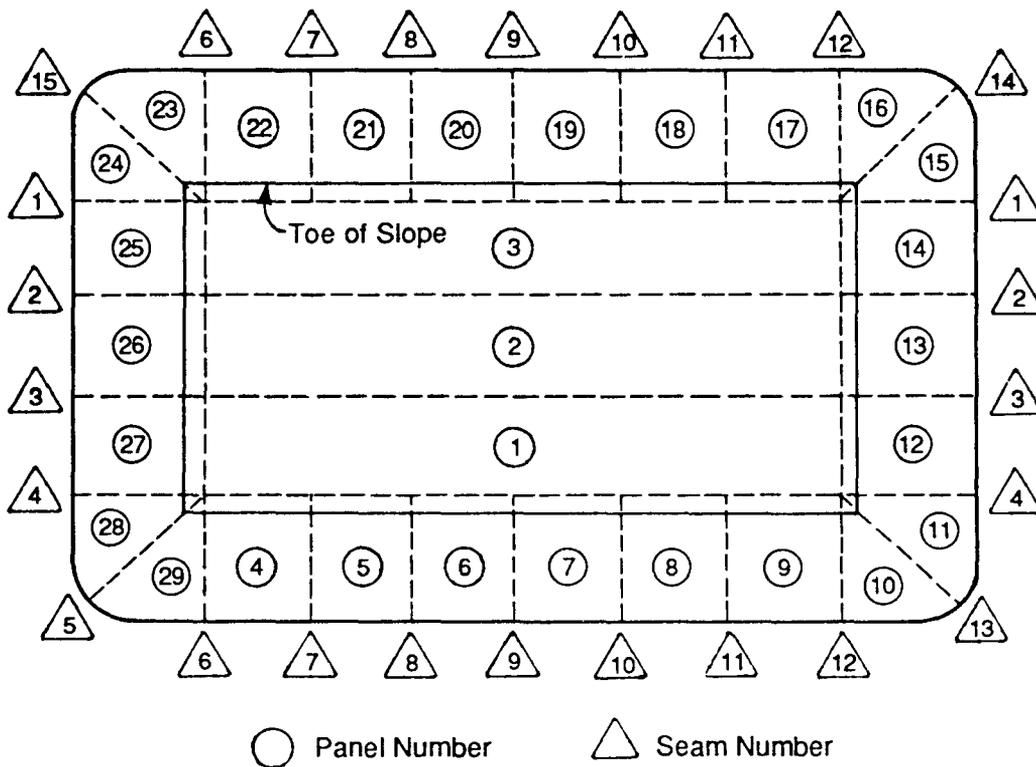


Figure 7-19. An FML panel layout.

7.5.3.3 The Interface Between the Soil and FML Components--

The draft Minimum Technology Guidance document on liner systems for hazardous waste landfills and surface impoundments states that the FML upper component and the soil lower component should directly contact each other (EPA, 1985). In this design, the uppermost lift of the compacted soil component serves as the bedding layer for the overlying FML component. Thus, the interface between the two components should be designed and constructed so as to provide a "compression connection" or contact between the two components so that lateral flow between them is minimized. Contact between the two components is maintained by the overburden load exerted by the overlying materials. The design and construction should minimize void space, channels, and other conditions promoting lateral flow of liquids at this interface. According to the draft guidance document, this requirement is not intended to preclude liner installers from purposely leaving designed folds in the FML to allow for thermal contraction (EPA, 1985). However, it is intended to preclude the use of a geotextile or other high-transmissivity bedding material between the upper and lower components.

The two potential drawbacks to the requirement for direct contact between the FML and soil components relate to the higher safety factor that results from using a geotextile underneath an FML to prevent puncture of the FML by sharp objects in the soil or to prevent soil erosion which could result in eventual rupture of the FML. Section 5.5 reports the results of various studies that simulated the effects of mechanical stress on the interaction between an FML and a subgrade. Studies that simulated the in-service behavior of an FML under hydrostatic pressure to evaluate the ability of an FML to conform to the irregularities in a subgrade indicated the effectiveness of using a geotextile to reduce an FML's susceptibility to puncture (Frobel et al, 1987; Fayoux, 1984). Brown et al (1987) studied the rate at which liquids flow through flaws in the FML component of composite FML-soil liners. It was noted that lateral flow between the two components resulted in higher leakage rates. However, results of tests in a pressurized system indicated that erosion of the soil liner can occur just below a flaw in an FML, particularly when the liquid head is large and when the hydraulic conductivity of the underlying soil liner is greater than $1 \times 10^{-6} \text{ cm s}^{-1}$. Erosion of the soil liner can result in stretching and eventual rupture of an overlying FML. Placing a geotextile between the FML and the soil liner could protect the soil from erosion. However, given the proper preparation of the soil liner as a bedding layer for the FML and an in-place hydraulic conductivity of $1 \times 10^{-7} \text{ cm s}^{-1}$ or less, given that liquid head on the bottom (composite) liner should never be very large, neither of these two concerns should ever be a problem.

7.5.4 Design of the Secondary Leachate Collection and Removal System (LCRS)

The function of a secondary LCRS, which is located between the top and bottom liners of a double-liner system, is to detect and collect any liquid that has entered the system, i.e. leaked through the top liner, throughout

the lifetime of the unit including the post-closure care period. Thus, a secondary LCRS functions as a system for detecting leaks in the top liner. To fulfill this function, a secondary LCRS must be constructed of materials that are able to maintain their functional integrity after exposure to the waste or leachate being contained. In addition, the system must be able to withstand the stresses and disturbances from overlying wastes, waste cover materials, and equipment operation, and be able to function without clogging throughout the lifetime of the unit including the post-closure care period.

A secondary LCRS typically is comprised of a number of subcomponents including:

- A drainage layer consisting of either granular or synthetic drainage media.
- A filter system to prevent clogging of the drainage layer and/or the pipe collection network.
- A strategically-placed network of perforated pipe for transporting leachate or a waste liquid from the drainage layer to the sump/manhole system.
- A bedding layer for the pipe network.
- A sump/manhole system which allows collection of the leachate or waste liquid and access to the pipe network for inspection and possible repairs through the operational and post-closure care periods.
- Mechanical and electrical equipment for conveying the liquid collected in the sump/manhole system to a separate storage or treatment area and for monitoring and controlling the level of leachate above the bottom liner.

In order to meet the basic performance requirements of a secondary LCRS, the design engineer needs to consider the following:

- The hydraulic transmissivity of the drainage layer.
- The slope of the drainage layer bottom and the pipe collection network.
- The required size and strength of the collection pipes.
- The spacing and layout of the collection pipes.
- The number and location of the monitoring and leachate/waste liquid withdrawal points.
- Design capacity of the system.
- The type of drainage system, i.e. granular or synthetic.

- The compressibility of the drainage system, i.e. the ability of the system to withstand overburden pressure while remaining functional.
- The mechanical compatibility of the LCRS with the lining system.
- The chemical compatibility of the LCRS with the leachate or waste liquid to be contained, particularly the compressibility of the drainage system after exposure to organic constituents of the waste liquid or leachate.
- The methods of monitoring and maintaining the performance of the system. Due to concerns about clogging, periodic inspection of the pipe system using television equipment may be required. To remove incrustations and deposits, the pipes may be flushed out using high-pressure rinsing devices developed for use in sewer systems. The requirements for using specific inspection and cleaning systems need to be considered.

At present, there are no performance standards for secondary LCRSs. In May 1987, the EPA proposed a series of standards for leak-detection sensitivity and minimum detection time (EPA, 1987b). In these proposed regulations, a secondary LCRS intended for leak detection must be capable of detecting a rate of top liner leakage that does not exceed 1 gal/acre/day (gpad) and be capable of detecting top liner leakage of 1.0 gpad or greater within 24 h of the leakage having entered the LCRS. The one-day criterion was established based on saturated, steady-state analyses of drainage layer materials that exhibit minimal wetting up. In order to meet these performance standards, the EPA proposed the following design requirements:

- A 2% minimum bottom slope of the drainage layer.
- A minimum hydraulic conductivity of 1 cm s^{-1} for a granular drainage layer.
- A minimum thickness of 12 in. for a granular drainage layer.
- A minimum hydraulic transmissivity of $5 \times 10^{-4} \text{ m}^2 \text{ s}^{-1}$ (2.4 gal/min./ft) for a synthetic drainage layer.

Requirements were also stated for sump capacity and monitoring.

As part of the design process, the EPA presently requires the compatibility testing of each component of an LCRS for a hazardous waste containment unit with the leachate or waste to which it could be subjected to be demonstrated (EPA, 1986d). The materials to be used must be exposed to the leachate or waste liquid under controlled conditions [e.g. those outlined in Method 9090 (EPA, 1986c; Appendix L)] and tested for appropriate properties. Polymeric components that have demonstrated compatibility with the waste liquid to be contained will also need to be fingerprinted so that it can be demonstrated that the material actually used in the field was equivalent to that tested for compatibility.

This section discusses the pipe used in an LCRS, LCRSs with granular media and synthetic media, pipe network layout, and basic requirements for the sump/manhole system.

7.5.4.1 Pipe Used in an LCRS--

The primary use of pipe in an LCRS is to collect leachate or waste liquid from the drainage layer and transport it to the sump/manhole system. Openings in the pipe should be sufficiently large and spatially arranged to allow free flow of liquids but not result in significant reduction of pipe strength. Pipe is also used in constructing monitoring ports and system cleanouts.

Pipes used to collect and transport leachate or waste liquid in a secondary LCRS must be able to withstand the overburden pressure resulting from the overlying layers even after long exposure to the waste or leachate with which they may be in contact. In constructing waste containment units, flexible pipes (i.e. those made of polymeric materials) are generally used as the collection pipes. Stainless steel and carbon steel pipes have been used as risers and auxillary cleanouts. The pipes can be installed in an LCRS either in trenches or in positive projection above the liner. Factors which must be considered in determining the required structural stability of the collection pipe include (Bass, 1986, p 41):

- Vertical loading.
- Perforations.
- Deflection.
- Buckling.
- Compressive strength.
- Backfill compaction.
- Loadings during construction.
- Chemical resistance.

Design equations for calculating the vertical load acting on flexible pipe in both trench and projected conditions are presented in Appendix I. The weakness of these equations is that it may be difficult to determine the average unit weight of fill because dense waste may be placed in a single area rather than spread evenly over the site. The designer should include a safety factor to balance these uncertainties.

In designing the primary LCRS for a landfill or a waste pile, estimated leachate flow is used to size and space the pipe system. However, for secondary LCRSs, flow in the collection system will vary because the rate

depends on flow through leaks in the top liner. In this case, pipe size and spacing need to be sufficient to allow rapid transmission of liquids and need not be designed to remove some predetermined volume rate of flow (EPA, 1985). In the field, 2-in. diameter pipes have been used, particularly in early design. At present, 6-in. diameter pipes are generally used and are recommended since larger pipes allow for simpler system maintenance and greater protection against clogging (E. C. Jordan, 1984). Ramke (1986) recommends using 200-mm (8-in.) pipe in order to ensure that the pipes can be inspected by television probes and can be cleaned out with rinsing devices. Equations for using leachate flow rate to determine pipe size and spacing are presented in Appendix I.

The collection pipe design must consider the size, spacing, and orientation of holes or slots used to perforate the pipe. Perforations must allow the leachate or waste to pass but prevent the passage of granular drainage media into the collection pipe. The size or diameter of these perforations, therefore, must be matched with the particle size of the drainage media. Satisfactory performance can be expected (Young et al, 1982) if the drain gravel gradation and perforation, diameter, or slotting width selected for the drain pipe satisfies the following U.S. Army Corps of Engineers (1955) criteria for gradation of filter materials in relation to pipe openings:

For slots:

$$\frac{D_{85} \text{ of the drainage media}}{\text{slot width}} \geq 1.2.$$

For circular holes:

$$\frac{D_{85} \text{ of the drainage media}}{\text{hole diameter}} \geq 1.2.$$

The Bureau of Reclamation (1977, p 235) uses the following criterion for grain size of filter materials in relation to openings in pipes:

$$\frac{D_{85} \text{ of the drainage media nearest the pipe}}{\text{maximum opening of drain pipe}} \geq 2.$$

where D_{85} is the screen size through which 85% of the drain rock (by weight) can pass. Cedergren (1967) suggests that the above equations represent a reasonable range over which satisfactory performance can be expected. Another criterion for pipe hole size considers the movement of liquid into the pipe as a function of the ratio between slot width and the wall thickness of the drain pipe. Knobloch (1969) recommends that the ratio of the slot width to wall thickness should be greater than or equal to 1.5 in order to maintain the widest possible hole with low flow resistance. The spacing of perforations depends on flow as well as pipe strength considerations (Mohammad and Skaggs, 1983).

Further discussion of pipe used in LCRSs can be found in Section 4.2.7, E. C. Jordan (1984), and Bass (1986).

7.5.4.2 Drainage Systems and the Design of a Secondary LCRS--

The drainage layer of an LCRS can be either a granular or a synthetic system. However, even though the basic function and operation of these two types of systems are the same, the specific design considerations are different. Therefore, the design of LCRSs with granular and synthetic systems are discussed separately.

7.5.4.2.1 Granular drainage systems--A wide range of sands and gravels can be used in LCRSs. Limestone, however, should be avoided because contact with high pH liquids can result in Ca precipitates that can clog pipe perforations and the stone itself. Table 7-3 lists granular media, their possible function in an LCRS, and other factors that need to be taken into account for media selection. The functions that granular media can serve in an LCRS include:

- As protectors, to protect an FML against puncture by coarser-grained media (e.g. drainage gravel).
- As drainage media, to allow drainage of leachate or waste liquid so that leakage can be detected, collected, and removed.
- As filters, to allow seepage flow while restricting particle movements.
- As bedding, to give structural strength to flexible and semiflexible pipes.

Geotextiles have also been used in granular drainage systems as protectors and as filters.

The draft Minimum Technology Guidance document for double liner systems (EPA, 1985) requires granular drainage layers to have a minimum hydraulic conductivity of $1 \times 10^{-2} \text{ cm s}^{-1}$. More recently proposed regulations require a minimum hydraulic conductivity of 1 cm s^{-1} for granular leak-detection systems (EPA, 1987b). Both require a minimum granular drainage layer thickness of 12 inches. The draft Minimum Technology Guidance also requires a minimum 12-in. bedding layer of material no coarser than Unified Soil Classification System (USCS) sand (SP) with 100% of the washed, rounded sand passing the 0.25-in sieve. The material for the bedding above the bottom FML was intended to function also as the drainage layer. However, the recently proposed regulations require a coarser grained material necessitating the use of either granular or synthetic protectors above and below the drainage layer (EPA, 1987b).

There has also been concern about the clogging of granular drainage media caused by both physical-chemical and biological mechanisms (Haxo and

TABLE 7-3. GRANULAR MEDIA THAT MIGHT BE USED IN LEACHATE COLLECTION AND REMOVAL SYSTEMS

Media type	Particle size (diameter in inches)	Potential function	Hydraulic conductivity ^a , cm s ⁻¹	Construction considerations	Availability
Sand (fine, medium, coarse)	1/64 to 1/8	Protection Filter Drainage ^b Bedding	1×10^{-3} to 1×10^{-1}	High compactive effort necessary if used as bedding.	Availability commonly good for bank run and clean. Clean sand necessary for use as drainage medium.
Well-graded gravel	1 (maximum)	Filter Drainage ^b Bedding	3×10^{-1} to 10	High compactive effect necessary if used as bedding.	Availability good, especially for bank run.
Coarse, uniform gravel	1/4 to 3	Drainage ^b Bedding	10 to 50	Easy to install and compact.	Regional availability. Optimal functional characteristics.

^aValues for hydraulic conductivity are for saturated flow conditions.

^bFor drainage layers, minimum recommended hydraulic conductivity is 1×10^{-2} cm s⁻¹ in the draft Minimum Technology Guidance document for double liner systems (EPA, 1985) and 1 cm s⁻¹ in proposed regulations for leak-detection systems (EPA, 1987b).

Source: E. C. Jordan, 1984, p 22.

Haxo, 1988). Ramke (1986) investigated the clogging of the primary LCRSs in MSW landfills in West Germany. He concluded that granular drainage systems could be effectively clogged by deposits resulting from biological activity and physical-chemical reactions. In particular, fine-grained filter materials and well-graded mixed sand filters appeared to clog relatively quickly. Ramke (1986) recommends using narrowly graded washed gravel, 16-32 mm (0.63-1.26 in.) in size.

Construction of a top composite liner on top of the secondary LCRS will require a barrier above the drainage layer to prevent clogging of the voids in the drainage layer by infiltration of fines from the soil component and prevent potential damage to the soil component by piping. This barrier can be either an FML or a filter layer. Either geotextiles or granular media can be used as the filter layer. Granular filters consist of a soil layer or combination of soil layers having a coarser gradation in the direction of seepage (i.e. leakage) than the soil above the filter. In designing a granular filter, it is important that the relationship of grain sizes of the filter medium and the drainage layer be appropriate if the filter is to prevent rather than contribute to clogging. Criteria for granular filters are discussed by Bass (1986), Bureau of Reclamation (1974 and 1977), and Cedergren (1967). Permittivity and filtration criteria for using geotextiles are discussed in Section 4.2.3.3 and by Bass (1986). A geotextile used as a filter between an LCRS and an overlying soil liner should not allow clay particles to extrude through its voids. Thus, the percent open area (POA) of a geotextile used as a filter between an LCRS and an overlying soil liner should be equal to zero (Koerner, 1988). POA is defined by the Corps of Engineers in CW-02215 as the sum of open areas divided by the total area and expressed as a percentage. The sum of the open areas is determined by projecting a light through the geotextile onto a screen. A needle-punched, nonwoven fabric with a POA equal to zero and mass per unit area greater than or equal to 12.0 oz yd⁻² is recommended. To increase the safety factor and prevent the extrusion of clay particles, a thin FML may be placed on top of the geotextile.

Figure 7-20 illustrates two possible drainage layer configurations for granular drainage systems in FML/composite double-liner systems. In Figure 7-20a, sand is used as the primary drainage layer material. The pipe is buried in coarse uniform gravel to provide additional structural stability. The bedding media is wrapped in a geotextile to prevent the migration of the sand particles into the bedding media. In constructing this system, the sand layer would be placed on top of the liner and then excavated in the required runs using special equipment (e.g. a backhoe with a rubber blade) to allow placement of the pipes. This system probably would not meet the proposed hydraulic conductivity requirement of 1 cm s⁻¹. Figure 7-20b presents a granular drainage system using coarse, uniform gravel throughout the drainage layer. A geotextile is placed above and below the drainage layer to protect the FML liners. It is generally considered the better practice to wrap a pipe trench with a geotextile (as is shown Figure 7-20a) rather than the pipe itself. Some engineers have proposed wrapping the pipe with a geotextile to prevent drainage media from migrating into the pipe, thus allowing

larger pipe perforations. However, this is not the recommended practice because of concerns about clogging of the geotextile filter, particularly around the pipe perforations, by fines or other mechanisms. It should also be noted that some designers may place FML scruff strips underneath all pipe runs (Salimando, 1988).

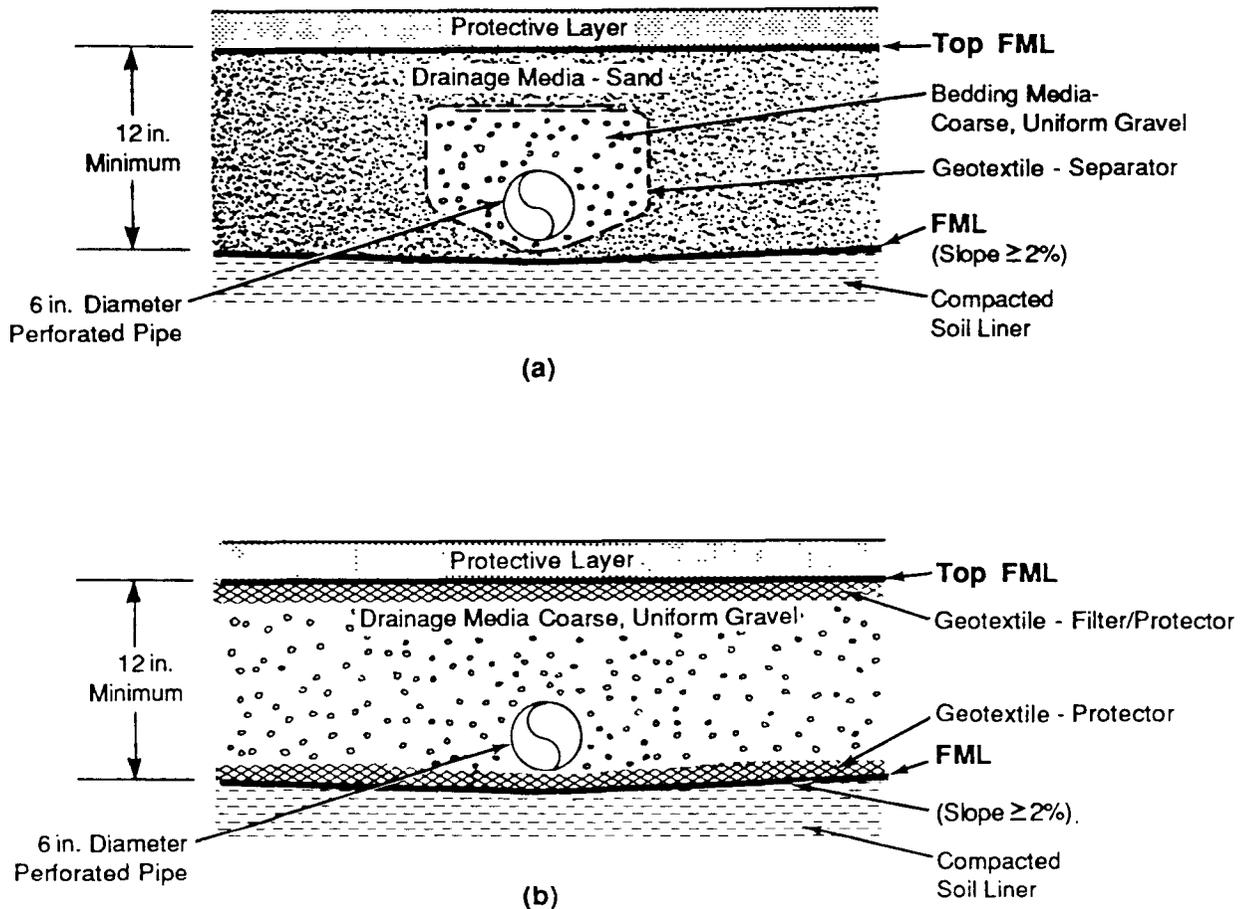


Figure 7-20. Schematic of granular drainage systems in secondary LCRSs for double-lined surface impoundments. (Based on E. C. Jordan, 1984, p 29).

Two important problems in designing an LCRS with granular media are (1) the difficulty of constructing a granular drainage layer on the slopes, and (2) potential difficulties with constructing components on the slopes on top of a granular drainage system, particularly those designed with relatively coarse materials. In order to maintain the integrity of the unit, a granular drainage system on the slopes needs to be structurally stable so that sloughing does not occur. Thus, there must be adequate friction (1)

between the granular media and the bottom FML, (2) between the granular media and itself, and (3) the granular media and the overlying components (e.g. an FML). The required slope may be relatively flat, resulting in an inefficient use of space. Because of the difficulty of installing a granular LCRS on the slopes, many engineers are designing LCRS systems that use granular media on the floor and synthetic drainage media on the slopes. In addition, the drainage system has to stay in place while the layers above are constructed. In constructing granular drainage systems, it should be noted that single-size rounded gravel is more difficult to construct on top of than single-size crushed and washed gravel; however, to obtain the same conductivity, the required grain size for crushed and washed gravel is significantly higher than for rounded gravel. When crushed gravel is used in an LCRS, special measures have to be taken to protect the FML, e.g. a geotextile is placed above and below the gravel.

7.5.4.2.2 Synthetic drainage systems--The types of synthetic drainage media that can be used in an LCRS include geotextiles, geonets, and geocomposites. With the recent commercial development of high drainage capacity geonets and geocomposites, however, geotextiles are at present generally used in LCRSs as filters, separators, or protectors. Some engineers are concerned about the ability of geotextiles to maintain their transmissivity after long-term exposure because of potential clogging by biological activity or other means. The use of geonets and geocomposites as drainage media are discussed in Sections 4.2.5 and 4.2.6, respectively.

Synthetic drainage media have many potential advantages over granular drainage media:

- Synthetic drainage media may be easier to obtain commercially or be less expensive than granular media.
- Synthetic drainage media are thin compared with granular drainage layers and, therefore, allow for larger disposal capacity.
- Synthetic drainage media can be placed on steeper side slopes than granular materials and, therefore, again allow for larger disposal capacity.
- Construction can be performed on top of synthetic drainage media, whereas granular layers ($k > 1 \text{ cm s}^{-1}$) will not stay in place while overlying components are constructed.
- Construction quality is easier to evaluate.

The potential disadvantages of synthetic drainage media include:

- The influence of large normal loads on the transmissivity of the system initially due to the elastic compression of the synthetic layer and over a period of time due to compressive creep. This is of particular concern with geonets because of the possibility of intersecting rib "layover."

- The effects of exposure to constituents of the waste liquid or leachate on the compressive creep of the synthetic drainage system and the subsequent effects on transmissivity. Of particular concern are organic constituents which can soften polymeric compositions and which can enter the secondary LCRS, both by leakage and by vapor transmission through the top FML.
- The effect of intrusion by the lining system (above and below) into the synthetic drainage media. The effects of intrusion into geonets and geocomposites are discussed in Sections 4.2.5 and 4.2.6. Limited results of testing the hydraulic transmissivity of three types of geonets under different boundary conditions are discussed in Section 5.5.3.2. Of particular concern is the effect of constructing the soil component of a composite liner on top of a synthetic drainage layer.

An example of a synthetic drainage layer system is presented schematically in Figure 7-21. In this example, a trenched pipe network underlies the synthetic drainage layer. The gravel used for the pipe bedding is wrapped in a geotextile to protect the FML components of the bottom composite liner and, depending on the type of synthetic drainage media, to protect the top FML liner and the drainage media.

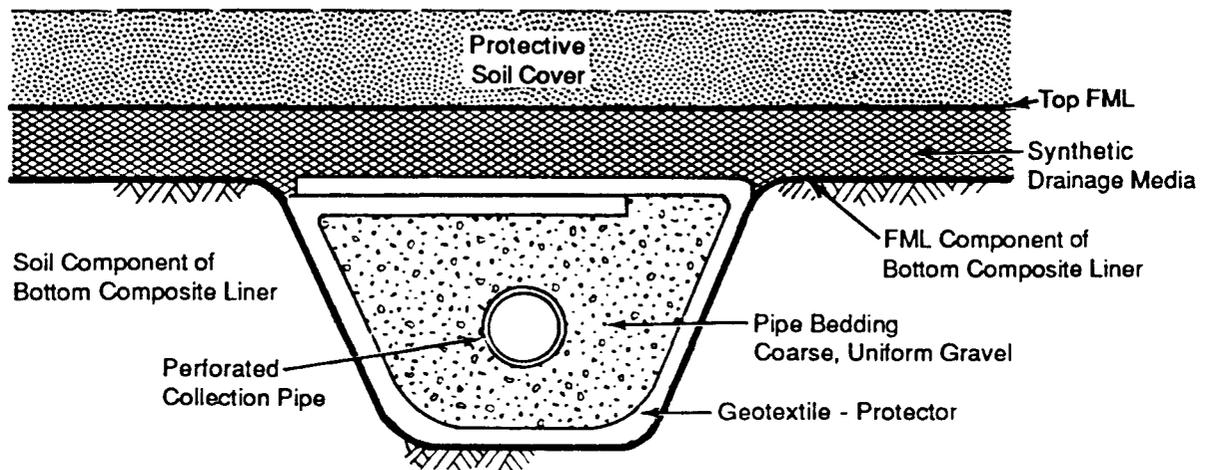


Figure 7-21. Schematic of an LCRS for a surface impoundment with a synthetic drainage layer (not to scale). (Based on E. C. Jordan, 1984, p 39).

In the case of a double-lined unit for the containment of hazardous wastes, one problem with constructing a system containing trenches is the difficulty of meeting the requirement that the bottom soil liner have a minimum thickness of 3 ft. The solution to this problem is to overbuild the clay liner, which, however, can significantly affect costs. In addition,

care needs to be taken to prevent stress concentrations when fitting the FML into the trenches, particularly with stiffer, thicker FMLs. Because of these concerns, some engineers in designing a secondary LCRS have stacked two or more layers of geonets instead of installing a trenched pipe network. However, it should be noted that experience with synthetic drainage media in land-disposal applications is limited, and their ability to perform on a long-term basis remains unproven.

It is also possible to design a secondary LCRS which uses granular drainage media along the bottom of the unit and synthetic drainage media on the side slopes, as is shown schematically in Figure 7-22.

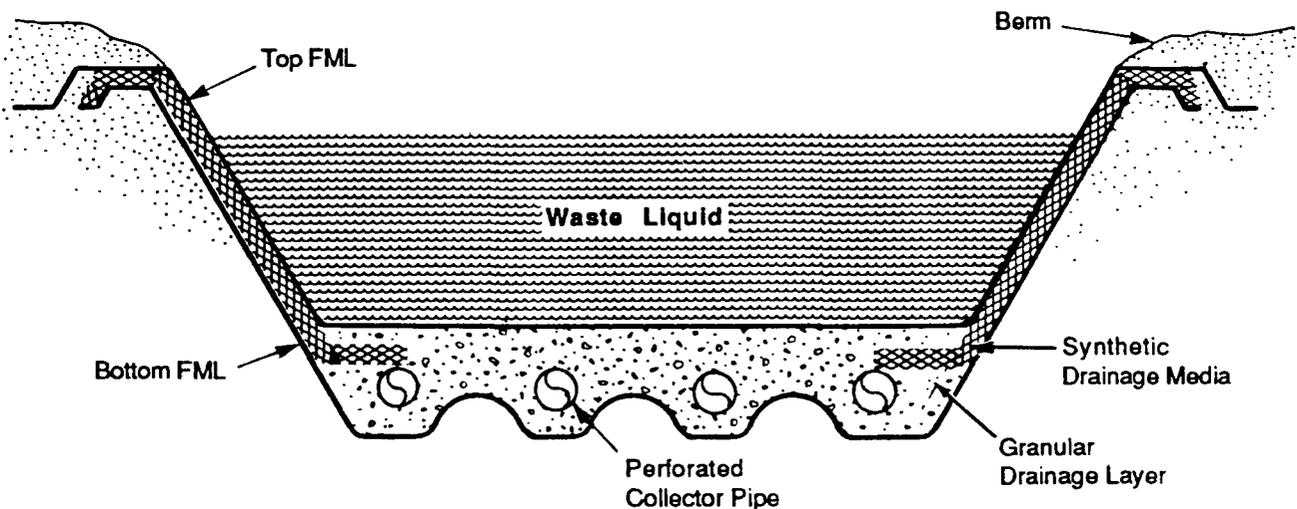


Figure 7-22. Schematic showing the use of synthetic drainage material on side slopes and a granular drainage system on the bottom of a surface impoundment. (Based on E. C. Jordan, 1984, p 38.)

7.5.4.3 Bottom Slope--

A relatively high rate of liquid movement is necessary to allow rapid collection and removal of liquids present in the system and to minimize the deposition of particles and silt. Because the rate of liquid movement through an LCRS is proportional to the bottom slope, present EPA guidance requires an LCRS to have a minimum bottom slope of 2% (EPA, 1985). The preamble to proposed regulations on leak detection systems (EPA, 1987b) indicates that this minimum slope requirement applies to all components of an LCRS, including the bottoms of the drainage media, the collection pipes, the collection laterals, and all other piping and/or drainage features. Depending on the design, this requirement may result in areas of the unit with bottom slopes greater than 2%. It may be necessary to increase the minimum bottom slope requirements to alleviate concerns that units designed with 2% bottom slopes could actually end up with slopes less than 2% due to imperfect construction or post-construction settlement.

7.5.4.4 System Layout--

The layout or configuration of the pipe collection system in an LCRS varies from site to site depending on factors such as site topography, unit size, climatic conditions, design preference, regulatory requirements, and the type of waste liquid or leachate that will contact the LCRS. The spacing of the pipe network is discussed in Appendix I. Layout of the system should provide alternate paths for the leachate or waste liquid to flow to the collection point, should allow for access to the drainage layer and collection sump for inspection and maintenance, and should allow for minor subsidence of the drainage layer (Bass, 1986). An example of a system layout for a secondary LCRS for a surface impoundment is presented in Figure 7-23. In this schematic, the collection header penetrates the bottom liner to connect with a cleanout manhole and a monitoring/collection manhole, and

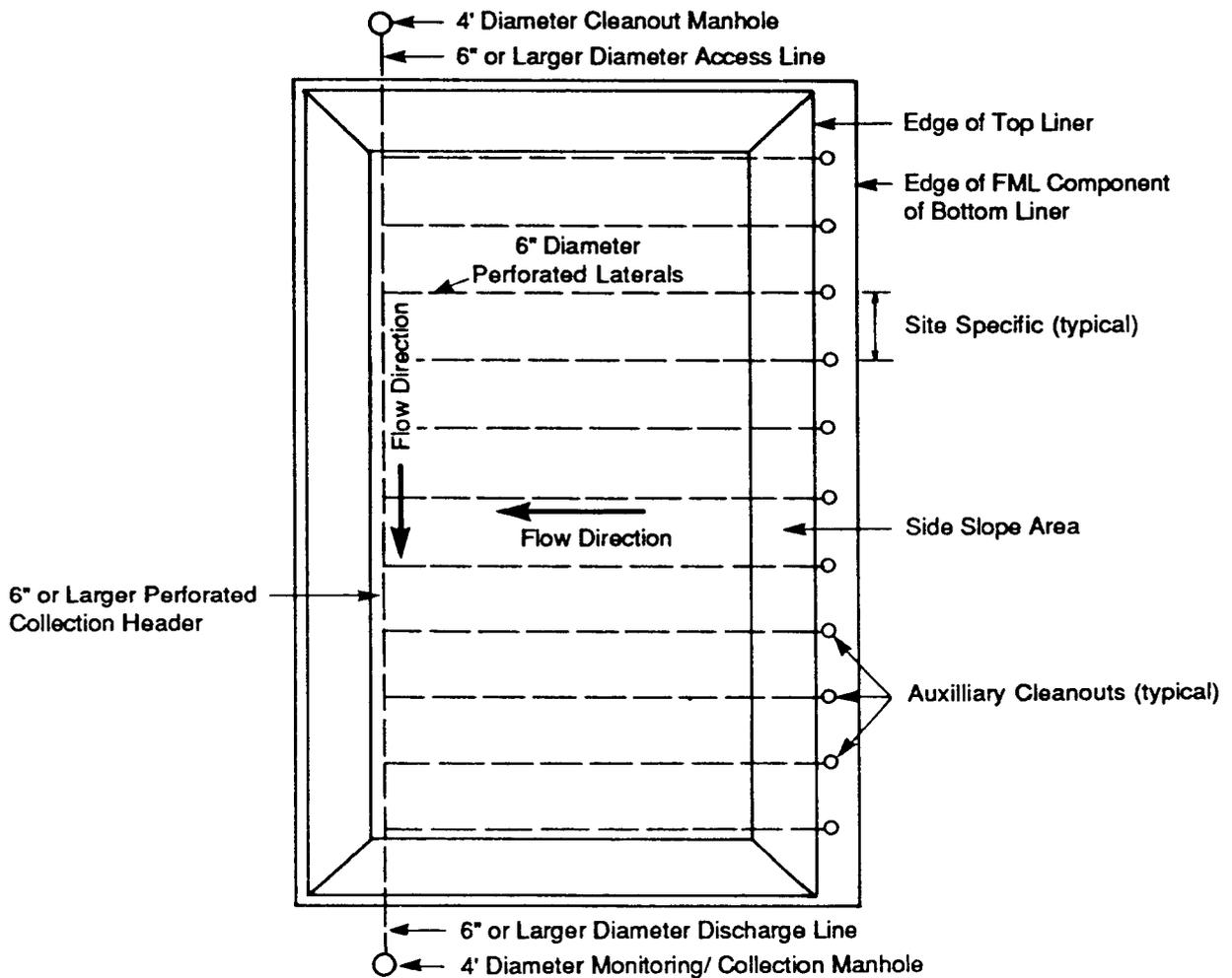


Figure 7-23. Schematic layout of pipe in a secondary LCRS for a surface impoundment. (Based on E. C. Jordan, 1984, p 32).

the auxiliary cleanouts are installed between the top and bottom liners and penetrate the top liner on the berm. The decision to penetrate the liner and place a sump outside the containment should be made only after assessing the relative advantages and disadvantages of such a decision.

7.5.4.5 Sump Requirements--

Leachate or waste liquid is conveyed through the pipe collection network by gravity to one or more sumps depending on the system layout. The sump system should be of appropriate size to collect liquids efficiently and to prevent liquids from backing up into the drainage layer. Proposed EPA regulations require each unit to have its own sump and require the design of the sump and removal system to provide a method for measuring and recording the liquid volume present in the sump and the amount of liquid that has been removed on a daily basis (EPA, 1987b). In addition, in the case of a landfill, the LCRS above the top liner and the LCRS between the top and bottom liners should have separate sump systems. The draft Minimum Technology Guidance document (EPA, 1985) states that sumps should be capable of functioning automatically and continuously. The EPA also interprets the requirement for a maximum 12-in. hydraulic head on a liner to include the sump.

Sumps for secondary LCRSs can be either outside the unit, as is shown in Figure 7-23, or inside the unit on top of the bottom liner. Six- and eight-in. riser pipes have been used for removing liquids from a sump. Riser pipes can be placed so that they go up the unit's slope in between the top and bottom liners and penetrate the top liner at the berm. When side slope risers are used in conjunction with synthetic drainage media on the slopes, the riser pipes are placed in trenches that run up and down the slopes. A schematic of a sump system with a side slope riser is shown in Figures 7-24A, B, and C.

To facilitate inspection and maintenance, manholes have also been used. Manhole systems inside the unit will need to penetrate the top liner, in which case the top FML liner will need to be attached to the manhole and special measures need to be taken to prevent differential settlement under the sump system to prevent tearing of both the top and bottom FMLs. Because of concerns about differential settlement, down-drag forces, and potential damage to the lining system, manhole-sumps inside the unit for secondary LCRSs are generally discouraged.

Manhole-sump systems can also be placed outside the unit. The leachate or waste liquid entering the secondary LCRS flows to the manhole by gravity drainage. The placement of a manhole-sump system outside the unit is shown in Figure 7-23. A manhole-sump placed outside the unit is presented schematically in Figure 7-25. It must be recognized, however, that the outlet piping must penetrate the secondary composite liner system. In addition, it should be noted that piping and sump systems that penetrate a secondary liner for a hazardous waste containment unit will also require a secondary liner.

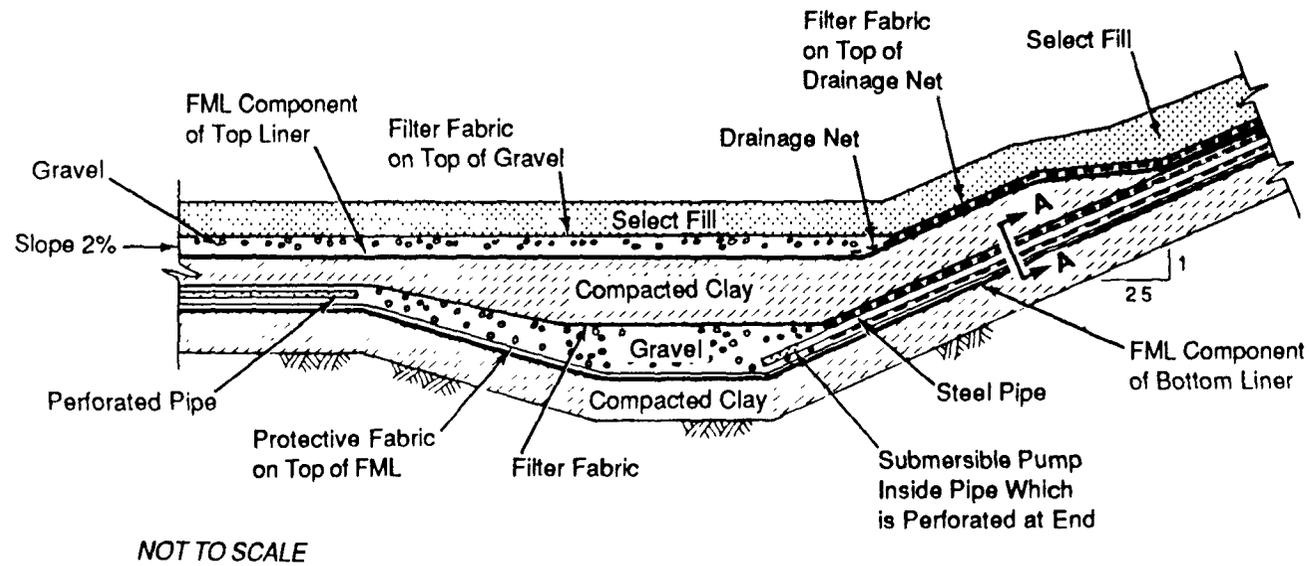
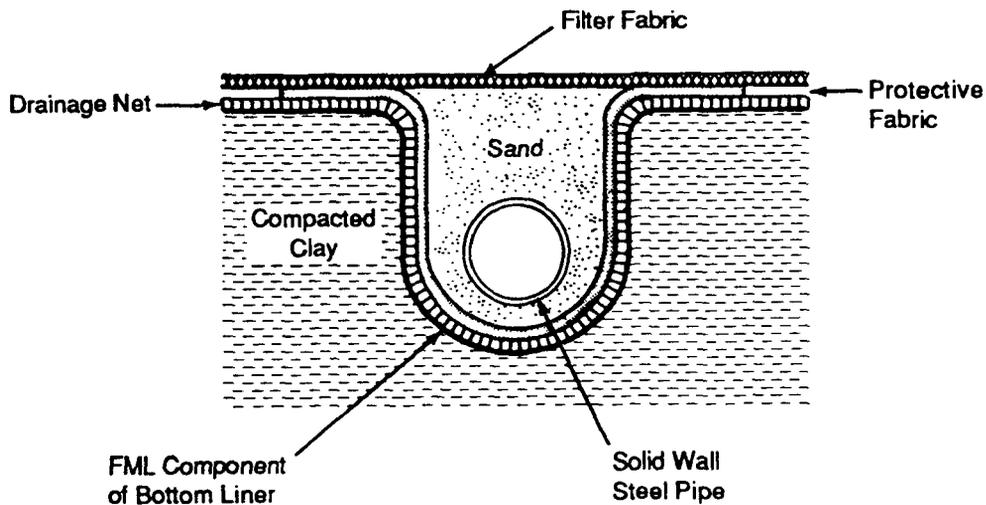


Figure 7-24A. Schematic of a sump system inside the unit for a secondary LCRS with liquid removal through a side slope riser pipe--Floor of the unit and partway up the slope. Cross-section A-A is presented in Figure 7-24B. (Based on a drawing courtesy of Chemical Waste Management, Inc.).



Not to Scale

Figure 7-24B. Schematic of a sump system inside the unit for a secondary LCRS with liquid removal through a side slope riser pipe--Detail of cross section A-A from Figure 7-24A showing trench for riser pipe on the slopes. Protective fabric extends 5 or more feet on each side of the trench. (Based on a drawing courtesy of Chemical Waste Management, Inc.).

The advantage of placing the manhole-sump outside the unit over using side slope risers is that liquid flow out of the unit depends on gravity drainage rather than a pump. The advantages of using side slope risers over placing a manhole-sump outside the unit include:

- Side slope riser pipes penetrate the primary FML at the berm. The discharge liner from a containment must penetrate both components of the secondary liner at a low point in the unit.
- If the site is subject to seismic activity, there will be concern about the ability of the discharge liner to withstand such activity.
- Placing a sump-manhole outside the unit effectively increases the space required for a unit, resulting in a less efficient use of overall space.

The hydraulic head in an LCRS sump located inside a unit needs to be kept at 12 in. or less for three reasons:

- Sumps are often of complex geometry, resulting in a greater potential for breaches in both FMLs (seam defects, tears, etc.) and compacted soil components (cracks).

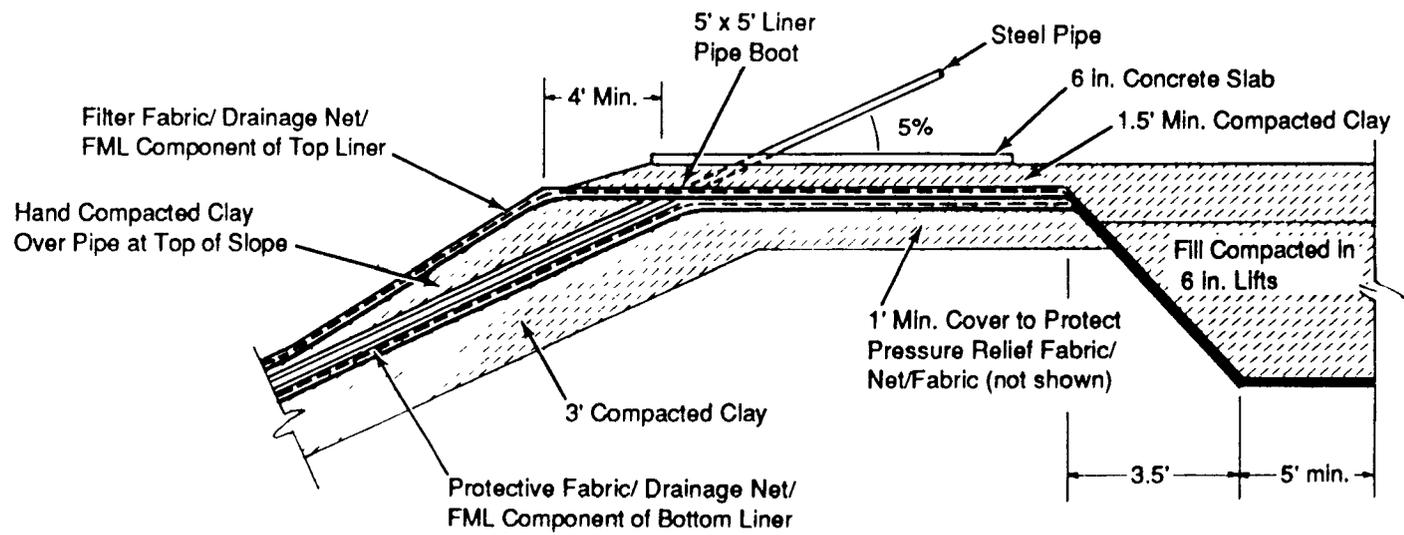


Figure 7-24C. Schematic of a sump system--Berm of the unit. (Based on a drawing courtesy of Chemical Waste Management, Inc.).

- Since the area around the sump may not have an adequate bottom slope, liquid entering the sump may pond over the bottom liner.
- Regulatory requirements.

One disadvantage of the requirement is that the submersible pump will always be working with little or no head.

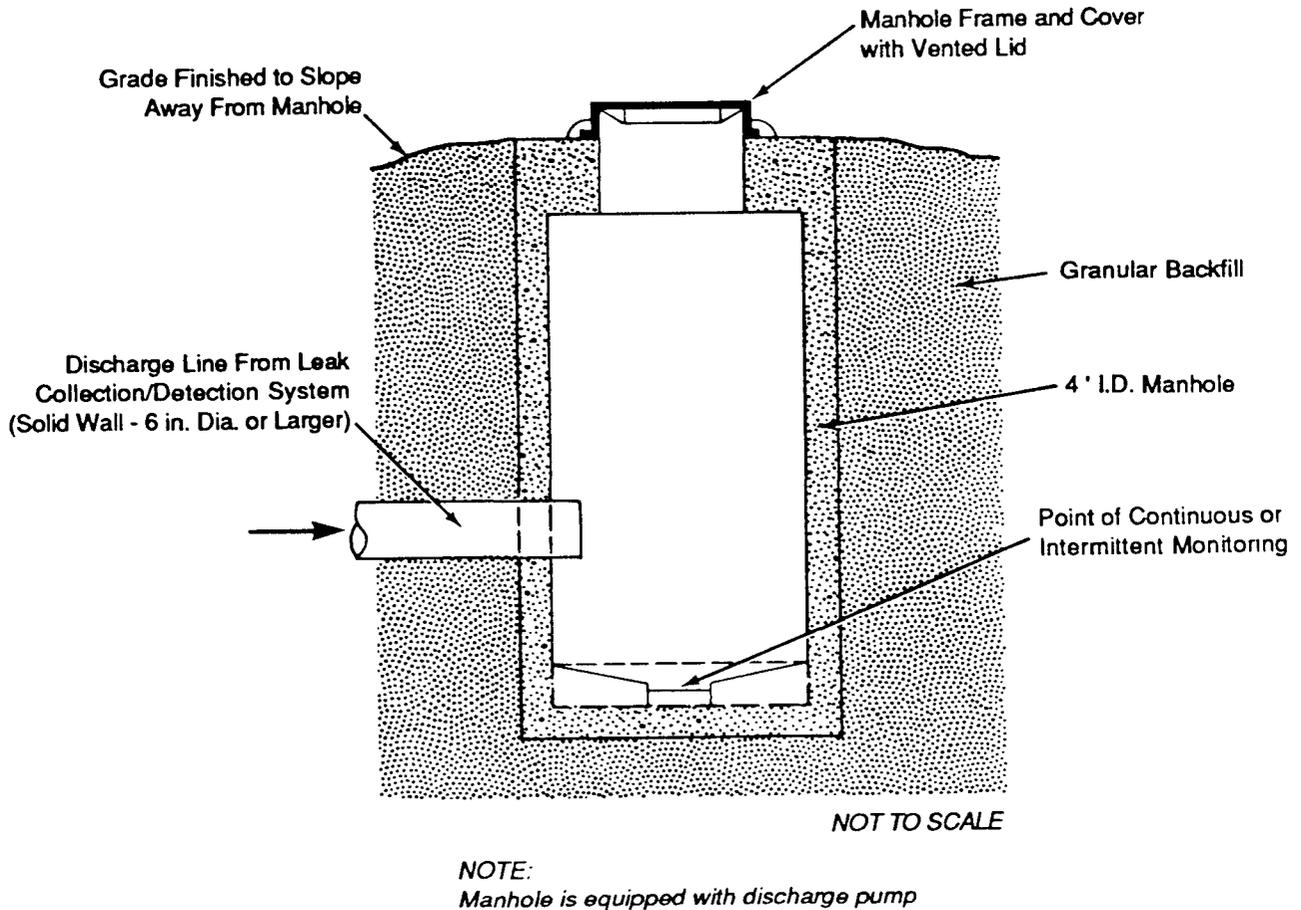
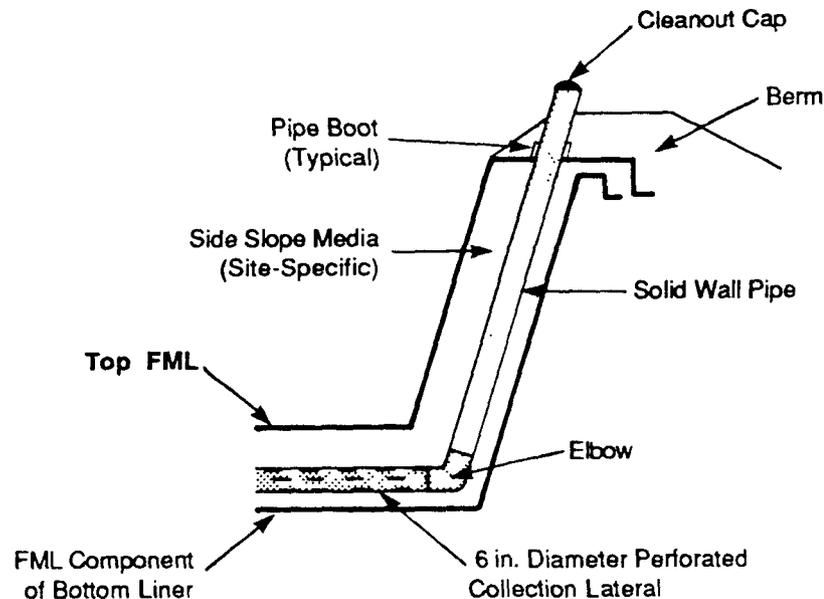


Figure 7-25. Schematic of a monitoring and collection manhole located outside a unit (not to scale). (Based on E. C. Jordan, 1984, p 34).

7.5.4.6 Auxiliary Cleanouts--

Auxiliary cleanouts allow access to collection laterals from the up-gradient end. When included in a design, they can extend up the slope and penetrate the top liner at the berm. Auxiliary cleanouts can be made of the same materials used to make the collection pipes, and their diameter is usually equivalent to the collection lateral diameter. An example of an

auxiliary cleanout is presented in Figure 7-26. As with side slope riser pipes, if a synthetic drainage medium is used on the slopes, the auxiliary cleanout pipes will be installed in trenches that run up and down the slopes.



NOTE:
Diameter of cleanouts complementary with collection laterals. Vertical scale is exaggerated.

Figure 7-26. Schematic of an auxiliary cleanout (not to scale). (Based on E. C. Jordan, 1984, p 34).

7.5.5 Design of the Top Liner

The top liner of a double liner system for a hazardous waste containment unit can be either an FML or a composite liner made up of an upper FML component and a lower compacted low-permeability soil component similar in design to the bottom composite liner. This section describes these two basic design options.

7.5.5.1 An FML-only Top Liner--

The basic requirements for an FML top liner are the same as those for the FML-component of a bottom composite liner. These requirements include:

- Low permeability to constituents of the waste liquid or leachate to be contained.

- Chemical compatibility with all constituents of the waste liquid or leachate to be contained.
- Mechanical compatibility with the service conditions.
- Durability.
- Capability of being installed.

These requirements are discussed in Section 7.5.3.2. It should be noted that the service conditions of a top FML liner can be significantly different from the service conditions for a bottom liner, depending on the type of containment unit. This section discusses design problems specific to top liners. These include special considerations regarding mechanical interaction with the drainage layer of the secondary LCRS and considerations about thickness, particularly of unreinforced FMLs.

7.5.5.1.1 Interaction between an FML and a drainage layer--An FML can interact with a drainage layer either above or below the liner in two ways, depending on whether the drainage system is granular or synthetic. A relatively coarse granular medium can puncture an FML because of the combined overburden and hydraulic forces acting on the FML. In addition, potential interaction with constituents of the leachate or waste liquid may decrease puncture resistance of the FMLs. To alleviate concern about puncture, a relatively thick FML could be specified in conjunction with either a geotextile or a granular bedding layer placed on top of the drainage gravel.

Because of its flexibility, an FML can interact with a synthetic drainage medium by intruding, when under load, into the voids necessary for drainage. This intrusion can significantly affect the transmissivity of the drainage system. The intrusion of FMLs into geonets and geocomposites is discussed in Sections 4.2.4 and 4.2.5. The mechanical compatibility of the FML with a synthetic drainage system should be investigated in a transmissivity test in such a way that the drainage system is exposed to mechanical stresses that simulate actual service conditions. The profile of layers tested in the transmissivity apparatus should simulate the profile of the lining system to be used in the field (see Section 5.5.3). Testing may indicate the need for a different combination of FML and synthetic drainage media.

7.5.5.1.2 FML thickness considerations--The physical properties of unreinforced FMLs are proportional to their thickness, and, therefore, the historical trend has been to use thicker membranes. Whereas in the 1960's, FMLs were generally 10 to 20 mils in thickness, at present they range from 30 to 120 mils. The draft Minimum Technology Guidance document on double liner systems for hazardous waste landfills and surface impoundments requires the FML top liner to be at least 30 mils in thickness (EPA, 1985). However, if the FML is to be exposed to the weather for an extended period before it is covered by a protective soil layer or waste, or if the FML is to be used without a protective cover, a minimum thickness of 45 mils is proposed (EPA, 1985).

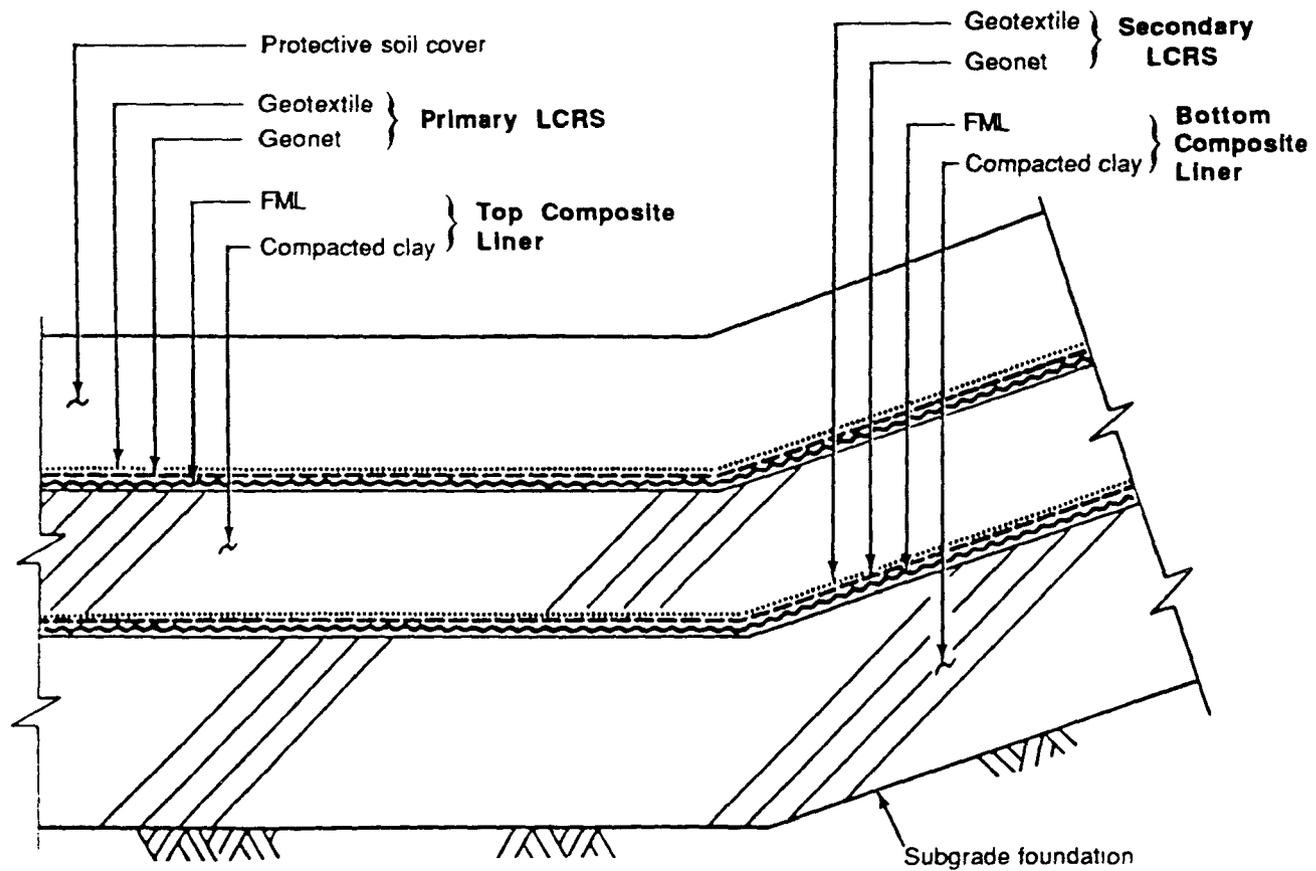
If an unreinforced FML is being used, a thicker liner may be required to prevent failure while the unit is operating, including the post-closure care period. The adequacy of the selected thickness should be demonstrated by an evaluation that considers the type of FML and site-specific factors such as expected operating period of the landfill or surface impoundment unit, pressure gradients, physical contact with the waste and leachate, climatic conditions (environmental factors), the stress of installation, and the stress of daily operation (e.g. placing wastes in the landfill or sludge removal in surface impoundments). Operational stresses tend to be higher for surface impoundment units than for landfill units. As is discussed in Section 5.2.4, service conditions in surface impoundments tend to be more severe than those in landfills because of factors such as:

- Cleaning or maintenance activities.
- Thermal stress.
- Hydrostatic pressure (head and wave action).
- Abrasion.
- Weather exposure (ultraviolet light, oxygen, ozone, heat, and wind).
- Operating conditions (inlet and outlet flow, active life, exposure to animals, treatment processes).

Because of these factors, uncovered surface impoundments lined with unreinforced FMLs are frequently lined with FMLs 60 to 100 mils in thickness. A protective layer covering the top liner in surface impoundments can reduce the operational stresses on the FML. Overburden stresses on landfill and waste pile liners will depend on the height and density of the waste placed in the unit. Units designed to contain large volumes of dense waste may also require FMLs thicker than the minimum specified thickness.

7.5.5.2 Composite Top Liner--

The results of a study performed by Brown et al (1987) indicate that flow rates through small holes in an FML are significantly affected by the permeability of the layer underlying the FML. These results showed that when an FML is in contact with an underlying low-permeability soil (with a hydraulic conductivity in the range of $1 \times 10^{-6} \text{ cm s}^{-1}$), the flow rates through small holes in the FML were approximately five orders of magnitude lower than they were when the same size holes were underlain by a gravel (with a hydraulic conductivity in the range of $1 \times 10^{-1} \text{ cm s}^{-1}$). Because of these results, Buranek and Pacey (1987) and other designers have recently proposed the use of a composite soil and FML liner as the top liner of a double liner system, resulting in a double composite liner system [see also Buranek (1987)]. An example of a double composite liner system is presented in Figure 7-27.



NOTES:

1. Primary LCRS components are not applicable for surface impoundments.
2. Primary and secondary LCRS may be granular materials.
3. Protective soil cover may be optional for surface impoundments.

Figure 7-27. Schematic of a double composite liner system. (Source: Buranek and Pacey, 1987, p 379).

The primary potential advantage of a composite top liner over an FML-only top liner is that a composite liner will reduce the amount of leachate that enters the secondary LCRS between the top and bottom liners. The disadvantages of a composite top liner include:

- An increase in the amount of time necessary to detect a leak in the top FML since the leachate or waste liquid must pass through the clay component of the liner before entering the leak-detection system.
- An increase in cost of the top liner.
- An increase in the complexity of constructing a containment unit.
- A decrease in the capacity of the unit.
- Potential damage to the FML component of the bottom composite liner due to the construction above the liner.
- Lack of knowledge about the mechanical interaction between the soil component of a top composite liner and a secondary LCRS designed with synthetic drainage media.

The results of a study evaluating the mechanical interaction between a synthetic drainage media, a geotextile, and an overlying soil were presented in Section 5.5.3.2. These results show that a geonet tested in a cross section simulating a liner system with a top composite liner allowed a flow rate that was 20 to 40% that of a geonet tested in a cross section simulating a liner system with an FML-only top liner, indicating intrusion of the geotextile into the drainage medium. Stresses during the compaction could result in (1) further intrusion into the drainage layer preventing flow in the system or (2) excessive loadings on the geotextile-filter component of a geocomposite, causing the fabric to tear and allow soil to enter the drainage system. In addition, the compactive effort used to construct a soil liner could cause the collapse of the drainage media. It should be noted that long-term creep of the geotextile or geonet could also result in all of these same effects; the effects of creep need to be investigated.

Another important consideration is the possibility of the clay extruding through the voids of the geotextile and clogging the drainage systems. As is discussed in Section 5.5.3.2, results of tests with a needle-punched, non-woven polyester, continuous filament fabric of 16 oz yd⁻² mass per unit area indicated that the clay did not extrude through the geotextile. After analyzing the data, Koerner (1988) recommended two minimum requirements for a geotextile used as a filter above a geonet serving as the drainage media for a secondary LCRS:

- The geotextile should have a percent open area (as defined by the Corps of Engineers in CW-02215) equal to zero.
- The geotextile should be a needle-punched nonwoven fabric with a mass per unit area greater than or equal to 10.0 oz yd⁻².

At the present, there are no guidelines concerning the construction or performance of the soil component of a top composite liner. However, the first layers of soil placed on top of the LCRS will probably not be compacted as part of the soil component. Depending on the type of drainage system used in the secondary LCRS, the soil may not be compacted with the same effort as the soil component of the bottom composite liner; thus, some designers may require it to be compacted for a lower hydraulic conductivity than that required of the lower soil liner. It should be noted that some engineers have designed and constructed 18-in. thick liners compacted in 6-in. lifts and required the liner to have a minimum hydraulic conductivity of 1×10^{-7} cm s⁻¹.

Some experimentation has been performed using prefabricated rolls of dry bentonite pellets sandwiched between geotextile layers as the soil component of a top composite liner. The prefabricated rolls are unrolled on top of the secondary LCRS, and the top FML is installed directly on top of them. When moisture meets the dry clay, it swells and forms an in situ barrier. No quantitative data are currently available.

7.5.6 Design of a Primary Leachate Collection and Removal System (LCRS)

The primary LCRS system is installed above the top liner in waste piles and landfill units. The function of the primary LCRS is to minimize the head of leachate on the top liner during operation of the containment unit and to remove liquids through the end of the post-closure care period. Current EPA regulations require that the primary LCRS be designed to ensure that the leachate head above the top liner does not exceed 1 ft [40 CFR 264.251 and 264.301 (1986 ed.)]. Other basic requirements for a primary LCRS are the same as those for a secondary LCRS (see Section 7.5.4). Thus, a primary LCRS must be constructed of materials that are able to maintain their functional integrity after exposure to the leachate, be able to withstand the stresses and disturbances from overlying materials and equipment, and be able to function without clogging throughout the lifetime of the unit including the post-closure care period. However, it should be noted that some designers are choosing to use different types of drainage media for the primary and secondary LCRSs.

The design considerations for a primary LCRS are essentially the same as those for a secondary LCRS. The major difference is that primary LCRSs are designed to handle an estimated amount of leachate. One tool for estimating the amount of leachate that can be generated by a landfill is the HELP computer model (Schroeder et al, 1984a and 1984b), which is discussed in Section 7.3.1.1.7. The estimate for the amount of leachate generated (i.e. the amount of leachate that will enter the LCRS) is used in design equations to size and space the pipe system. Equations for using leachate infiltration rate to determine pipe size and spacing are presented in Appendix I.

The draft Minimum Technology Guidance document on double-liner systems states that a primary LCRS should have (EPA, 1985):

- At least a 30 cm (12-in.) thick granular drainage layer that is chemically resistant to the waste and leachate, with a hydraulic

conductivity not less than 1×10^{-2} cm s⁻¹ and with a minimum bottom slope of 2%. Leachate collection systems incorporating synthetic drainage layers may be used if they are shown to be equivalent to or more effective than the granular design, including chemical compatibility, flow under load, and protection of the FML (e.g. from puncture). Granular drainage material should be washed to remove excess fines before installation.

- A graded granular or synthetic fabric filter above the drainage layer to prevent clogging.
- A drainage system of appropriate pipe size and spacing on the bottom of the unit to efficiently collect leachate. These pipe materials should be chemically resistant to the waste and leachate. The piping system should be strong enough to withstand the weight of the waste materials and vehicular traffic placed on or operated on top of it.
- A drainage and collection system that covers the bottom and sidewalls of the unit.
- A sump for each unit or cell capable of automatic and continuous functioning and which should be able to remove accumulated leachate at the earliest practicable time to minimize the leachate head on the top liner which should not exceed 12 inches. The sump should contain a conveyance system for removing leachate from the unit such as either a sump pump and conveyance pipe or gravity drains. Examples of manhole sumps for a primary LCRS are shown in Figures 7-28 and 7-29. A plan view for the sump design presented in Figure 7-29 is presented in Figure 7-30. Side slope risers can also be used for removal of leachate from a primary LCRS sump. It should be noted that many engineers believe the maximum 12-in. head requirement, if the sump is placed inside the unit, to be too stringent because of the consequent requirements for the sump pump.
- The collection lines should be capable of being cleaned out periodically.

If the manhole sump is placed within the containment unit, as is shown in both Figures 7-28 and 7-29, special care will need to be taken in designing and constructing the system to prevent differential settlement of the supporting soils and to prevent down-drag forces from affecting the integrity of the lining system. Differential settlement of the supporting soils could result in tipping of the standpipe and eventual puncture of the FML. The down-drag forces arise from the differential settlement that occurs between the consolidating waste fill and the rigidly supported manhole pipe. These forces are transmitted to the base of the standpipe and can generate high stress concentrations on the underlying liner system components. Special measures may be taken to prevent the consolidating waste from pulling down on the manhole standpipe by lowering the friction between the pipe and the waste. Richardson and Koerner (1987) present design equations for evaluating down-

drag forces to compare coatings for reduction of these forces and to evaluate whether down-drag induced settlement of the standpipe will cause failure of an underlying LCRS.

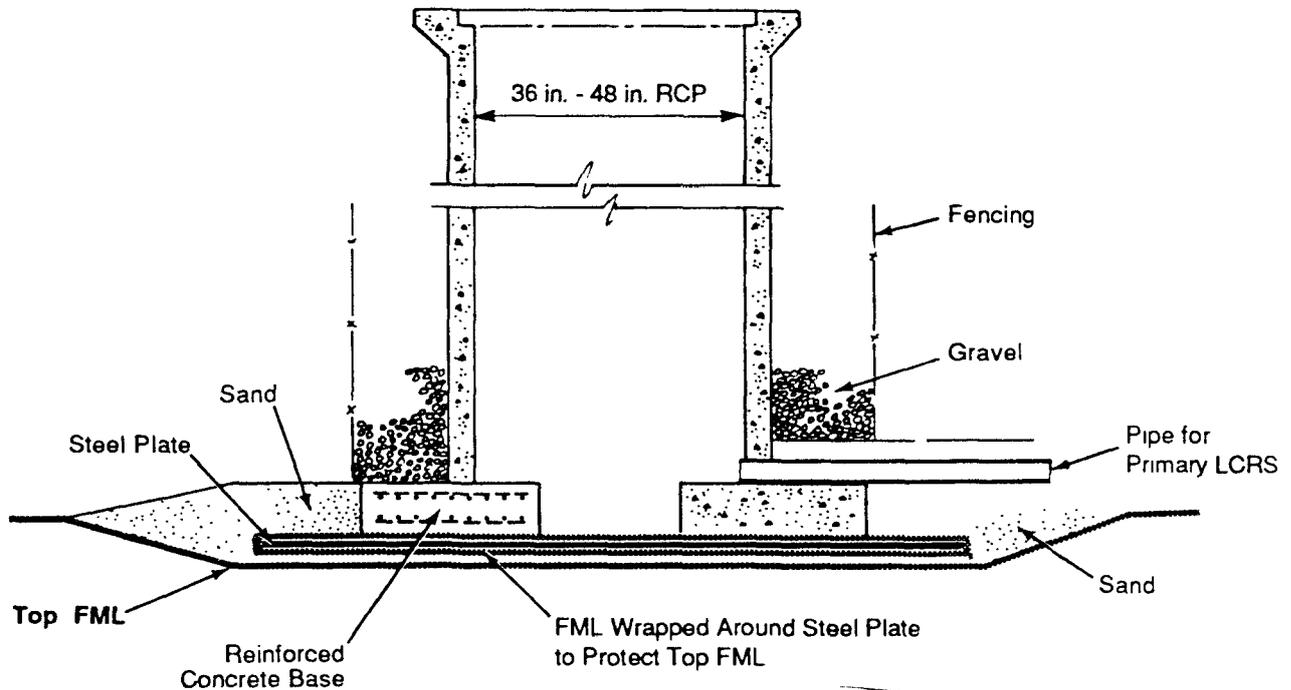


Figure 7-28. Schematic of a low-volume sump for a primary LCRS. Sump pump is not shown. The zone of gravel around the standpipe is retained during operations by fencing. The steel plate below the concrete pad is included to allow stress transitions. (Based on Richardson and Koerner, 1987, p IV-6).

In general, penetration of the lining system is strongly discouraged. However, under special conditions, a designer may decide to place the sump/manhole system for a primary LCRS outside the containment unit, even though the discharge pipe will penetrate the lining system. For example, a designer may consider placing a manhole sump outside a containment unit if the unit is a single-lined MSW landfill that is being constructed above-grade and if the MSW height is projected at 100 ft or higher. If the sump/manhole is placed outside the containment unit, the penetrating pipe will require special foundations and seals. An example of a sump placed outside a unit is presented in Figure 7-25.

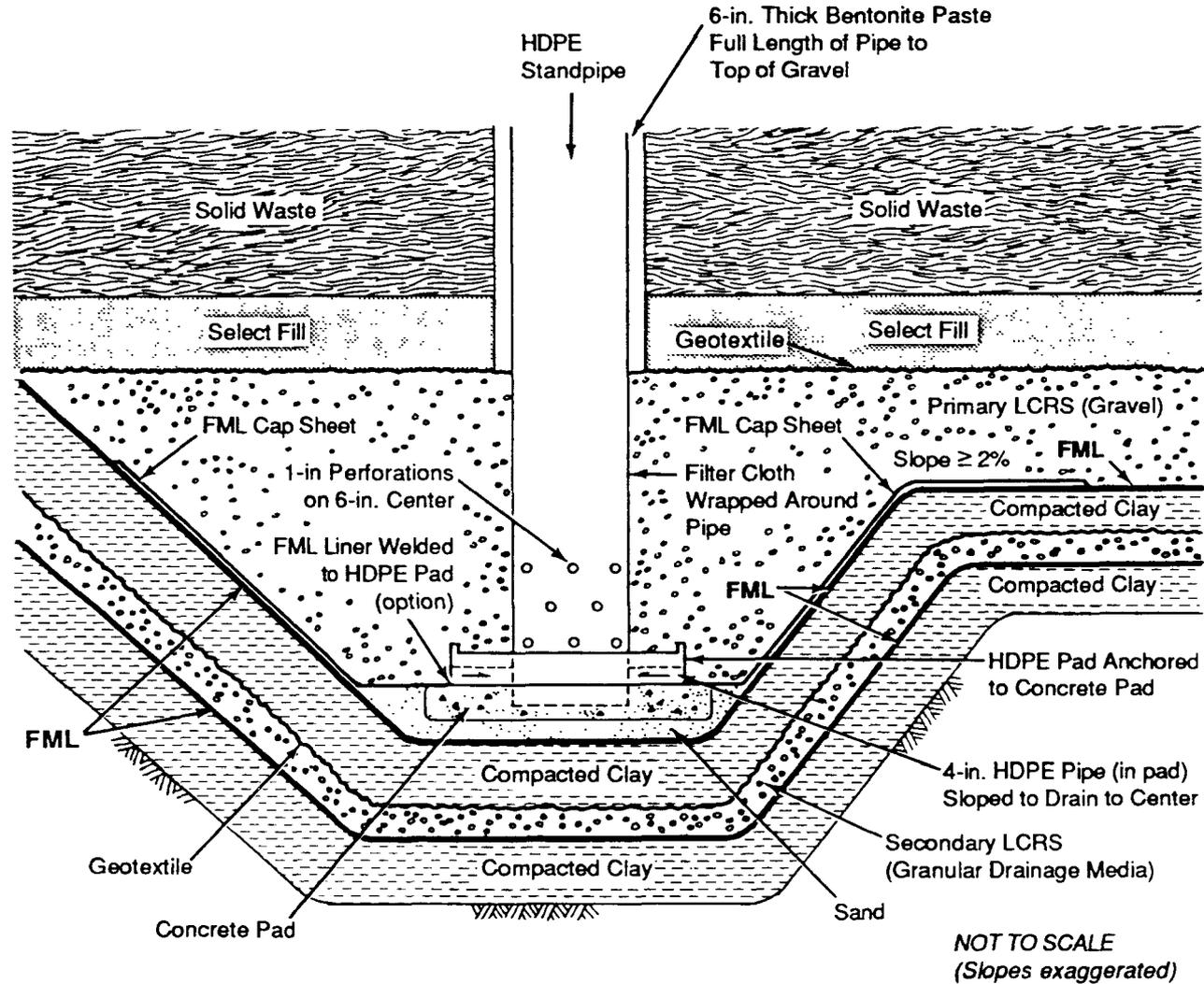


Figure 7-29. Schematic of a high-volume sump for a primary LCRS. The pump is not shown. Plan view of the HDPE pad is presented in Figure 7-30. (Based on a drawing courtesy of Chemical Waste Management, Inc.).

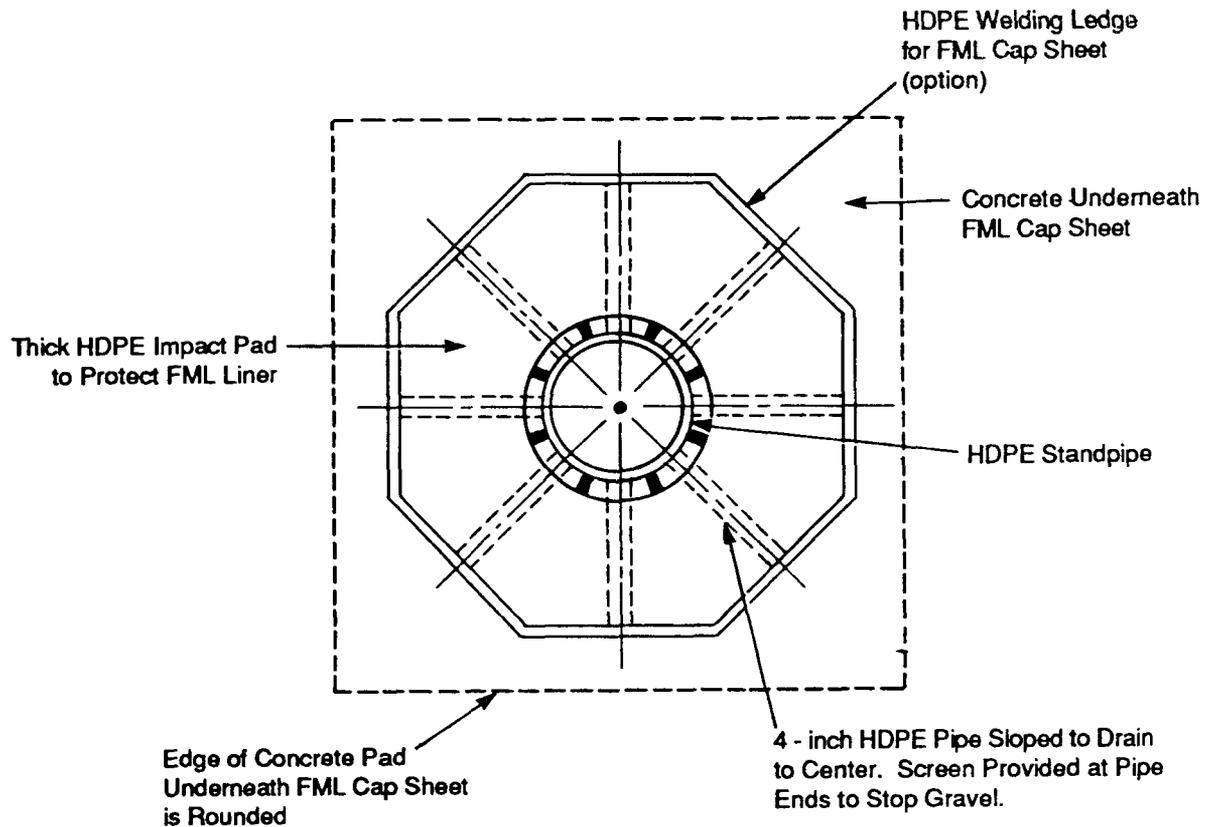


Figure 7-30. Plan view of a high-volume sump for a primary LCRS. (Based on a drawing courtesy of Chemical Waste Management, Inc.).

7.5.7 Design of Ancillary Components

This section discusses the design of various ancillary components of a double-liner system and a waste containment unit. These components include:

- Anchor trenches.
- Penetrations.
- Liner protection from pipe outfall.
- Gas vents.
- Soil covers.
- Coupon testing for monitoring FML performance.
- Groundwater monitoring systems.

7.5.7.1 Anchor Trenches--

Proper anchoring of the FML at the top of the slopes around the unit perimeter is essential to prevent the FML from sliding down into the unit. An anchor should provide sufficient restraint to prevent this movement but should not be so rigid or strong that the FML tears before the anchor yields. Generally, the FML is anchored at the top of the berm using one of the following methods:

- A friction method.
- A trench and backfill method.
- Anchoring to a concrete structure.

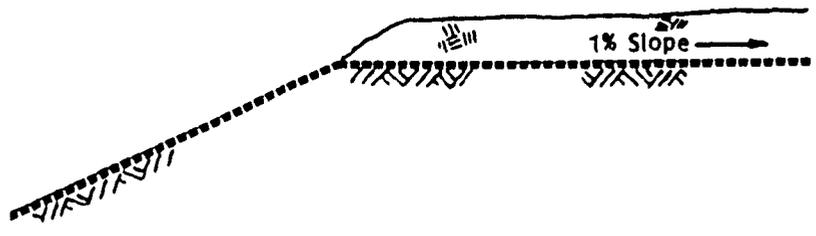
These methods are presented schematically in Figure 7-31. The trench and backfill method is the one that is recommended most often by FML manufacturers, probably due to its simplicity and economy. Richardson and Koerner (1987) have developed design equations for determining the anchor capacity for an FML placed in various anchorage configurations.

7.5.7.2 Penetrations--

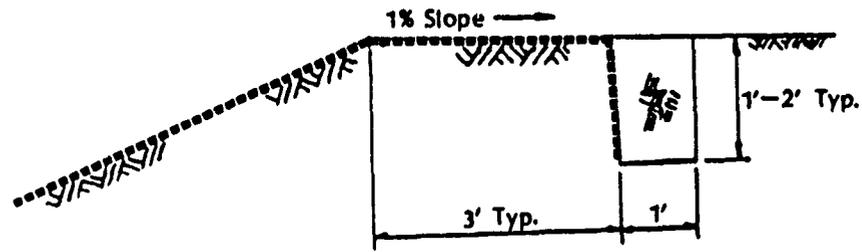
Depending on the design and purpose of the unit, one or more types of structures may penetrate the lining system. These penetrations could include inlet, outlet, overflow, or mud-drain pipes; gas vents; level-indicating devices; emergency spill systems; pipe supports; or aeration systems. Penetrations may occur in the bottom, through one of the sidewalls, or on the berm, depending on the purpose for the penetration. Because tailoring and sealing an FML around structures can be difficult and offers a possibility for failure of the FML, many engineers, designers, FML manufacturers and facility owners recommend that over-the-liner pipe placement be used whenever possible. This design facilitates future repairs or maintenance to the piping system. However, some penetrations of the lining system may still be necessary; for example, a side slope riser pipe for a secondary LCRS will need to penetrate the liner, if only through the berm.

Most manufacturers recommend specific materials and procedures to be used to establish an effective seal around penetrations. Proper design of the penetrations and use of a bonding system that is practicable with the geometry of the penetration are important factors in long-term liner performance. When piping systems penetrate a lining system, concrete structures or collars around the pipe are used to support the area around the penetration. Since FMLs are not easily bonded to concrete with an adhesive, they are usually mechanically anchored to the structure. The edges of the concrete structure or collar in contact with the FML are rounded to prevent damage to the liner in case of differential settlement between the structure and the soil subgrade.

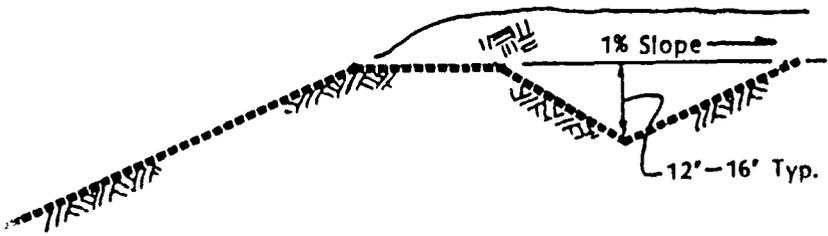
Most FML manufacturers offer standardized engineering designs for (a) seals made in the plane of the liner, and (b) boots to be used around



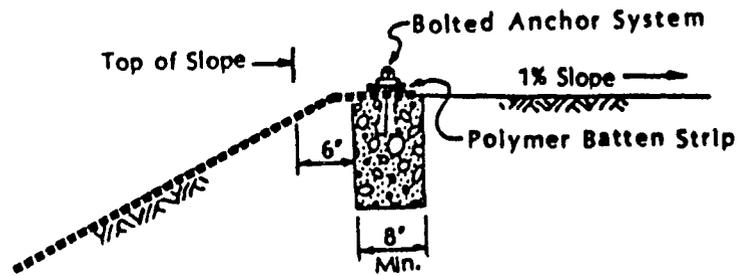
HORIZONTAL ANCHOR



TRENCH ANCHOR



SHALLOW "V" ANCHOR



CAST CONCRETE ANCHOR

7.93

Figure 7-31. Schematic presenting different methods of anchoring FMLs. Note that in the trench anchoring system, the edge of the berm where the FML enters the trench is rounded. (Source: Richardson and Koerner, 1987, p III-22).

penetrations. If inlet or outlet pipes are introduced into the unit through a concrete structure, the seal can be made in the plane of the lining system. An example of this type of seal is presented in Figure 7-32. The specific FML-to-concrete bonding system that is used will depend on the type of FML. Anchor bolts embedded in the concrete and stainless steel or thick polymeric batten strips can be used to secure the FML to the concrete. An appropriate mastic should be used under the edges of the FML to effect a complete seal.

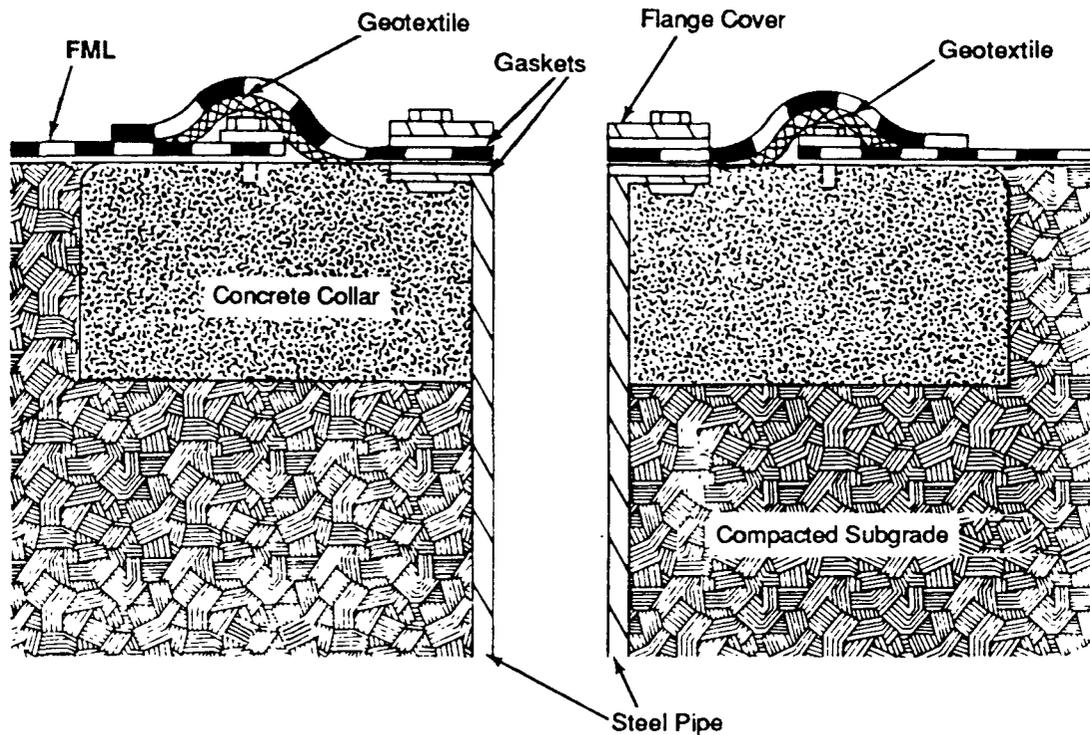


Figure 7-32. Example of a flange seal around a penetration. (Courtesy of Poly-America, Inc.).

Typically, specialized features such as pipe boots or shrouds are fabricated at the manufacturing facility to design specifications, although they can sometimes be prepared in the field by experienced personnel. Boots (or shrouds) are designed to fit over an appurtenance (e.g. pipe) and then be bonded directly to the installed FML so as to create a continuous membrane around the base of appurtenance. Boots are generally fabricated out of materials of the same composition as the FML that is being installed so that they can be bonded to the FML using thermal or solvent-based techniques. Where fabric-reinforced FMLs are being installed, manufacturers sometimes recommend that boots be constructed of unreinforced material so that the slightly undersized boot can be stretched over the appurtenance to assure

good physical contact. This also allows some expandability in case the adjacent FML stretches due to settling. A pipe boot is slipped over the pipe after the FML roll or panel has been cut and fitted around the base of the pipe. The appropriate adhesive, mastic, or seal (e.g. a closed cell sponge) is placed between the pipe and boot as required, and a stainless steel band is placed around the boot where the adhesive, mastic, or seal has been applied between the pipe and boot. The base of the boot is seamed to the main part of the FML liner using the same bonding system used to make the field seams. Boots need to be checked prior to installation to ensure that the angle of intersection with the base is consistent with the angle created between the pipe and subgrade. An example of a seal created through the use of a pipe boot is presented in Figure 7-33.

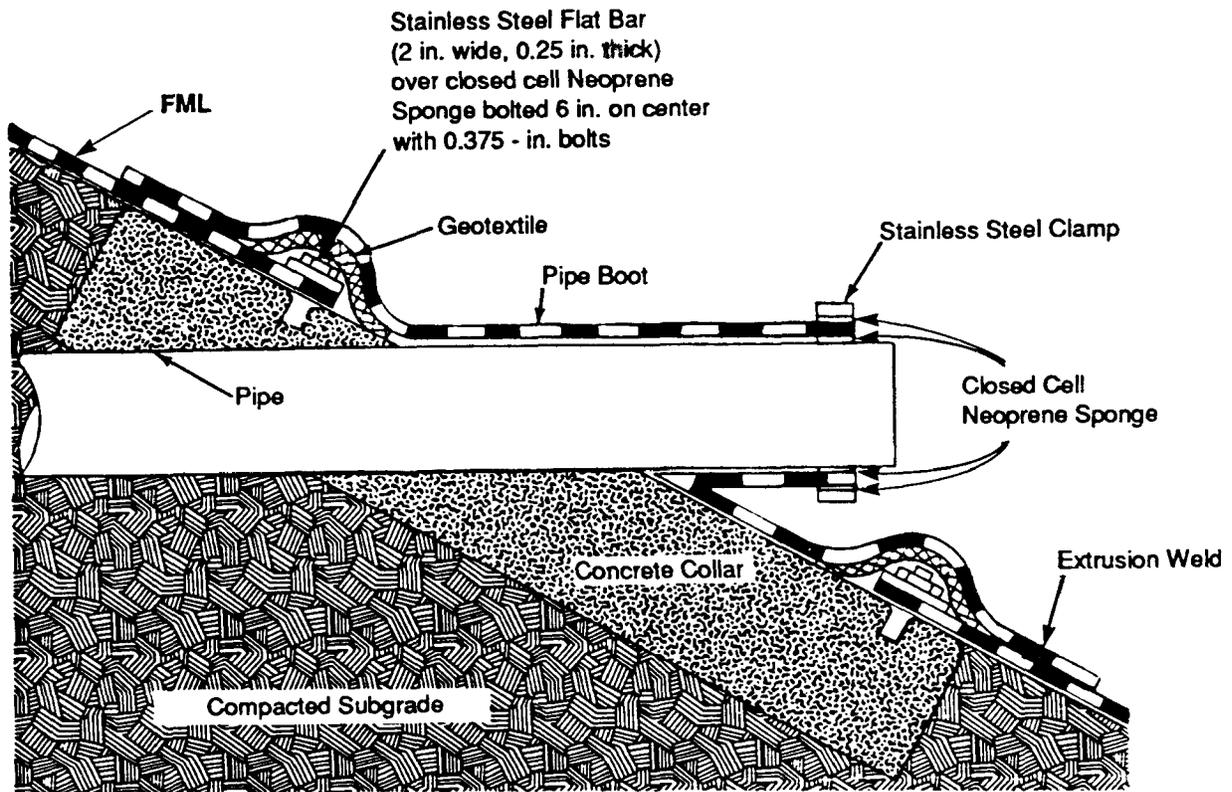


Figure 7-33. Example of a seal around a penetration using the boot-type method. (Courtesy of Poly-America, Inc.).

7.5.7.3 Gas Vents--

Certain conditions require the venting of gas that may accumulate beneath an FML. If organic matter exists in the soils under the lining system, or if natural gas is present in the region, gas generation is inevitable. If a unit has a flat bottom, gas will tend to accumulate under the liner. In the case of a surface impoundment, if the pressure is permitted to increase,

the FML can be lifted creating a cavity for additional gas accumulation. The higher the FML bubble is allowed to rise, the more the FML stretches and the less hydrostatic pressure is available to restrain the FML. As a result, the FML can float to the surface. In landfills, due to the weight of the waste and overburden, the FML cannot float upwards.

Venting must also be considered when a fluctuating water table is present immediately below the unit bottom. When the water table falls, void spaces in the soil under the liner are created. Air is then drawn into these voids from the surrounding soil. Conversely, when the water table rises, air which was pulled into the voids is displaced upward. The amount of fluctuation, proximity of the water table to the unit bottom, and the area of the base of the unit will dictate the reaction of the lining system to this air pumping mechanism. The need to vent this accumulating gas is best accomplished by constructing a venting underdrain system (see Section 7.5.1) underneath the entire lining system. One method is to install above the foundation a layer of clean sand of which less than 5% by weight will pass the 200 sieve (0.075 mm). Synthetic systems using geonets and geotextiles can also be used. In order for these media to be effective, the bottom of the unit should slope up from its lowest point to the toe of the embankment a minimum of 2%, and the lining system must have sufficient stiffness. The venting medium should cover the entire bottom and the side slopes. In the case of surface impoundments, venting to the atmosphere is accomplished through gas vents located on the inside slope of the berm, approximately one foot down from the crown of the embankment. Simplified representations of two designs of gas vents for single-lined surface impoundments are presented in Figure 7-34 and 35. A schematic showing a venting system for a double-lined surface impoundment is presented in Figure 7-36.

7.5.7.4 Liner Protection from Pipe Outfall--

Special considerations must be given if hydraulic impact head is going to be dissipated onto the top liner. This could occur, for example, at an inlet structure where liquids flow into the unit. In addition, the main liner may need to be protected from any abrasive material that might be present in the liquid discharged into the unit. A splash pad can be constructed under the inlet structure by placing one or more additional layers of the FML used to line the unit at the point of impact to help absorb energy resulting from the inflow of water (Figure 7-37). A concrete pad or a filter fabric geotextile placed under the FML can also be used to ensure further mechanical stability. Alternative solutions include sluice-type troughs and splash tubes. Troughs can be constructed out of the FML used to line the unit and placed on top of the main FML liner (Figure 7-38). Splash tubes are flexible polymeric tubes which are attached to the inlet pipe so that liquids flow out the inlet pipe through the tube directly onto the FML liner.

7.5.7.5 Aeration System--

If an aeration system is included in the design of a surface impoundment, appropriate precautions need to be taken to ensure that the FML surrounding the structure remains in position. With a floating aerator, this is

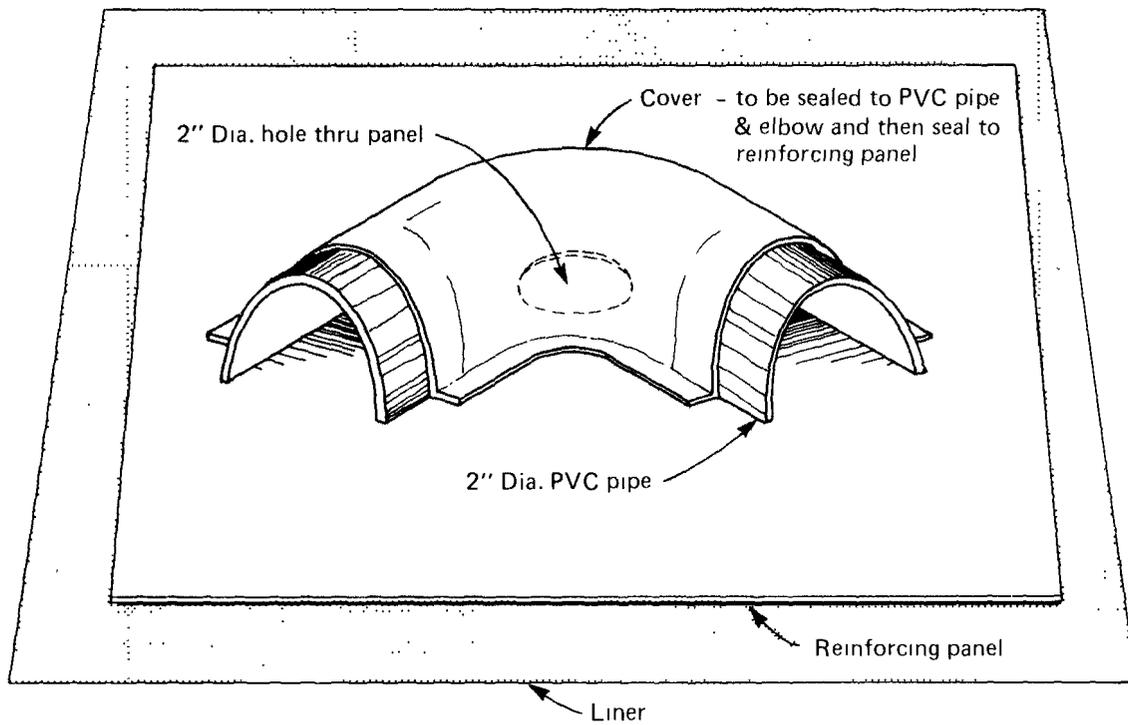
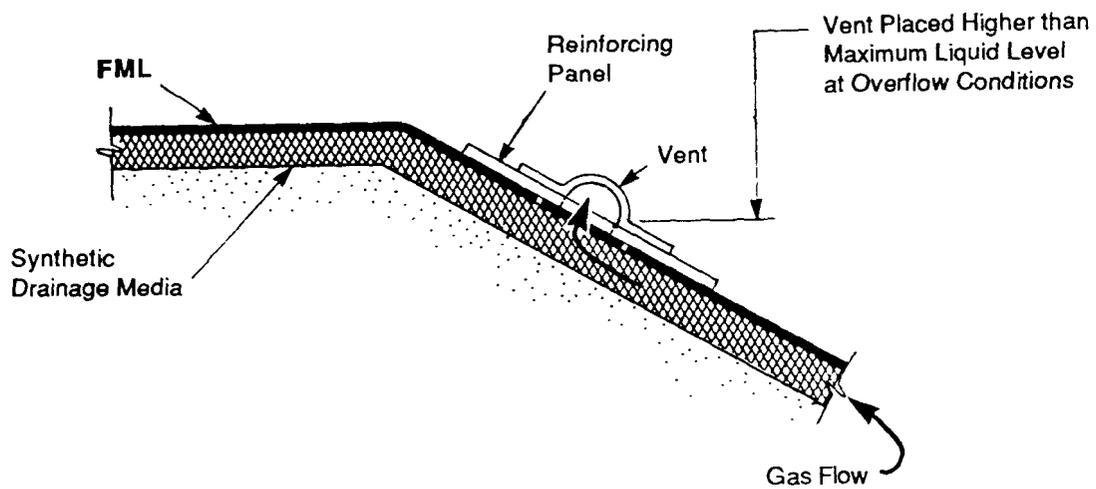


Figure 7-34. Two views of a gas vent design for a single-lined surface impoundment. The reinforcing panel is placed over a hole cut in the liner to allow gases to escape from underneath the liner. (Design based on a drawing courtesy of Sta-Flex Corporation).

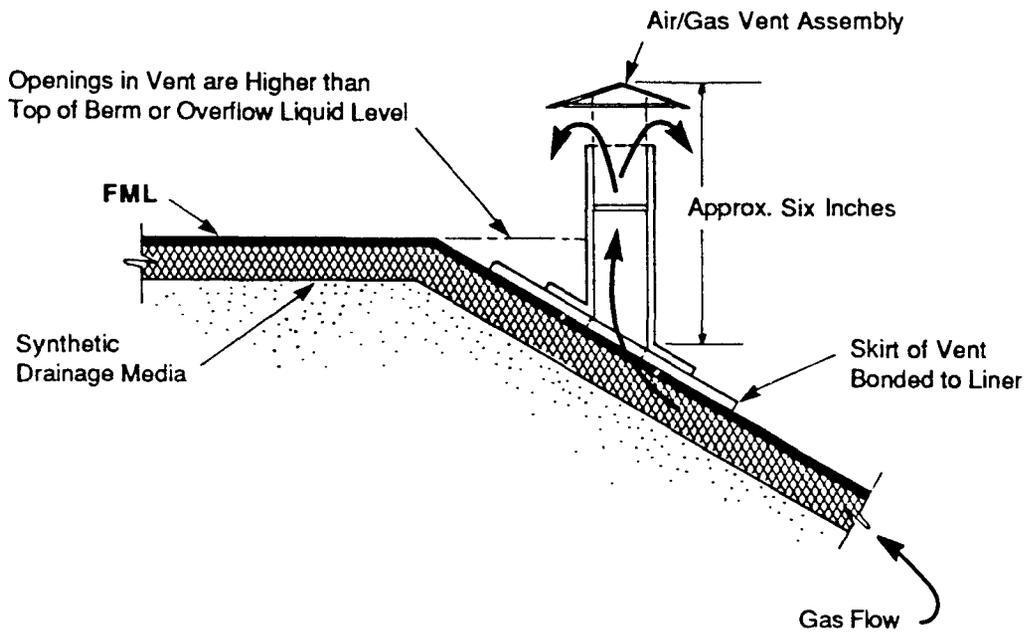


Figure 7-35. A gas vent design for a single-lined surface impoundment. (Based on Koerner and Richardson, 1987, p III-29).

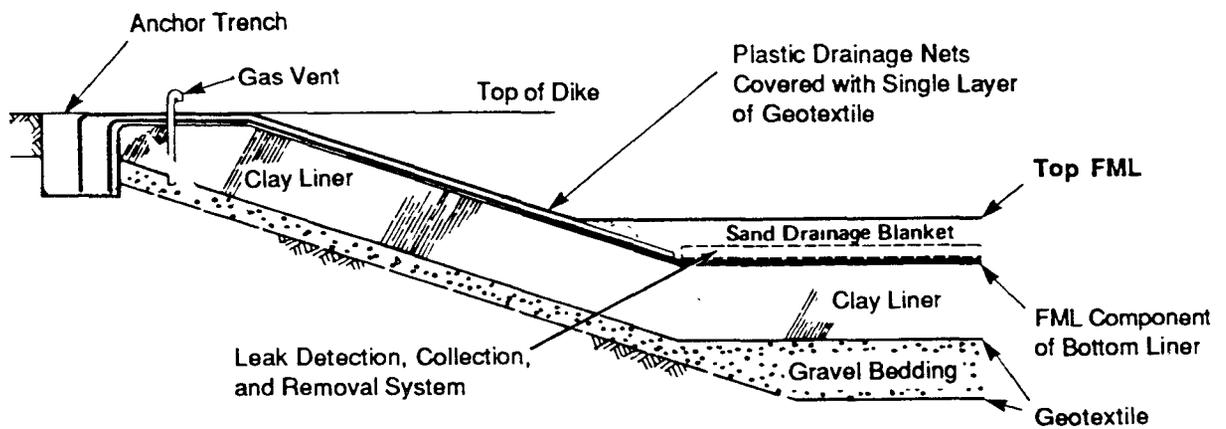


Figure 7-36. Schematic of a double-lined surface impoundment with a gas-venting system underneath the lining system. (See Figure 7-41 for a more detailed treatment of a gas-venting pipe system in a final cover for a landfill).

usually accomplished by using a mooring pad placed on top of the FML liner. The mooring pad also prevents mechanical damage to the FML immediately adjacent to the aerator. It is recommended that an additional layer of FML be placed between the mooring pad and the main part of the liner. When a fixed aerator is used, the FML liner may cover the foundation pad, and an additional pad can be placed on top of the liner. An additional layer of FML can be sandwiched between the top pad and the FML liner. Permanent anchors can be placed 10 ft apart in a circle approximately 20 ft from the base of the aerator to prevent the FML liner from being lifted from the subgrade. Figure 7-39 shows some typical design details for aeration structures.

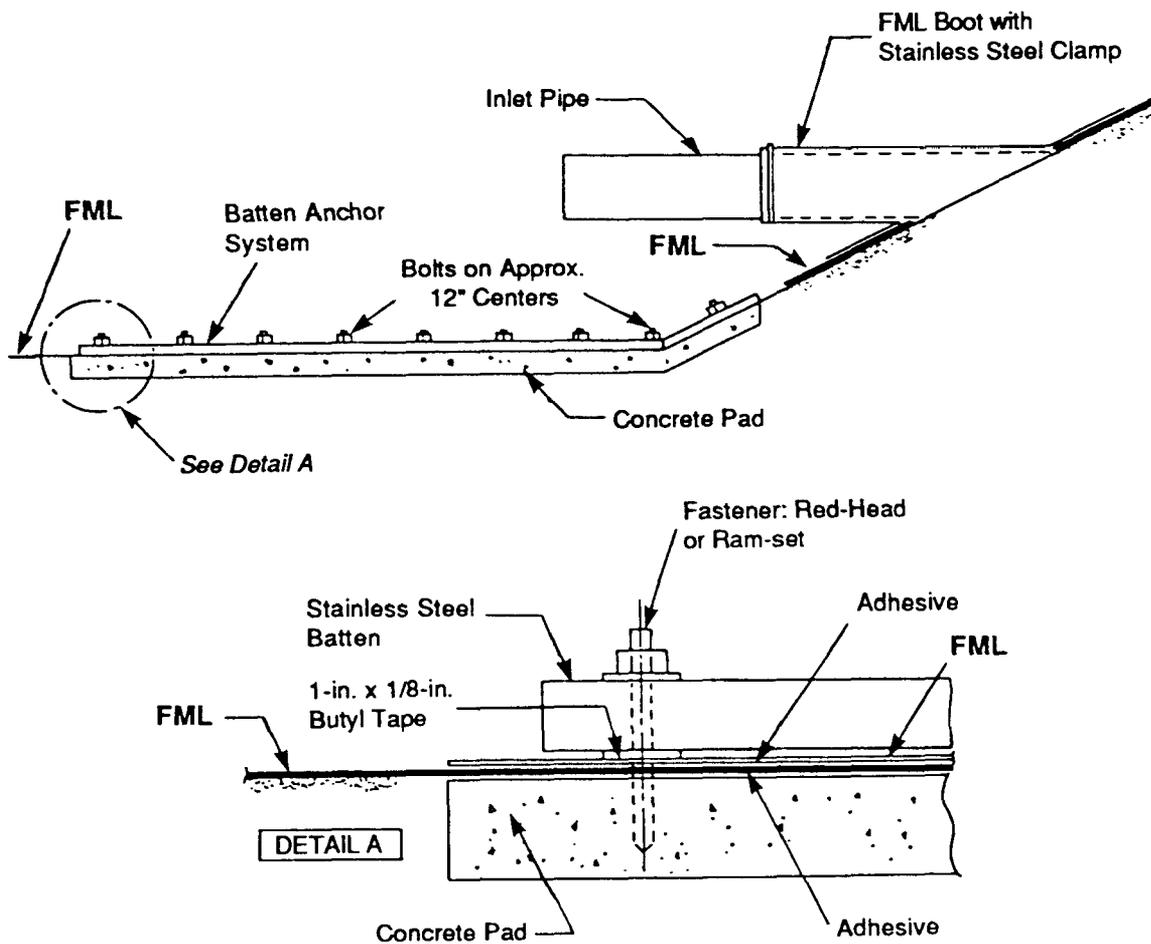


Figure 7-37. Splash pad construction using a concrete subbase. (Courtesy of Burke Rubber Company)

7.5.7.6 Protective Soil Covers--

An earth cover is commonly placed on an FML as a protective layer against mechanical, weather, and other environmental damage. FMLs have relatively little structural strength, and some are quite sensitive to such environmental conditions as:

- Ultraviolet light which can degrade FMLs not properly compounded or protected.

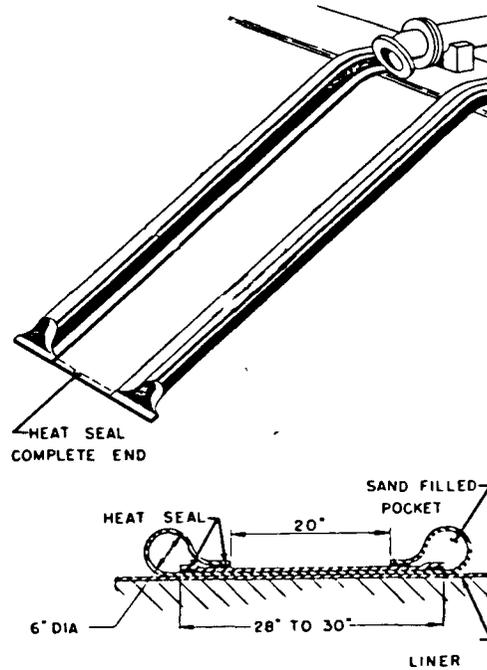


Figure 7-38. Sluice-type trough constructed of FML. The easiest method of placing inlet and outlet pipes into an FML-lined surface impoundment is over the top of the berms, using a protective FML layer to contain the discharge, thus protecting the top FML liner. The fewer protrusions that are designed into a lining system, the easier it is to install and maintain both the lining system and the piping. (Courtesy of B. F. Goodrich).

- Infrared radiation which, by heating the FML, can cause evaporation of the volatile constituents and oxidative degradation of the polymer.
- Mechanical damage from solid waste primarily during placement of the waste in the unit.
- Wind, which can cause increased evaporation of constituents in some FML compounds, and possibly cause mechanical damage to the liner itself.
- Wave action in a surface impoundment.
- Oxygen and ozone.
- Freeze and thaw.
- Hail and rain.
- Animals - hoofed, gnawing, etc.
- Vandalism.

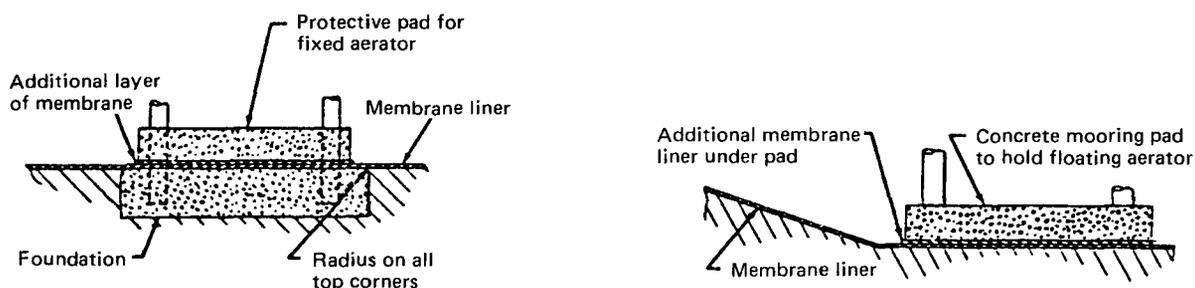


Figure 7-39. Typical design details for floating and fixed aeration systems. (Courtesy of B. F. Goodrich).

It may be necessary to place a soil cover on the installed FML before the containment unit can begin to be filled. In the case of a landfill, the soil cover may be installed to provide a suitable working surface for equipment to unload waste and to protect the filter layer of the primary LCRS.

The manufacturers of PVC FMLs recommend placing an earth cover on top of the liner to protect the lining material. Ultraviolet light degrades PVC FMLs by causing chemical changes to occur along the polymer main chains. These changes, which can cause embrittlement of a PVC FML, can be avoided or minimized by compounding the PVC with UV light absorbers and other stabilizers. However, PVC FMLs should be covered regardless of end use. Manufacturers and installers of HDPE and CSPE question whether the benefit of placing a cover is worth the cost and the risk of potential damage to the liner. However, all FMLs are susceptible to sun aging if not properly compounded. Thus, the function of a cover can also be to block out the sun and prevent sun aging.

In addition, a cover is necessary wherever vehicular traffic is anticipated on top of the FML even though thick liners can resist damage caused by light vehicles. In the case of surface impoundments in which hot fluids are introduced, the cover acts to protect the FML from the initial high heat factor and subsequently to insulate the FML from residual heat by decreasing the temperature at the liquid/FML interface versus the temperature of the fluid body. In cases in which liquid is conveyed into the impoundment over the top, a soil cover with riprap placed on top of the cover to prevent erosion can be used to protect the FML. In the case of a lined wastewater treatment impoundment where mechanical aeration is used, a cover may be required to mitigate the potential for the liner to be drawn off the bottom or side by hydraulic wave action. On-site weather conditions influence the use of a soil cover. In extreme climates, such as the northern plains or the desert Southwest, covers are often used to protect against mechanical damage due to freeze-thaw cycles and subsequent ice movement, or sun degradation. Wastewater impoundments in the northern states often become ice covered in winter. Spring thaws can result in ice movement, greatly increasing the chances for damage to an exposed liner.

Other weather conditions often dictate the necessity for special design or performance features. Hail can cause failure of some exposed liner materials, particularly on flat berms where a thermoplastic FML has been installed. Such damage can be easily prevented by the use of a soil cover. Liners exposed to high wind can be stretched and damaged by air lift, if compensations are not made in the design.

In specifying a soil cover, the engineer needs to state that the cover soil should never be pushed down the slope during placement since the gravitational stresses may pull the FML out of the anchor trench or cause the FML to tear.

Richardson and Koerner (1987) have developed a design equation for analyzing the stability of a soil cover placed on top of the slope of an FML-lined unit.

7.5.7.7 Use of Coupons to Monitor the Liner and Other Materials of Construction During Service--

In light of the limited experience with FMLs in lining waste containment units and the lack of information on actual liner performance, it is desirable to monitor the condition of an in-service FML during operation of the unit. One method of monitoring the condition of a liner is to place samples or "coupons" of the same lot of an FML that is used to line the containment unit in the unit before the addition of the waste. These coupons should be withdrawn on a planned schedule and tested. Means to accomplish such a program must be incorporated in the original design of the unit and plans made for the withdrawal and testing of the coupons during service. Coupon placement should allow for essentially the same exposure and environment to the waste as the installed FML, safe and easy access and retrievability, economical placement, precise location, and precise identification. Use of coupons is discussed in more detail in Section 11.7.

7.5.7.8 Groundwater Monitoring Wells--

Monitoring wells are a tool for monitoring the hydrology surrounding a waste containment unit. A monitoring well is built specifically to give access to the groundwater so a "representative" sample of water can be withdrawn and analyzed. There are several components to be considered in designing a monitoring well. These include:

- Location and number of wells. The wells need to be located spatially and vertically to ensure that the groundwater flow regime of concern is being monitored.
- Diameter of the well.
- Casing and screen material. The type of material used in constructing a monitoring well can have a distinct effect on the quality of the water sample to be collected. Thus, the materials of choice should neither absorb nor leach chemical constituents which would bias the monitoring tests.

- The length of screen and the depth of placement. The screen length determines the height of the zone being monitored.
- Sealing material and procedures. Vertical movement of groundwater can greatly influence sample quality; therefore, monitoring wells are usually sealed to isolate the screened interval selected for sampling and to inhibit downward leakage of surface water.
- Methods of preventing the well screen from clogging.
- Security.

These design considerations are discussed in more detail by Barcelona et al (1987). EPA (1986e) presents current EPA guidance on groundwater monitoring. Monitoring wells are also discussed in Section 11.5.1.

7.5.8 DESIGN OF A LANDFILL COVER SYSTEM

At the end of the active life of a landfill, a final cover is constructed over the fill to minimize leachate formation within the landfill by preventing surface water from infiltrating the fill throughout and beyond the post-closure care period. The final cover system also controls the venting of gases that may be generated within the fill and isolates the wastes from the surface environment. Cover systems can also be installed on surface impoundments at the time of final closure if it has been decided that the impoundment can be closed as a landfill [40 CFR 264.228 (1986 ed.)]. If this is the case, free liquids will need to be eliminated either by removing the liquid wastes and/or solidifying the remaining wastes and waste residues, and the remaining waste will need to be stabilized to a bearing capacity sufficient to support a final cover. The final cover system should be designed and constructed so that it can function with minimum maintenance, promote drainage, minimize erosion, accommodate settlement and subsidence, and have a transmission rate less than or equal to that of the bottom liner system [40 CFR 264.310 (1986 ed.)].

In designing a cover system, it is important to allow for settlement within the close waste containment unit because of potential damage to the cover. Even though settlement of the impounded waste may be uniformly distributed throughout the unit and occur primarily before the unit is closed, localized subsidence (i.e. unevenly distributed settlement) can disrupt the integrity of the final cover. In addition, such subsidence due to the collapse of drums (which will occur mainly in older units) or the leaching of soluble waste constituents may not occur until several years after final closure or may occur gradually over decades. In designing the cover, the following need to be considered:

- Consolidation of soils and foundation materials underlying the site.

- Consolidation of the lining and the leachate collection and removal systems.
- Consolidation of all waste layers and daily and intermediate soil covers.
- Consolidation of all final cover components.

Gilbert and Murphy (1987) describe techniques for predicting, reducing, and preventing landfill settlement and related cover damage caused by subsidence.

The final cover system is similar to the lining system in that both consist of a number of different components, each of which must function properly and maintain its integrity if the system as a whole is to function adequately. Final cover systems are multilayer structures constructed in layers on top of a mass of waste that may settle unevenly. The barrier layer is the most important layer because it prevents water from infiltrating the fill. Depending on the type of waste contained in the unit, the barrier layer can be comprised of either a clay liner or a composite clay-FML liner. Other layers are included to protect or enhance the performance of the barrier layer. An example of a final cover system is presented in Figure 7-40. This example consists of a low-permeability soil layer, an FML layer, a surface water drainage system, and a soil cover layer capable of supporting vegetation. Draft EPA guidance on final covers for hazardous waste landfills recommends the following requirements (EPA, 1987a):

- The low-permeability soil layer should have a minimum thickness of 60 cm (24 in.) and a maximum in-place saturated hydraulic conductivity of 10^{-7} cm s⁻¹.
- The FML barrier should have a minimum thickness of 20 mils.
- There should be bedding above and below the FML.
- The drainage layer should have a minimum hydraulic conductivity of 10^{-2} cm s⁻¹ and a final bottom slope of 2% after settlement and subsidence.
- The cover topsoil or vegetative layer must have a minimum thickness of 60 cm (24 in.).

At the bottom of the cover system is the foundation layer which is installed above the waste fill. This foundation should provide a stable working and supporting surface on which the rest of the cover system can be constructed. However, the stability of the foundation layer also depends on the stabilization program implemented during filling of the containment unit to prevent any large localized subsidence such as that generated by the collapse of waste packages or soil bridges between packages, or by the presence of cavities in the soil or rock beneath the waste.

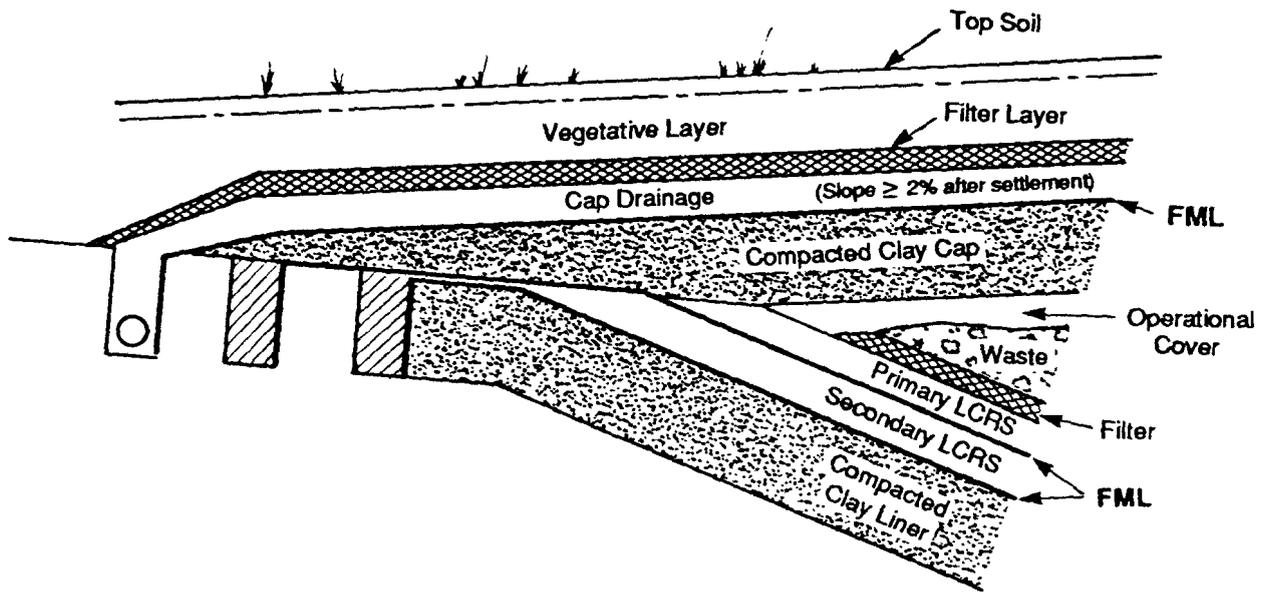


Figure 7-40. Schematic profile of a closed landfill. (Based on Richardson and Koerner, 1987).

A gas-control layer may be incorporated into the design underneath the compacted clay cap layer. A gas-control layer can intercept any gases produced by waste decomposition or other processes and, by proper venting through a riser pipe that penetrates the cover system, allow the gases to escape to the atmosphere. Thus, a gas-venting system (1) relieves any pressure resulting from gas that might build up underneath the hydraulic barrier system, (2) controls the escape of these gases, and (3) allows their collection. It should be noted that some engineers believe that gas generation is not a problem at hazardous waste landfills, and, therefore, recommend that the cover not be penetrated with a gas-venting system. Gas-venting systems are necessary in MSW landfills because of gas generation resulting from the decomposition of wastes. If a gas-control layer is required, a filter layer between the foundation and the gas-control layer may also be required. A schematic of a gas-venting system is presented in Figure 7-41.

Current regulations require controlled discharge by collection and/or treatment of hazardous or nuisance gases from covered containment units (Northeim and Truesdale, 1986). Controlled discharge of gases accumulating in the unit is necessary because of the potential harm that toxic, combustible, and/or malodorous gas may have on human health and the environment. The gas may be collected at the discharge point and transported for treatment or incineration. Alternatively, devices for removing harmful components from the gas or incinerating the harmful components in place may be devised and installed at gas discharge points.

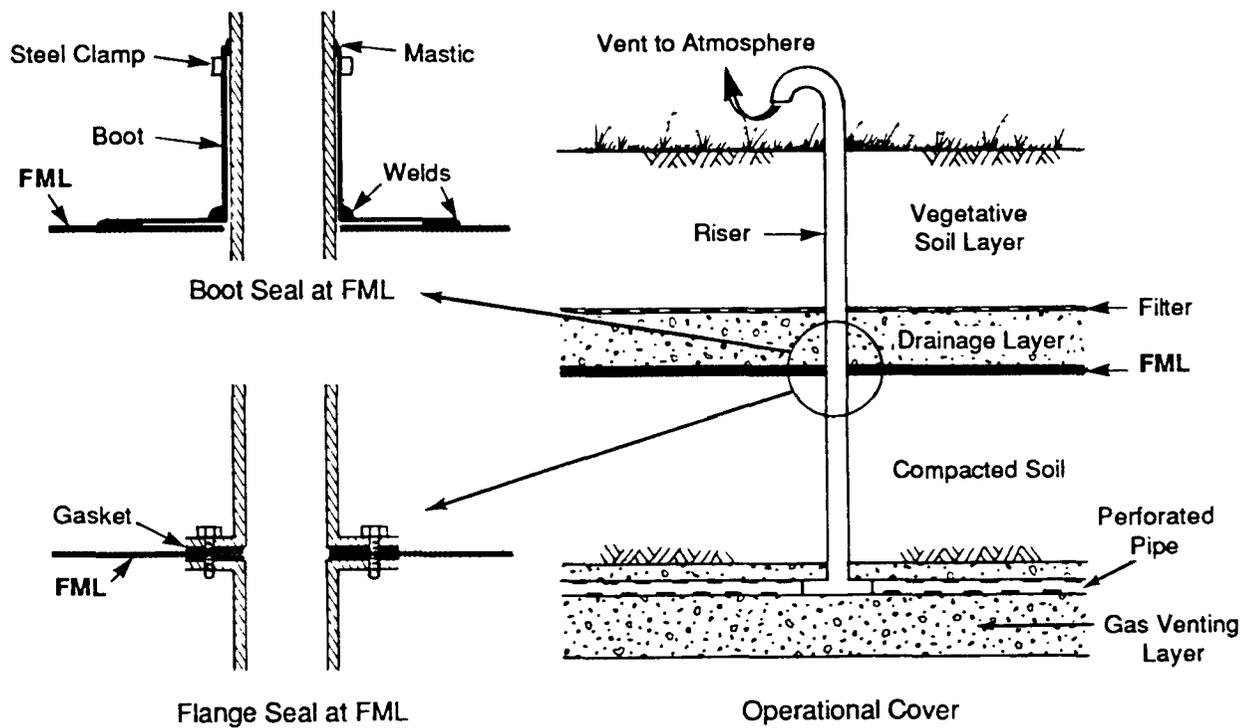


Figure 7-41. Schematic of a gas-venting pipe system for a landfill cover. (Source: Richardson and Koerner, 1987, p V-16).

The low-permeability soil barrier can provide a base for an overlying FML barrier and can provide long-term minimization of liquid infiltration into the landfill by serving as a secondary hydraulic barrier in case the FML barrier fails. The low-permeability soil barrier is designed and constructed in much the same manner as the soil component of the bottom composite liner. Potential soil materials need to be evaluated, a soil material selected, and the procedure for constructing the soil barrier specified. Because the cover system foundation may have a lower bearing strength than the soil liner foundation, different equipment and procedures than those used to construct the soil liner may be required. To prevent free-thaw damage to the constructed soil barrier, the liner can be required to be below the average depth of frost.

The FML barrier prevents the surface water from passing through the cover and infiltrating the underlying waste. Exposure conditions for an FML in a cover system differ significantly from those for an FML in a landfill lining system. The cover FML will not be exposed directly to leachate, but it may be exposed to significant environmental conditions (e.g. freeze-thaw cycling) and potential straining due to settlement within the waste mass. The cover FML can be anchored in a trench that is placed beyond the trenches in which the liner FMLs are anchored, as is shown in Figure 7-40. Special

measures may be required to prevent water from entering the landfill between the cover FML and the lining system. Some states (e.g. New York) presently require the cover FML to be attached directly to the underlying FML liner.

At units exposed to significant surface water or potential subsidence, the design engineer may require a double FML system with a leak collection system between the two FML subcomponents of the final cover.

The surface water drainage system is designed to conduct away any precipitation that infiltrates the top soil layer before it can penetrate the barrier layers. This surface water needs to be diverted to a collection or disposal system. Synthetic or granular drainage media can be used in designing the surface water drainage system, which is similar in design to leachate collection and removal systems. The important differences are that the collected liquid is water and not leachate or a waste liquid and that the overburden stresses on a surface water drainage system are much lower than those on an LCRS underneath a containment unit. Either a granular or a synthetic filter layer will probably be required above the drainage layer to prevent the migration of fine particles in the surface layer into the drainage layer immediately below. The migration of these particles could plug the drainage layer and render it ineffective.

The uppermost layer is called the surface or vegetative layer. Its primary requirements are to (McAneny et al, 1985):

- Provide for vegetative growth.
- Minimize wind and rain erosion.
- Resist cracking.
- Resist freeze-thaw deterioration.
- Preserve slope stability.
- Provide protection from the elements for the layers below it.
- Provide a compatible host material for the site's surface water management program.
- Provide an aesthetically pleasing appearance.

Topsoil specifications are likely to include properties (e.g. nutrient and organic content) not required for the other soil components of the unit. Soil specifications typical of the other earthwork components may also be included, e.g. slope of the final cover surface.

The vegetation planted on the soil helps prevent erosion. In addition, careful selection of short-rooted grasses is the most feasible method of preventing plant roots from penetrating the underlying components of the cover system, particularly the FML and the compacted soil barrier. Type of

seed and rate of seed application, type of soil additive and rate of additive application, filling depth, and watering instructions may be specified. In arid areas of the country, where it is difficult to establish vegetation, coarse materials such as cobbles and riprap may be used as protection against erosion.

Depending on site specific conditions, additional layers may be required to protect the barrier layers against burrowing animals (Johnson and Duderar, 1988) and deep-rooted plants.

EPA (1987a), Johnson (1986a and b), Lutton (1982 and 1986), Lutton et al (1979), McAneny et al (1986), and Richardson and Koerner (1987) discuss the design of cover systems in more detail. Greathouse (1988) describes expert systems that are being developed by the EPA to assist in reviewing closure plans for land disposal sites.

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CHAPTER 8

SPECIFICATIONS FOR THE MATERIALS AND CONSTRUCTION OF WASTE STORAGE AND DISPOSAL UNITS

8.1 INTRODUCTION

After developing the design of a waste containment unit, the designer/engineer must prepare the necessary plans, technical specifications, and drawings for the bid package and for use in constructing the containment unit. In designing a containment unit, assumptions are made by the designer about the quality of the materials of construction and the quality of work to be performed during construction. Technical specifications and drawings are necessary to communicate and clarify these assumptions.

As in all engineering projects, the preparation of good specifications is essential to obtaining competitive bids and satisfactory construction and to meeting the design goals of the project (Ebenhoeh, 1965; Goldbloom and White, 1976). Incomplete drawings and specifications can result in high-price bids, construction uncertainties, and inadequate product and performance. It is not possible to prepare adequate performance specifications on such a complex product as a waste containment unit which must meet many regulatory as well as site-specific requirements. Too many uncertainties exist with respect to the performance of different materials, and long periods of time are required to demonstrate effective performance. As a consequence, the specifications must be based on accepted construction procedures, stated property values for the materials of construction used in the project, which represent a consensus about the necessary values for the particular construction materials, and quality control at all stages of construction.

This chapter discusses the specification document prepared by a designer/engineer, the different types of technical specifications, and elements of technical specifications for the different components of a lining system. Particular reference is made to specifications for hazardous waste containment units.

8.2 SPECIFICATION DOCUMENT

The designer/engineer prepares a document for the project for the purpose of obtaining competitive bids for construction and to guide the

successful contractor in the construction. This document includes three major sections:

- A copy of the agreement between the owner and the contractor.
- The general conditions, if a general contractor is used, with special conditions that pertain directly to the specific project.
- The drawings and technical specifications.

This chapter deals principally with the technical specification documents that the designer prepares for the bid package. These specifications include the drawings and specifications for the materials and workmanship.

The specification document incorporates the output of the design process which probably includes the basic approval of the design by the appropriate regulatory agencies. If the unit is to be used to contain hazardous materials or wastes, the design process will include a compatibility testing of all components of the lining system with the waste stream to be contained, as is required by EPA directive (EPA, 1986a). The technical specifications, which are a written description, and the drawings, which constitute a diagrammatic presentation of the project, are complementary. The specifications are addressed to the prime contractor and present the overall project in an orderly logical manner. The specification document should be specific and accurate in describing the requirements of the project; it should expand on the notes and drawings, define the materials and workmanship, establish the scope of work and state the responsibilities of the prime contractor.

By following the procedures and meeting the requirements set forth in the specification document, the probability of meeting the project requirement of constructing an effective waste containment unit should be increased. The technical specifications should include specific instructions for the following as necessary:

- Site preparation and foundation.
- Embankments and other earthworks.
- Subgrade preparation.
- Drainage and gas venting systems.
- Leachate collection and removal systems.
- Appurtenances and penetrations.
- Liner construction (for soils, admixes, sprayed-on materials).
- Liner installation, particularly for field seaming of FMLs.

- Quality control by the construction and installation contractors.
- Quality assurance by the owner or his representative.

Construction details are discussed in Chapter 9. Construction quality assurance is discussed in Chapter 10.

8.3 TECHNICAL SPECIFICATIONS

There are five basic types of technical specifications which, in the construction of waste containment units, tend to be used in combinations of two or more. They are:

- Performance specifications.
- Descriptive specifications.
- Reference specifications.
- Proprietary specifications.
- Base bid specifications.

Performance specifications define the work to be done by specific results; they give the contractor complete freedom to employ his knowledge and experience to carry out a particular project. At the present time, the basic performance goal for a hazardous waste containment unit is to control the escape of constituents so as to protect human health and the environment, i.e. to allow no more than de minimis leakage. Because the technology to achieve this goal is in the process of being developed, the EPA has promulgated, and is in the process of revising, minimum technology requirements based on available technology as guidance for meeting the basic performance specification. The minimum technology requirements are stated as descriptive specifications. Nevertheless, specific components of a hazardous waste containment unit may be specified on the basis of performance, e.g. the capacity of pumps that might be used in the leachate collection and removal systems.

Descriptive specifications define the scope of work for each base-bid item of a project and describe the required properties of the materials used in construction and the construction details for individual items. In the case of a waste containment unit, descriptive specifications describe the unit and the methods by which they are to be constructed; for example, descriptive specifications are used in describing the construction and quality control of the test fill, the earthworks, and the lower compacted soil liner component of an FML/composite double liner. In the case of the compacted soil liner, compaction of the soil can be described in terms of the thickness of the lift and the type of equipment that is needed to obtain the necessary permeability or strength of the soil. If a requirement for compatibility with the waste liquid or leachate is introduced, however, the specific soil that has been tested for compatibility during the design

phase would be specified. Generally, such a specification is avoided unless it is backed up by a simulated performance requirement, such as a test fill.

Reference specifications are standards for construction materials and processes that have been developed by recognized authorities, including professional engineering societies, government agencies, and industry associations. For example, standards for FMLs include those developed by the American Society for Testing and Materials (ASTM), the American Society of Agricultural Engineers (ASAE), and the National Sanitation Foundation (NSF). Reference specifications or standards can be either used as a basis for developing the descriptive specifications or incorporated directly into the descriptive specifications. For example, an FML may be required to meet NSF's specification for that type of FML. These types of standards are generally used in conjunction with one or more of the other types of specifications. For instance, in the case where an FML is required to meet NSF specifications, it would also be required to meet a simulated performance standard as indicated by a compatibility test and requirements for field seam strength.

Proprietary specifications call for materials and components by trade name, model or style number, and manufacturer. For example, such a specification is used to specify a particular FML or liner system component in the construction of a given hazardous waste containment unit if that FML is the only one that has been tested and met specified criteria in an acceptable compatibility test. This type of specification can also be used to specify other components in leachate collection and removal systems. However, even in cases in which a particular FML is specified, the technical specifications will also include material property specifications for QA/QC inspection and a fingerprint of the FML so that it can be demonstrated that the FML installed at the site is the same as the one that passed the compatibility test. "Or equal" materials cannot be used unless the specific materials have been tested for compatibility as required.

Base-bid specifications establish acceptable materials of construction by naming one or more materials so that the selection can be made by the bidder or on the basis of cost. The bidder is usually required to prepare his proposal with prices submitted from manufacturers and suppliers. However, if the materials are to be used in lining a hazardous waste containment unit, they must all be tested for compatibility with the waste liquid to be contained as part of the design process (EPA, 1986a). This compatibility requirement includes FMLs, geotextiles, geonets, pipe, soils, and any other components of the lining system that may come in contact with the waste liquid or leachate.

8.4 SPECIFICATIONS FOR EARTHWORKS, EMBANKMENTS, AND SOIL COMPONENTS OF FML/SOIL COMPOSITE LINERS

The purpose of construction specifications is to describe the quality of work which is required to meet design requirements. Specifications for embankment construction and other earthwork can incorporate language very

similar to that used for standard dam construction. A set of sample specifications have been developed by the Bureau of Reclamation (Fink, Larkins, and Lewandowski, 1977). These specifications are the result of many years of earthwork construction and are a worthwhile starting point. However, the incorporation of any standard specification should be approached with caution because of potential differences in site conditions, materials of construction, and overall design.

8.4.1 Specifications for the Foundation and Embankments

The basic difference in the performance requirement for embankments and earthworks and that for the compacted soil liner, i.e. the lower component of the bottom liner in a double liner system, is that the foundation and embankments are constructed for strength and stability while the liner is compacted to achieve low hydraulic conductivity. Therefore, the materials required for embankments can include slag, ash, or rubble, so long as the design can accommodate such materials, and proper installation techniques are followed (Norheim and Truesdale, 1986 and Goldman et al, 1985).

The minimum elements of specifications for the foundation and embankments are discussed in the following paragraphs.

8.4.1.1 Purpose of the Foundations and the Embankments--

The function of the foundation is to provide structural support to the liner and all of its components for the operational life of the unit through the post-closure care period. The purpose of an embankment is to function as a retaining wall that resists the lateral forces of the stored wastes.

8.4.1.2 Material Specifications for Foundations and the Embankments--

Uniformity of materials with no soft or structurally weak components is critical. Criteria for rejecting unsatisfactory materials and inspection procedures should be stated. Examples of specifications for soil materials include acceptable value ranges for various properties including particle-size distribution, Atterberg limits, hydraulic conductivity of laboratory-compacted soils, and moisture-density relationships.

Geogrids may also be included in the design for use in soil reinforcement. Specifications for geogrids should include the following (Carroll, 1988):

- Geometry.
 - Aperture size.
 - Percent open area.
 - Rib thickness.

- Strength and dimensional stability:
 - Long-term design load.
 - Tensile modulus.
 - Junction strength.
 - Flexural rigidity.

8.4.1.3 Specifications for Excavation and Foundation Construction--

Strength requirements and the means for determining whether or not soils meet design specifications should be defined. Any requirement for excavating in situ soils, and the placement and compaction of replacement soil in the excavation should be stated.

8.4.1.4 Embankment Construction Specifications--

Construction of an embankment is generally performed by compacting a specified material to a required strength at a specified moisture content using a specified compactive effort to a specified dry density, all of which have been correlated in laboratory testing during the design phase. Thus, specifications for constructing the embankments will include construction specifications and procedures for verifying construction performance. In addition, the required slope and height, the placement of reinforcing materials (i.e. geogrids or geotextiles), and the method of construction (i.e. whether the embankment should be constructed in horizontal lifts, continuous lifts, or a combination of both, depending on whether the embankment is homogeneous or includes zones, or whether construction is performed on cut slopes). Construction specifications should specify:

- Density.
- Soil water content.
- Lift thickness.
- Type and level of compactive effort, including:
 - Type of roller.
 - Weight of roller.
 - Number of passes.
- Maximum clod size.
- Method for tying together the lifts.

Procedures for verifying construction performance can include:

- Water content determinations.
- Density determinations.
- In-place strength tests.

Dimensions of the completed embankment should also be stated and supported by the design drawings.

8.4.1.5 Requirement for Test Fill Construction to Verify Embankment Design and Compaction Procedure--

Before constructing a hazardous waste containment unit, a test fill may be required to verify that the specified soil density/moisture content/compactive effort/strength relationships developed during the design phase hold true for actual field conditions and to verify the adequacy of the construction equipment and requirements for embankment construction. This test fill can be constructed in conjunction with the test fill construction of the soil component of the bottom liner for a double-lined unit. Because of the importance of embankment strength, tests performed on the test fill slopes should concentrate on confirming the relationship between moisture content, density, and strength. The results of these tests should be correlated with the construction specifications, which may need to be revised depending on the test results.

8.4.1.6 Specifications for Appurtenances--

Drainage systems, seepage control structures, and erosion control measures which may include berms, and/or vegetative covers should be included in the specifications. Specifications for concrete, pipe, and related materials for such adjunct structures should also be stated in the specifications.

8.4.1.7 Construction Quality Control and Assurance--

The specific actions that must be taken by the designer and construction contractors to ensure that materials and workmanship are accurate and correct and meet the specifications should be specified. All aspects of foundation and embankment construction should also be covered by the construction quality assurance plan, which is discussed in Chapter 10.

8.4.2 Specifications for Compacted Soil Component of a Composite Bottom Liner of a Double Liner System

Except in cases where the conditions for statutory variance are met, current RCRA regulations for the design of hazardous waste containment units require two liners with a leak-detection system between the top and bottom liner (40 CFR 264). The minimum elements included in technical specifications for the compacted soil liner component of a composite bottom liner in

a double liner system are discussed in the following paragraphs. Much of the information presented is also applicable to specifications for soil liners in general.

8.4.2.1 Purpose of the Soil Component of a Composite Bottom Liner--

The function of the soil component of a composite liner is to control constituent migration through breaches of the overlying FML component. The liner should also provide support and function as a protective bedding layer for the overlying FML component.

8.4.2.2 Material Specifications for the Soil Component of a Bottom Composite Liner--

The specifications for the soil materials used in constructing the compacted soil liner will reflect the properties of the soil selected as a lining material and properties that will affect the performance of the compacted liner. Requirements can include acceptable values or ranges for the following properties:

- Hydraulic conductivity of laboratory-compacted soil.
- Soil density/moisture content relationships.
- Particle-size distribution.
- Atterberg limits.

In regions where swelling or other unusual soils are known to occur, or when the liner may be exposed to extreme climatic conditions during or following construction, additional property requirements can be included. A demonstration that the soil used in constructing the bottom soil component is compatible with the waste liquid to be contained may be required, depending on the type of waste to be contained. If compatibility testing is required, the specific soil that is tested must be well characterized, and the results of this characterization incorporated into the materials specifications so that it can be verified that the soil used in construction is equivalent to the soil that was tested. The test method recommended by the EPA to verify compatibility of the soil with the waste liquid or leachate to be contained is EPA Method 9100 (EPA, 1986b), which determines the effect of the leachate or waste liquid on the hydraulic conductivity of the compacted soil. It should be noted that Method 9100 is currently (May 1988) under review. Rejection criteria, test methods required to determine the properties, and sampling requirements should be stated.

8.4.2.3 Requirements for Construction of the Soil Component of a Composite Bottom Liner--

Construction of a soil liner is performed by compacting a specified material at a specified moisture content using a specified compactive effort

to a specified dry density. The various specified elements have been correlated with laboratory results obtained during the design phase to the required saturated hydraulic conductivity. Construction specifications will include:

- Overall thickness of the soil liner.
- Moisture content to produce the specified density.
- Specified dry density, which is usually expressed as a percentage of the density obtained by testing in accordance with a specified test method, e.g. 95% Proctor.
- Depth of the unit-layer to be compacted at one time, i.e. the lift thickness.
- Surface preparation, e.g. scarification, for tying together lifts.
- Maximum clod size and uniformity of moisture content throughout the soil at the time of compaction.
- Method of constructing the liner on the slopes, i.e. whether the liner will be constructed in parallel or horizontal lifts.
- Type of compacting equipment.
- Weight of compacting equipment.
- Number of passes of compacting equipment over one unit-layer.
- Trade-name and model of the compacting equipment, if applicable.

Procedures for monitoring the construction of the liner should be stated in the specifications. Included should be test methods to be performed on the compacted soil, acceptable ranges for the results of these tests, sampling requirements, and remedial actions that should be performed if the compacted soil does not meet specification values (e.g. further compaction). Tests that can be performed on the compacted soil include:

- Density.
- Moisture content.
- Hydraulic conductivity.

If field hydraulic conductivity testing is required as the basis for accepting the liner (e.g. by a regulatory agency), a test fill will probably be constructed, and the field hydraulic conductivity testing will be performed on the test fill liner. Test fills may also be required to verify that

the materials, design (i.e. moisture content and density), equipment, and construction procedures are adequate for constructing the full-scale soil liner. If a test fill is required, construction specifications for the compacted soil liner should be designed to replicate the product that was accepted after evaluation of the test fill. The same construction materials and methods used in constructing a successful test fill, including any design modifications, should be used in constructing the actual liner. If the test fill has been successful, then the actual liner should meet or exceed design criteria, assuming quality control and quality assurance procedures are rigorously followed.

Because of the general heterogeneity of soils, even from a single borrow pit, and depending on the results of QA/QC testing, changes in some construction specifications (e.g. number of passes) may be required in the course of construction so that a soil liner with the required permeability can be constructed.

8.4.2.4 Requirement for Test Fill to Verify Soil Liner Specifications--

Present EPA Guidance on constructing hazardous waste landfills and surface impoundments recommends constructing a test fill to verify the adequacy of the materials, design, equipment, and construction procedures proposed for the soil liner (EPA, 1985; Northeim and Truesdale, 1986). In addition, regulatory acceptance of a soil liner may require the results of field hydraulic conductivity measurements because of uncertainties about the relationship between laboratory tests and actual in-place soil liner hydraulic conductivity. Because of the disadvantages in performing field hydraulic conductivity tests on an in-place liner, constructing a test fill before full-scale unit construction can be used as a method of assuring the in situ hydraulic conductivity of the actual liner. Design specifications for a test fill should duplicate those proposed for the full-scale unit. The dimensions of the test fill and the measures taken to facilitate field permeability testing should be stated. The test fill should be of sufficient length to allow construction equipment to achieve normal operating speed over a test area, and at least four times wider than the widest piece of construction equipment to be used (Northeim and Truesdale, 1986).

The results of the test fill construction can only be extrapolated to the construction of the full-scale liner if the full-scale liner is constructed in accordance with the same design specifications, using the same soil materials, construction procedures, and equipment that were used to construct the accepted test fill. In addition, if field hydraulic conductivity testing of the compacted liner is specified as the method of verifying that the actual liner meets the requirement for hydraulic conductivity, then the results of the field hydraulic conductivity testing need to be correlated with the construction parameters and the results of potential surrogate tests, as is discussed in Section 7.5.3.1.5. Potential surrogate tests include:

- Hydraulic conductivity of laboratory-compacted samples.

- Hydraulic conductivity of undisturbed samples.
- Atterberg limits.
- Particle-size distribution.
- Compacted moisture content.
- Compacted soil density.
- Penetrometer strength tests.

In order for successful replication of the test fill to occur, it is essential to observe, evaluate, and document the construction and evaluation procedures used during test fill construction, and to incorporate what was learned from test fill construction into the specifications. The need for rigorous observation, evaluation, and documentation should be well understood by designer, owner, inspector, and contractor before construction of the test fill has begun.

The procedures by which the test fill construction is observed, evaluated, and documented should be stated in the construction specifications, with allowances made in advance so that any design and construction modifications resulting from the test fill construction can be incorporated into the specifications.

Northeim and Truesdale (1986) and Goldman et al (1985) discuss the design, construction, and evaluation of test fills for compacted soil liners in more detail.

8.4.2.5 Requirements for Miscellaneous Components of the Soil Liner and Earthworks--

Depth of sidewalls, width of berm, slope of embankments, liner thickness, slope of liner along bottom of the unit, and requirements for trench excavation in preparation of the installation of the leak-detection system should all be stated in the specifications and supported by detailed design drawings.

8.4.2.6 Acceptance of Soil Surface as Bedding for an FML--

Acceptance criteria, and the test methods by which to determine acceptability of the final product before the FML can be placed, should be described in the specifications. In some situations, it has been the responsibility of the FML installer to accept the bedding layer on which the FML will be placed. Issues of concern will include desiccation cracking, holes, defects, or areas of subsidence. The means by which to protect the liner after completion of the final lift should also be specified, as should methods by which to repair the liner should damage have occurred in the course of construction operations.

8.4.2.7 Construction Quality Control and Assurance--

Construction quality control and quality assurance procedures for the compacted soil liner should be specified.

8.4.3 Specifications for the Compacted Soil Component of the Upper Composite Liner of a Double Liner System

As is described in Chapter 7, a composite liner has been suggested as the top liner in a double liner system for the containment of hazardous wastes. In such a design, the soil component would have to be compacted on top of the leak-detection system, which may either be a granular system or a synthetic system made up of a combination of geonets, geotextiles, or geocomposites. At present, specifications for the soil component of a top composite liner with respect to either permeability or thickness have not been fully described and documented. However, considerable care needs to be exercised in constructing such a liner component in order to avoid damage to the leachate collection and removal system between the liners, such as intrusion of the soil into the system. Consequently, the construction method should be carefully stated in the specifications. Double-liner designs with a top composite liner should include test data verifying that a secondary LCRS using synthetic drainage materials can perform adequately with the geotextile and clay above it. The elements that should be included in specifications for the compacted soil component of an upper composite liner of a double liner system at a minimum are discussed in the following paragraphs.

8.4.3.1 Purpose of the Soil Component of a Composite Top Liner--

The function of the soil component of a composite top liner is similar to that of the soil component in the bottom composite liner, which is to reduce the leakage of the leachate through an overlying FML at the time of a breach.

8.4.3.2 Material Specifications for the Soil Component of a Composite Top Liner--

The material specifications for the soil component of a composite top liner will probably be the same as those for the soil used in constructing the soil component of the composite bottom liner.

8.4.3.3 Construction Specifications for the Soil Component of a Top Composite Liner--

Since the soil component of a composite top liner is constructed on top of the secondary LCRS, particular care must be exercised in placing and compacting the soil. As is described in Chapter 7, the first lifts must be applied without compaction and care taken to prevent damage to the secondary LCRS. The upper lifts can be compacted, and the total depth and the hydraulic conductivity of the lifts in immediate contact with the FML component of the top liner should be stated, though the hydraulic conductivity may not be as low as 10^{-7} cm s⁻¹. Specifications describing construction parameters

will be similar to, if not the same as, those for the soil component of the composite bottom liner.

8.4.3.4 Construction Quality Control and Quality Assurance--

Procedures for monitoring the quality of compaction should be specified; in addition, observations and tests must be specified to assure that the top surface of the soil is correctly finished, as is discussed in Section 8.4.4. It may be desirable to construct a test fill on top of that used to test the permeability of lower component of the bottom composite liner. This test fill would assess the effect of the construction methods and equipment on the LCRS underneath a top composite liner by assessing the transmissivity of the drainage system after construction of the soil liner.

8.4.4 Specifications for the Subgrade Below an FML

General requirements for subgrade preparation and placement of a protective bedding layer for cushioning the FML, if required, should be stated in the specifications. The specifications will depend on what is intended to contact the FML in the design, e.g. a soil liner or a geotextile, and on how the FML is being used, e.g. as the top component of a composite liner, as the top liner in a double-liner system (i.e. indirect contact with the secondary LCRS), or as a liner for a single-lined unit which is installed on top of recompacted, in situ soil. Elements of specifications for an FML subgrade are discussed in the following paragraphs.

8.4.4.1 Purpose of Bedding Layer for an FML--

The subgrade and protective bedding layer should support the FML and protect it from irregularities in the foundation soils for the operational life of the unit, as well as for the post-closure care period.

8.4.4.2 Material Specifications for a Bedding Layer for an FML--

Depending on the design of the unit, the materials used as the bedding layer for an FML can include surficial foundation soils, the uppermost lift of the soil component of a composite liner, and protective bedding materials such as granular media and geotextiles. Requirement of the subgrade soil with respect to maximum particle size, and the presence of debris and foreign matter should be stated. Present EPA guidance recommends that the bedding layer should have a minimum nominal thickness of 30 cm (12 in.) and an actual minimum thickness of 25 cm (10 in.), that the bedding material should be no coarser than Unified Soil Classification System (USCS) sand (SP) with 100% of the washed, rounded sand passing the 0.25-in. sieve, and that the bedding material is free of rock, fractured stone, debris, cobbles, rubbish, and roots unless it can be shown that the FML will not be physical impaired by the bedding material under service loadings (EPA, 1985). Also, if the bedding layer contains seeds for vegetation that could affect FML performance, the application of a herbicide may be required. However, it should be demonstrated that the specified herbicide will not affect liner performance

and groundwater monitoring results. If a geotextile is specified for protecting the FML, material specifications including strength requirements should be stated. Performance specifications for each material and the test methods to be used should be described.

8.4.4.3 Construction Specifications for a Bedding Layer--

Depth and extent of bedding materials should be stated. Criteria relating to the foundations and embankments are discussed above. Techniques for finishing the uppermost soil lift, which are described in Chapter 9, should be covered. If a geotextile is specified, seaming methods should be described.

8.4.4.4 Construction Quality Control and Quality Assurance--

Observations and tests required to determine that the subgrade has been correctly finished and the bedding materials placed in accordance with the final plans should be treated in both the quality control protocols and the Construction Quality Assurance Plan. Proof rolling may be required before the bedding can be accepted.

8.4.5 Specifications for a Protective Soil Cover

8.4.5.1 Purpose of a Protective Soil Cover--

A soil cover will serve as a protective cover for the FML or for the primary LCRS, depending on the type of unit.

8.4.5.2 Material Specifications for a Soil Cover--

Soil properties should be stated. If there is a requirement for a geotextile to protect the FML or act as a filter for the primary LCRS, the properties of the geotextile should be stated.

8.4.5.3 Construction Specifications for a Protective Soil Cover--

Thickness of the protective cover material and the extent of coverage should be defined. The soil cover should be placed very soon after installation and seaming is completed and the FML seams are tested; because of potential damage to the uncovered FML, the length of time the FML is allowed to remain uncovered may be stated. In addition, insofar as the placement of the protective cover is a potential source of damage to the liner, methods by which to protect the FML during this process and limitations as to what types of earthmoving equipment may be used on top of the FML should be stated in the specifications. Finally, methods of repairing damage to the FML, should it occur, should be described.

8.4.5.4 Construction Quality Control and Quality Assurance--

Specific inspections and test procedures needed for both quality control and quality assurance should be specified; also, the specific property values that are acceptable should be indicated.

8.5 SPECIFICATIONS FOR FMLS

FMLs can be used in numerous ways in the construction of a waste storage or disposal unit including:

- As the FML component of a composite bottom liner of a double-liner system for the containment of hazardous wastes.
- As FML top liner or the FML component of a composite top liner of a double-liner system for the containment of hazardous wastes.
- As a single liner for the on-land storage or disposal of nonhazardous materials.
- As the FML component of a cover system constructed on a landfill during closure.

Correct specification, installation, and seaming of the FML is critical to meeting performance requirements of an FML-lined waste storage or disposal unit. Elements of technical specifications for FMLs are discussed in the following paragraphs.

8.5.1 Purpose of an FML

The function of the FML is to form barrier that controls or minimizes the migration of waste constituents from a waste containment for the operational life of the unit including, in the case of landfills, the post-closure care period.

8.5.2 Performance Requirements for an FML

In order to function successfully as a barrier, the FML has to meet the following requirements:

- The FML must have sufficiently low permeability to the constituents of the waste to be contained so that escape from the unit is below a level that may pose a danger to human health or the environment.
- The FML must be chemically compatible with all constituents of the waste to be contained, i.e. the waste must affect neither the FML nor the seams in such a way that the FML is no longer able to fulfill its function.
- The FML must be mechanically compatible with its service conditions.
- The FML must be sufficiently durable to maintain its integrity in the service environment throughout its required service life, including through the end of the post-closure care period.

- The FML must be capable of being installed under a sufficiently broad range of environmental conditions; in particular, the FML must be capable of being seamed in such a way that the seams approximate the strength and durability of the FML itself.

In addition, the expected service life of the FML should be stated in the specifications. The operational life of a unit can range from less than one year (in the case of some landfills units) up to 20 years; the post-closure care period of a landfill is a minimum of 30 years.

If the wastes or materials to be contained are hazardous, compatibility between the FML and the waste to be contained will need to be demonstrated to the permitting agency. Thus, compatibility testing of the FML with the waste or materials to be contained will need to be performed in accordance with an acceptable test procedure, such as EPA Method 9090 (EPA, 1986b; Appendix L), during the design phase (EPA, 1986a). The results of the compatibility testing are incorporated in the permit application, and the FML is specified by name and type. If two FMLs have demonstrated compatibility, both should be listed in the specifications.

The fingerprint of the FML that has passed the compatibility test should also be included in the specifications so that it is possible to demonstrate that the FML being placed in the field is equivalent to the FML that was tested for compatibility. In cases where the owner/operator has performed a compatibility test with a particular FML to meet the compatibility requirement, but proposes to install an FML of the same type as made by a different manufacturer or of a different "batch" or formulation, EPA presently requires that he either demonstrate that the alternate FML is compatible by further compatibility testing or that the alternate FML is essentially equivalent to the FML that was originally tested by comparing the fingerprints of the two materials (EPA, 1986a). However, the EPA recognizes that choosing the second option will present difficulties because there will need to be agreement on the testing program and interpretation of the test results. Fingerprinting of FMLs is discussed in Section 4.2.2.6.

8.5.3 Material Specifications for FMLs

The properties of an FML can be covered by a large number of different specifications, ranging from those prepared by the FML manufacturer, installer, and the designer/engineer, to reference specifications developed by various organizations such as ASTM, NSF (1985), and the American Association for Agricultural Engineers. The designer/engineer, however, selects the specific set of specifications to meet the material requirements of a specific site and includes these specifications in the design. The requirements can vary with the particular type of containment unit that is being designed and the type of waste stream that is being contained. In addition, the property specifications will depend on the type of FML that has been selected.

Ideally, selecting proper material specifications for an FML should ensure that the selected FML will also meet the performance requirements as stated in Section 8.5.2. However, there is no simple correlation between any one property (e.g. uniaxial tensile strength) and ultimate liner performance. Further field verification testing of in-service FMLs is required before a correlation between FML properties and performance can be developed with any confidence. Thus, no single property or set of property values should be used as a basis for selecting one type of FML over another except in cases where incompatibility with the waste to be contained or incompatibility with the engineering application is demonstrated. In setting the specifications, the designer should be aware that some properties are specified to help ensure that the selected FML will meet the performance requirements and that some are specified to ensure the quality of the selected FML given that a generic FML type has been selected. Those properties specified to ensure the quality of the FML form the basis of the QA/QC testing.

Depending on the type of FML that was selected, properties that may be included in the material specifications can include, but are not limited to:

- Analytical properties:

- Volatiles.
- Ash content.
- Extractables.
- Specific gravity/density.
- Crystallinity content (if FML is semicrystalline).
- Carbon black content.
- Melt flow index (if FML is semicrystalline).

- Physical properties:

- Thickness.
- Tensile properties.
- Modulus of elasticity (if FML is semicrystalline).
- Hardness.
- Tear resistance.
- Puncture resistance.
- Hydrostatic resistance.

- Scrim characteristics (if FML is fabric-reinforced).
- Ply adhesion (if FML is fabric-reinforced).
- Seaming characteristics:
 - Strength of factory-prepared seams.
 - Strength of field-prepared seams.
- Permeability characteristics:
 - Water vapor transmission.
 - Solvent vapor transmission.
 - Gas permeability.
- Tests that measure environmental and aging effects:
 - Resistance to ozone-cracking.
 - Resistance to environmental stress-cracking (if FML is semi-crystalline).
 - Low-temperature properties.
 - High-temperature properties.
 - Air-oven aging characteristics.
 - Dimensional stability.
 - Water absorption.
 - Resistance to soil burial.

These properties and specific tests for measuring them are discussed in Section 4.2.2.5.

Appendix K presents suggested reference standards for a variety of FMLs that are currently available. These property values do not reflect compatibility with the specific waste nor other site specific requirements. However, these specifications can be used for the quality assurance at the time the containment unit is constructed.

Other specifications of FMLs may include specifications for the raw materials constituents of an FML of a given polymer type. In the case of an FML for a hazardous waste containment unit, the fingerprint of the selected FML which has passed the compatibility test should be incorporated in the

specifications so that it can be demonstrated that the FML being placed in the field is equivalent to the FML tested for compatibility.

8.5.4 Specifications for Shipping and Storage of FMLs

Specific requirements for labeling, shipping, and on-site storage for the FML should be described in the specifications. Exact requirements will vary with the FML type.

FMLs are usually shipped and stored in rolls or folded on pallets. Depending on the polymer, particular attention may need to be paid to high temperature and other environmental conditions during storage prior to shipment, during shipment, and at the site prior to installation. Some FMLs, e.g. those based on CSPE and CPE, are sensitive to moisture and heat; these FMLs can partially crosslink (making the FML more difficult to seam) or block under improper storage conditions before being installed in the field. In addition, some FMLs may need to be protected from heat and sunlight to prevent the volatilization of plasticizer.

Depending on the type of FML, identification of the manufactured rolls or fabricated panels should include the following:

- Name of manufacturer/fabricator.
- FML type, including polymer type and details of construction (e.g. number of plies, type of scrim, nominal thickness, etc.).
- Manufacturing batch code (of rolls).
- Panel number or placement according to the design layout pattern.
- Date of manufacture (of rolls) or date of fabrication (of panels).
- Physical dimensions (length and width).
- Directions for unrolling or unfolding of the FML.

Storage facilities for the FML should be secure so as to prevent accidental damage (e.g. by animals) or damage by vandalism. In addition, storage facilities should protect the FML from dirt, dust, water, and extreme heat. In cases where the FML will be stored in direct contact with the ground, the surface should be relatively level, smooth, and free of rocks, holes, and debris.

8.5.5 Installation Specifications for an FML

The placement plan for the liner panels or rolls should be incorporated into the design drawings, which are then referenced in the specifications. Temperature and weather limitations for high quality installation and seaming of the particular FML should be specified, and the type and quality of field seams should be described. Depending on the type of FML, specifications for

seaming could include the overlap between panels, required preparation of the FML prior to seaming, the cleanliness required for seaming operations, and a description of the seaming equipment for the specific FML. A description of the base, e.g. a board, on which to prepare the field seams using solvent-based adhesives and the pressure and dwell time for proper formation of both adhesive and thermal seams can also be included in the specifications. Methods for assuring that the quality of workmanship called for in the specifications is actually met in the field installation should be defined in the construction quality control and assurance plans (see Chapter 10). The specifications should include specific criteria for acceptance/rejection of seams depending on the results of nondestructive as well as destructive tests; for the latter, specific types of breaks that are allowed as well as the minimum values for seam strength resulting from testing in accordance with a specified test method should be incorporated into the specifications. The number of specimens per sample that must be tested and the maximum number of allowed failures for a given sample also should be specified.

8.5.6 Specifications for Sealing the FML to Penetrations and Appurtenances

When penetrations through the lining system (as for structures and pipes) are included in the design, they should be detailed in the drawings, and requirements for their installation and sealing should be described in the specifications. The materials (e.g. pipe boots and sealing compounds) should be described, as should the installation techniques. Since the mechanical compatibility of materials for appurtenances with the FML can be critical, these materials require careful definition in the specifications.

8.5.7 Specifications for Anchoring the FML

The FML is usually anchored by the FML installer. Design of the anchor trench should be detailed in the design drawings, and any special requirements for construction and backfilling of the anchor trench should be described. A requirement for ensuring that all objects placed adjacent to the FML are smooth and will not cause undue wearing, penetration, or tearing of the FML should be stated in the specifications and supported by the CQA plan.

8.5.8 Construction Quality Control and Quality Assurance

Conduct of inspection activities and both nondestructive and destructive seam testing during this phase of construction will provide a reasonable degree of certainty that the FML will meet or exceed performance criteria. Tests of FMLs and FML seams are discussed in Section 4.2.2.5.

8.6 SPECIFICATIONS FOR LEACHATE COLLECTION AND REMOVAL SYSTEMS

Leachate collection systems and removal systems (LCRSs) can contain a wide variety of components. The complexity of the LCRS will vary depending upon the design, but each component that is designed into the systems will require discussion in the written specifications. The different types of LCRSs are discussed in Chapter 7.

8.6.1 Purpose and Performance Requirements

The purpose of an LCRS is to collect all liquids that enter the system and remove them for treatment, re-use, and/or disposal. LCRSs are used in controlling the hydraulic head on a liner and in leak detection. For a hazardous waste landfill, the EPA presently requires two LCRSs, including a primary system placed above the top liner and a secondary system placed between the two liners. The function of the primary LCRS is to minimize the leachate head above the top liner during operation of the unit and to remove liquids that are generated by the system through the end of the post-closure care period. The LCRS should be designed to keep the leachate head on the liner below a predetermined level which, in present EPA guidance, is a maximum of 1 ft. This requirement should be stated in the specifications. Furthermore, an LCRS will be required to have a service life equal to that of rest of the containment system. This will require that drainage and filter materials meet performance specifications for transmissivity and/or hydraulic conductivity. In addition, performance requirements for sump capacity and for mechanical equipment such as pumps, levels, and monitoring equipment should be stated.

The secondary LCRS is separate from the primary LCRS and acts as a leak-detection system to indicate that a breach has occurred in the top liner. This system must have a high transmissivity which is specified and a specified detection time, which is the time between when liquid enters the system and the appearance of liquid in the sump for that LCRS. In addition, the bottom slope of the LCRS should be specified. In permit applications, it may be necessary to demonstrate that the specified design is adequate for meeting the detection time requirement using a combination of modelling and experimental data.

Hazardous waste surface impoundments and waste piles have secondary LCRSs which have the same performance specifications as those for secondary LCRSs in a hazardous waste landfill.

In designing LCRSs with synthetic drainage media, test data for transmissivity should accompany the specifications demonstrating that the specified system can meet the performance specifications, particularly in the case of a secondary LCRS that will be installed underneath a clay liner. Testing should be performed using the boundary conditions that are specified in the design.

In addition, where granular materials are in contact with a perforated pipe, the adequacy of the perforations in relation to the grain size of the drainage media should be demonstrated.

As materials used in an LCRS either will be or may be in contact with the leachate or waste liquid to be contained, all materials used in an LCRS for a hazardous waste containment unit need to be tested for compatibility with the waste liquid or leachate during the design process as is required by EPA directive (EPA, 1986b). Compatibility testing of the granular components

of an LCRS includes determining whether the soil materials will dissolve or form a precipitant that would clog the LCRS when in contact with the waste liquid or leachate to be contained. Compatibility testing of the polymeric components of an LCRS involves exposing the materials in accordance with EPA Method 9090, which determines FML-waste compatibility, and comparing the results of testing the exposed material with the results of testing the unexposed material. Suggested testing includes testing the piping for strength (e.g. ASTM D2412), geotextiles intended for FML protection for grab strength (e.g. ASTM D1682) and puncture resistance (e.g. ASTM D751), and drainage materials for load deformation/transmissivity characteristics (e.g. ASTM D4716). In using transmissivity testing to determine compatibility, the EPA presently recommends the following test conditions (EPA, 1986a):

- The final pressure on the drainage material should be at least 1.5 times the maximum expected pressure to be experienced during the active life and post-closure care period of the unit.
- The drainage material should be tested in the transmissivity under expected field conditions, i.e. both sides of the drainage material should be contact with the materials with which it will be installed in the field (e.g. soil, sand/gravel, FML, or geotextile).

The polymeric materials should then be fingerprinted to ensure that the actual materials used in the construction are those that were tested in the compatibility tests. After a polymeric material has been selected, shown to be compatible, and fingerprinted, the specific name and style of the material and the fingerprint should be incorporated in the specifications. Section 4.2.2.6 presents a protocol for fingerprinting FMLs which is also applicable to characterizing all polymeric materials used in an LCRS.

8.6.2 Material Specifications for an LCRS

An LCRS is typically comprised of a number of subcomponents including:

- A drainage layer.
- A filter layer.
- A pipe network for collecting leachate or waste liquid from the drainage layer and transporting it to the sump/manhole system.
- A bedding layer for the pipe network.
- A sump/manhole system which allows collection of the leachate or waste liquid and access to the pipe network for inspection and possible repairs throughout the monitoring periods.
- Mechanical and electrical equipment for conveying liquid from the collection system to a separate storage or treatment area and for monitoring and controlling the level of leachate above the liner.

The materials used for these various subcomponents varies from design to design and can include granular materials, geonets, geotextiles, geocomposites, and plastic pipe. Each type of material will have its own set of specifications, which may also depend on the intended use of the material.

Specifications for pipe can include:

- Composition.
- Dimensions, including inside diameter, outside diameter, and wall thickness.
- Perforation size and spacing (if applicable).
- Specific gravity/density.
- Tensile strength.
- Modulus of elasticity.
- External loading properties.
- Coefficient of linear expansion.

Reference standards, such as the consensus developed by the Plastic Pipe Institute (Society of the Plastics Industry, 1979), NSF (1977), and ASTM (1988), can also be cited for specifying pipe.

Specifications for geotextiles can include:

- Dimensional properties:
 - Thickness.
 - Mass per unit area.
- Permeability/filtration properties:
 - Percent open area.
 - Equivalent opening size.
 - Permittivity.
- Mechanical properties:
 - Puncture resistance.
 - Trapezoidal tear strength.

- Mullen burst strength.
- Tensile properties.
- Durability characteristics:
 - UV resistance.

Specifications for geonets and other synthetic drainage media can include:

- Thickness.
- Standard crush strength.
- Load deformation/transmissivity characteristics.

Specifications for granular drainage media can include:

- Particle-size requirements.
- Hydraulic conductivity.
- Sensitivity to acids.

8.6.3 Construction Specifications for an LCRS

Because of the range of possible designs, the construction specifications will vary from site to site and design to design. A leachate collection system, particularly the collection pipe network, may require bedding which can also be a granular drainage media. The horizontal and vertical alignment of the foundation required to ensure that the leachate will flow toward the sump should be illustrated in the design plans and specified. Pipe layout and placement condition, as well as the location of riser pipes, manholes, and sumps, should be detailed. Methods and materials by which to join the pipes and seam the geonets and geotextiles should be stated. The requirement for the placement of filter materials, and wrapping of pipes, if required, should also be specified. Placement of the drainage layer, thickness of the layer, and degree of compaction should be stated, as should backfilling methods. It may also be necessary to verify the alignment of the pipe prior to backfilling. Synthetic drainage materials will have special requirements which should be stated in the specifications. These materials are discussed in Chapters 4 and 7. Installation of the mechanical components is usually the final activity performed during construction of the LCRS. Design specifications and manufacturers' recommendations for these components should be incorporated into the specifications.

8.6.4 Construction Quality Control and Quality Assurance

The observations and tests that are necessary to provide a reasonable degree of certainty that the LCRS and its components will meet or exceed

design criteria for the required service life of the facility should be detailed in the construction quality assurance plan.

8.7 SPECIFICATIONS FOR FINAL COVER SYSTEMS

A final cover system is constructed on top of a landfill at the end of the active life of the unit, i.e. at the time of final closure. The active life of landfill units can vary from less than 1 year to more than 10 years. In general, construction of the final cover will be performed under a contract separate from the one used for construction of the lining system. Lutton (1986) describes the design, construction, and maintenance of cover systems and presents several specific examples of specifications that could be followed for different designs of cover systems. These specifications follow, in many respects, the procedures used by highway engineers in the construction of embankments in view of the similarity of placing a cover system on backfilled solid waste and that of a pavement system on an embankment subgrade. Cover systems consist of a series of layers including soils and other materials such as FMLs and geotextiles, as is described in Section 7.5.8 and by Lutton (1986) and McAneny et al (1985).

8.7.1 Purpose and Performance Specifications for a Cover System

The purpose of the cover system is to minimize the generation of leachate within the landfill during the post-closure care period and beyond by preventing the intrusion of liquids into the landfill. The cover should also control gases that may be generated within the fill, function with minimum maintenance, accommodate settling and subsidence, promote drainage, minimize erosion, and allow a transmission of liquids at a rate less than or equal to that of the underlying liner.

The final cover is similar to the lining system in that both consist of a number of different components, which must all function properly and maintain their integrity if the system as a whole is to function adequately. Cover systems typically can consist of:

- - A vegetative layer.
- A filter layer.
- A drainage layer.
- A barrier (or low-permeability) layer.
- A gas-control layer.

Not all of these layers are present in all systems depending on the particular design, the type of waste disposed of in the fill, and other site-specific conditions. Each layer will have its own performance requirements. The vegetative layer should be capable of allowing surface runoff from major

storms without formation of erosion rills and gullies. The filter layer should prevent the vegetative layer soil from entering the drainage layer. The drainage layer should remove water that has infiltrated through the vegetative layer as to minimize infiltration into the barrier layer. The barrier layer should provide long-term control of the migration of liquids into and through the closed disposal unit. In cases where a unit is expected to generate gases, a gas-control layer with a venting system will be included in the design to relieve pressure resulting from the buildup of gases, to control the escape of these gases, and to allow their collection.

8.7.2 Specifications for the Components of a Cover System

The construction of and the materials used in the construction of a final cover system are similar to those of a lining system. Many of the construction and materials specifications will be similar to specifications for the different components of a lining system. One important difference is that the components of a cover system will not come into direct contact with constituents of the waste, with the possible exception of volatile organic compounds present in the landfill gases; thus chemical compatibility with the waste leachate is not a performance requirement for components of the cover system.

8.7.2.1 Specifications for a Gas-Venting System--

The design of a gas-venting system will be similar to that of an LCRS except that, instead of collecting liquids that drain to the bottom of the system, gases that rise to the top of a gas-control layer are collected and allowed to exit the system via vents. The performance requirements for flow through the system should be specified as well as the technical design requirements. In the case of a granular system, the specifications could include:

- Hydraulic conductivity.
- Thickness of layer.
- Particle-size distribution.
- Slope of the overlying barrier layer.
- Pipe specifications, including sizing and spacing and sizing of the perforations for the collection pipes.
- Bedding of the pipe and its depth in the drainage layer.
- Location of the venting riser pipes.

In addition, a filter layer will probably be required both above and below the system. Filter properties should be stated, and the properties of the

selected filter materials should be specified. The method of constructing the system, including the types of equipment that should be used should be stated.

8.7.2.2 Specifications for the Low-permeability Layer--

The low-permeability layer will consist of either compacted clay or a composite clay-FML liner. Specifications for this layer will be very similar to those for the comparable components of a lining system. Construction of the soil component is performed by compacting a specified soil material at a specified moisture content using a specified compaction procedure in order to achieve a specified hydraulic conductivity. Elements of specifications for soil materials and the construction of soil liners are discussed in Section 8.4.2. Important differences will include the level of the soil liner in relation to the average depth of frost and a requirement for the upper slope of the liner. The specifications for an FML component will be similar in form to those for an FML liner. FML specifications are discussed in Section 8.5. The method by which the cover is anchored in relation to the underlying liner system should be detailed.

8.7.2.3 Specifications for Drainage Filter Layers--

Specifications for the combined drainage and filter layers will be similar to those for primary LCRSs in a landfill. Elements of specifications for LCRSs are discussed in Section 8.6. Specifications should include requirements for:

- Hydraulic conductivity (in the case of granular media).
- Transmissivity under compressive loading (in the case of synthetic drainage media).
- The final bottom slope.
- Thickness of the layer (in the case of granular media).

8.7.2.4 Specifications for the Vegetative Layer--

The design of a vegetative layer will depend on a number of site specific conditions. Various elements of specifications for vegetative layers will include:

- Thickness of the overall layer. If more than one soil has been specified, the thickness of each soil type.
- Characteristics of the soil, including pH characteristic, organic content, grain-size characteristics, and requirements for nutrients.
- Requirements for placement and compaction of soil materials, including methods of placing the soil, loose lift thickness, the required

density (stated as a percent of maximum density determined in accordance with a standard method), and methods of inspecting the construction procedures.

- Final slope of the cover.
- Requirements for surface drainage systems for routing run-off.
- Procedures for establishing the vegetation on the top of the cover, including:
 - Materials to be used, i.e. type of fertilizer, seed, and mulch.
 - Seeding schedule.
 - Soil preparation prior to seeding.
 - Methods of applying seed, fertilizer, and mulch.
- If a nonvegetative cover has been specified (e.g. riprap), then the characteristics and the requirements for placing the top layer of the cover.
- A maximum rate of erosion (EPA, 1987).

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CHAPTER 9

CONSTRUCTION OF LINED WASTE STORAGE AND DISPOSAL UNITS

9.1 INTRODUCTION

In the construction phase of a project, design plans and specifications are converted into the actual waste storage or disposal unit. The construction contractor is responsible for constructing the unit in strict accordance with the design criteria, plans, and specifications that have been approved by the owner and the permitting agency. As part of the contractual arrangement made with the unit owner/operator, the contractor may be required to include the formulation and implementation of a formal plan for construction quality control.

This chapter discusses various steps in constructing the major components of both hazardous and nonhazardous waste containment units and several of the subcomponents that require special attention; construction and installation of the following components are discussed:

- Earthworks, including excavation and construction of the foundation, the embankment, and the soil component of a composite liner.
- FMLs.
- Leachate collection and removal systems.
- Final cover system.

Discussion of soil liners is limited to their construction as components of a composite liner. Goldman et al (1985) discuss the construction of clay liners in detail. This chapter also discusses special considerations in FML installation, such as around appurtenances, and the construction of admixed liners.

9.2 EARTHWORKS

In this section, the construction of the earthwork components of storage and disposal units are discussed. Earthwork construction begins with excavation and preparation of the foundation and includes construction of the soil component of a composite liner. The different components serve different

functions. These components will have different specifications, pose different construction problems, require different construction techniques, and require different types of quality control inspections.

In most instances, the earthwork is performed by a general engineering/construction contractor. The types of equipment used vary with the size and complexity of the job. Basically, equipment used in constructing waste storage or disposal units can be grouped as excavators, earthmovers, compactors, and special equipment. Small impoundments may require only tractors with dozer blades, water trucks, and compactors, while large jobs may require additional vehicles including side loaders, graders, trucks, backhoes, front end loaders, trenching machines, and conveyor systems (Figures 9-1, 9-2 and 9-3). Sources of general information on earthworks include Gregg (1960), Sain (1976), and Church (1981).

9.2.1 Excavation and Foundation Construction

Depending on the type of unit, its size and configuration, and the site location, the amount of excavation and site preparation will vary. If groundwater is encountered during excavation resulting in a significant amount of surface water, problems may develop that can adversely affect the subsequent liner installation. The presence of free standing water in the excavation will not only hinder the work of heavy equipment, but also will severely hamper construction of the soil component of a bottom composite liner. Similarly, rainfall can hinder excavation activities and, in some cases, halt work by creating adverse traffic conditions. If free water persists at the base, a special base may have to be constructed. Gravels of various sizes can be packed into the earth, then covered with sand or other available material such that a stable, firm working surface for later grading is achieved. Costs are greatly increased by the need to build a water-free surface for an FML installation in wetted areas.

During the excavation process, all vegetation (tree trunks and roots, in particular) and large rocks need to be removed from the site. In general, the upper 3 to 12 in. need to be removed at a minimum. This soil, which can be used elsewhere in the unit for miscellaneous construction purposes, may shrink 5 to 20% between excavation and use. Any depressions resulting from removing stumps, boulders, or similar conditions need to be filled in with suitable backfill.

Slopes will be constructed by usual techniques. Most construction equipment, including self-propelled compacting rollers, can be operated on slopes up to 3:1 during normal conditions. However, during periods of precipitation, additional arrangements may be needed to ensure that equipment can travel safely up and down slopes, even 3:1 slopes. A simple link to a large dozer, another heavy piece of equipment, or a winch stationed at the top of the sidewall/berm can be used. The equipment at the top then helps to pull the working unit up the slope, and helps to retard its down slope progress on the return trip.



Figure 9-1. Typical earthwork equipment used during impoundment construction: dozer with blade (top) and dozer with compactor and blade (bottom).



Figure 9-2. Trenching machine for anchor trenches (top). Dozer and earth mover for berm construction (bottom).



Figure 9-3. Conveyor system used during earthwork construction.

When the side slope is steeper than 2:1, the "helping hand" approach is mandatory. One method is to chain two similar pieces of equipment together for cross slope work, such that the "helper" traverses the flattened top of the embankment while its chainlinked "twin" works the slanting side slope. Of course, extreme care must be observed during operations of this type. Road graders or vibrating rollers linked side-by-side by chain are examples of the types of equipment that might be used in this manner.

9.2.2 Compaction of Soil

Compacting soil materials is an essential element in constructing components of all types of lining systems, whether they be soils for the clay soil component of a composite liner or for a subgrade on which admix or sprayed-on liners will be installed. Regardless of whether compaction is being performed to increase the strength or decrease the hydraulic conductivity of a soil, in the earthwork construction, the soil materials are usually compacted at a specified moisture content to achieve a minimum density. This density is usually stated as a percentage of the maximum dry density achieved by compacting the soil in accordance with a standard method, e.g. Standard Proctor. The compactive behavior of soils is presented schematically in Figure 9-4 as a function of moisture content. This figure shows a range of water contents at which the soil can be compacted to achieve the target density, given the specific compactive effort. Water contents outside this range will need to be adjusted to achieve the target density. Strict

control of water content is essential to achieving the target density and, in the case of soil liners, the specified hydraulic conductivity. The compactive behavior of soils and its relationship to soil properties is discussed in more detail in Section 7.5.3.1.2.

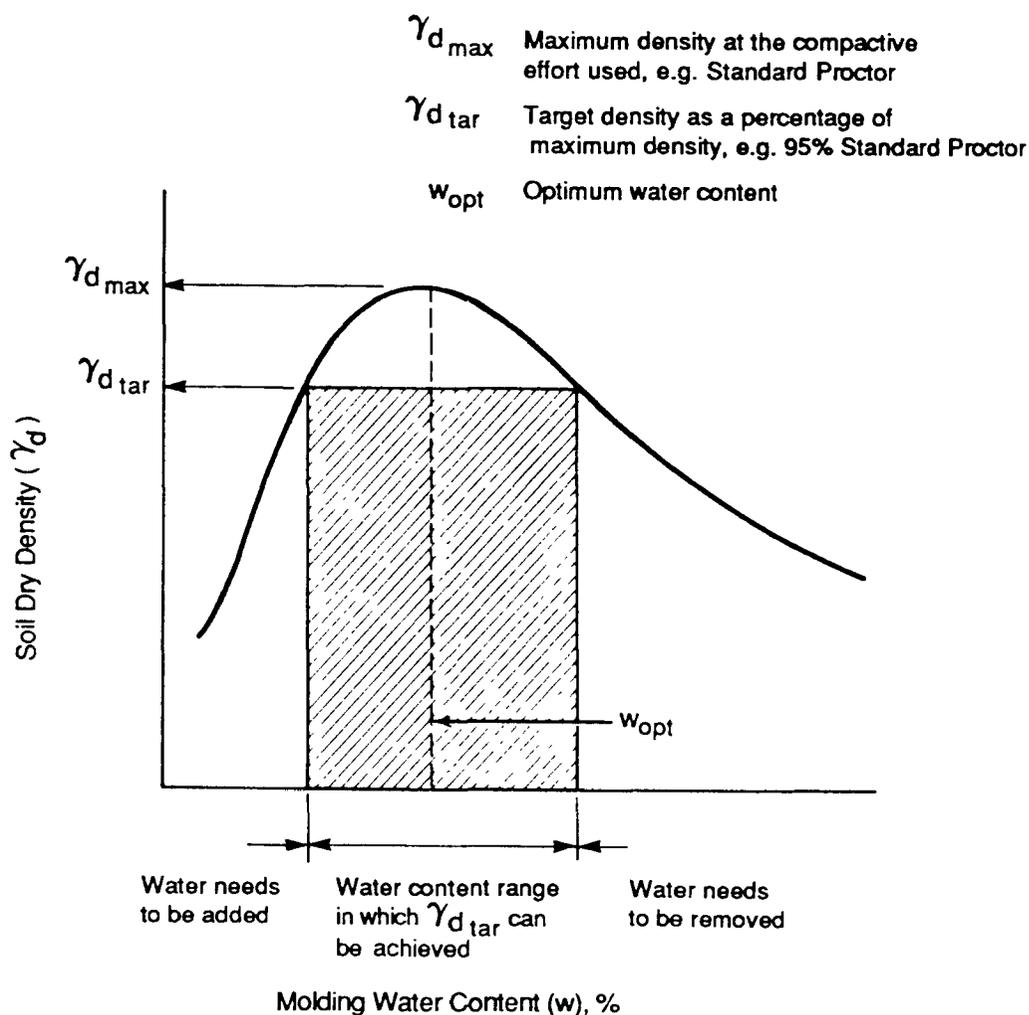


Figure 9-4. Schematic representation of the compactive behavior of soils as a function of molding water content.

Since the soil component of a composite bottom liner for hazardous waste containment units must have a low hydraulic conductivity (i.e. less than or equal to 10^{-7} cm s⁻¹), emphasis on compacting soil for use as a liner is placed on achieving as low an hydraulic conductivity as feasible. During the design phase, data were developed showing that the required hydraulic conductivity could be achieved at the specified density. Compaction for strength is secondary, but strength is necessary for the slopes. For the subgrade, compaction of soil is needed to improve structural strength, uniformity of the subgrade, and smoothness. The subgrade sidewall particularly needs

strength for stability. Some FML manufacturers have indicated that they believe soil materials should be compacted to 90 to 95% Proctor to achieve a firm, unyielding base for an FML.

In this subsection, field compaction of soil, the equipment, and the field tests required in the construction of lined waste disposal containment units are described. For further discussion of field compaction and tests of compaction see Goldman et al (1986), Spigolon and Kelley (1984), and Bureau of Reclamation (1974 and 1977). Even though Lutton (1986) is specifically discussing construction of covers, much of his discussion is also appropriate to soil liners.

The applicability and requirements for the various pieces of compaction equipment that can be used to achieve desired compaction are presented in Table 9-1. The adequacy, use, and efficiency of each piece of equipment varies with numerous factors including type, weight and transmitted energy, thickness of layers, placement water content, and material to be compacted.

The types of equipment in general use for gross compaction include sheepsfoot rollers, rubber tired rollers, smooth wheeled rollers, crawler tractors, and tampers. Vibrating baseplate rollers, power tampers (or rammers) and manual tampers (or rammers) are used for fine finishing work both in the base and sidewalls. Power tampers and manual tampers are necessary for backfill compaction of trenches or where penetrations of the base or sidewalls occur, e.g. around pipes, inflow/outflow/overflow structures, and specialized supporting structures.

Compaction equipment can be selected based on weight and transmitted energy requirements and the type of material to be compacted. For non-cohesive materials used in constructing of granular drainage systems, compaction can be adequately achieved with track-type crawler tractor and/or haulage units since light pressure and vibration is the most effective method of compacting these materials. Frequently, complete drying and rewetting is necessary to destroy the bulking effect of surface tension created by soil moisture. Very firm compaction can be achieved on sands, gravels, and rock-fill by the use of heavy vibratory wheeled compactors. Lifts of noncohesive material up to 24 inches in thickness can be compacted with the vibratory rollers. Generally, stones in the cohesionless material should be no larger than 2/3 of the specified lift thickness (Coates and Yu, 1977). Drainage and bedding requirements may result in the specification of materials much smaller in size.

Heavy sheepsfoot rollers, pneumatic rollers, and vibratory compactors are well suited for cohesive soil materials used in the construction of soil liners. Figure 9-5 shows a sheepsfoot roller and a steel roller used in soil compaction. Steel rollers are used particularly in final finishing of a soil surface before liner placement. For compacting clays, rubber-tired rollers are generally more successful than smooth steel rollers. When the clay component of the composite liner is compacted with rubber-tired equipment, the completed surface of a given lift will be smooth. Scarifying the compacted layer with equipment such as a disk harrow is necessary to

TABLE 9-1. COMPACTION EQUIPMENT AND METHODS

Equipment type	Applicability	Requirements for compaction of 95 to 100 per cent Standard Proctor, maximum density			Possible variations in equipment
		Compacted lift thickness, in. (cm)	Passes or coverages	Dimensions and weight of equipment	
Sheepsfoot rollers	For fine-grained soils or dirty coarse-grained soils with more than 20% passing No. 200 mesh; not suitable for clean coarse-grained soils; particularly appropriate for compaction of impervious zone for earth dam or linings where bonding of lifts is important.	6 (15)		Soil type	For earth dam, highway, and airfield work, drum of 60-in. dia. (152 cm), loaded to 1.5 - 3 tons per lineal ft (43.7 - 87.5 kN per lineal m) of drum generally is used; for smaller projects, 40-in. dia (101 cm) drum, loaded to 0.75 to 1.75 tons per lineal ft (21.9 - 43.7 kN per lineal m) of drum is used; foot contact pressure should be regulated so as to avoid shearing the soil on the third or fourth pass
			4-6 passes for fine-grained soil; 6-8 passes for coarse-grained soil	Foot contact area, in ² (cm ²) Foot contact pressures, psi (MPa) Fine-grained soil PI > 30: 5 - 12 (32 - 77) / 250 - 500 (17 - 34) Fine-grained soil PI < 30: 7 - 14 (45 - 90) / 200 - 400 (14 - 2.8) Coarse-grained soil: 10 - 14 (64 - 90) / 150 - 250 (1.0 - 1.7)	
Rubber tire rollers	For clean, coarse-grained soils with 4 - 8% passing No. 200 mesh.	10 (25)	3 - 5	Tire inflation pressures of 60 to 80 psi (0.41 - 0.55 MPa) for clean granular material or base course and subgrade compaction; wheel load 18,000 - 25,000 lb (80 - 111 kN), tire inflation pressures in excess of 65 psi (0.45 MPa) for fine-grained soils of high plasticity, for uniform clean sands or silty fine sands, use large size tires with pressure of 40 to 50 psi (0.28 - 0.34 MPa).	Wide variety of rubber tire compaction equipment is available; for cohesive soils, light-wheel loads such as provided by wobble-wheel equipment, may be substituted for heavy-wheel load if lift thickness is decreased; for cohesionless soils, large-size tires are desirable to avoid shear and rutting.
	For fine-grained soils or well graded, dirty coarse-grained soils with more than 8% passing No. 200 mesh.	6 - 8 (15 - 20)	4 - 6		
Smooth wheel rollers	Appropriate for subgrade or base course compaction of well-graded sand-gravel mixtures.	8 - 12 (20 - 30)	4	Tandem type rollers for base course or subgrade compaction, 10 - 15 ton weight (89 - 133 kN), 300 - 500 lb per lineal in. (3.4 - 5.6 kN lineal cm) of width of rear roller.	3-wheel rollers obtainable in wide range of sizes, 2-wheel tandem rollers are available in the range of 1 - 20 tons (8.9 - 178 kN) weight, 3-axle tandem rollers are generally used in the range of 10 to 20 tons (89 - 178 kN) weight; very heavy rollers are used for proof rolling of subgrade or base course
	May be used for fine-grained soils other than in earth dams, not suitable for clean well-graded sands or silty uniform sands.	6 - 8 (15 - 20)	6	3-wheel roller for compaction of fine-grained soil; weights from 5 - 6 tons (40 - 53 kN) for materials of low plasticity to 10 tons (89 kN) for materials of high plasticity.	
Vibrating baseplate compactors	For coarse-grained soils with less than about 12% passing No. 200 Mesh, best suited for materials with 4 - 8% passing No. 200 mesh, placed thoroughly wet.	8 - 10 (20 - 25)	3	Single pads or plates should weigh no less than 200 lb (0.89 kN); may be used in tandem where working space is available, for clean coarse-grained soil, vibration frequency should be no less than 1,600 cycles per minute.	Vibrating pads or plates are available, hand-propelled or self-propelled, single or in gangs, with width of coverage from 1.5 - 15 ft (0.45 - 4.57 m), various types of vibrating-drum equipment should be considered for compaction in large areas.
Crawler tractor	Best suited for coarse-grained soils with less than 4 - 8% passing No. 200 mesh, placed thoroughly wet.	10 - 12 (25 - 30)	3 - 4	No smaller than D8 tractor with blade, 34,500 lb (153 kN) weight, for high compaction.	Tractor weight up to 60,000 lb.
Power tamper or rammer	For difficult access, trench backfill; suitable for all inorganic soils.	4-6 in (10 - 15 cm) for silt or clay; 6 in. (15 cm) for coarse-grained soils		30 lb (0.13 kN) minimum weight, considerable range is tolerable, depending on materials and conditions	Weights up to 250 lb (1.11 kN); foot diameter 4 to 10 in (1.57 - 3.93 cm).

Source: Coates and Yu, 1977, pp 90-91.

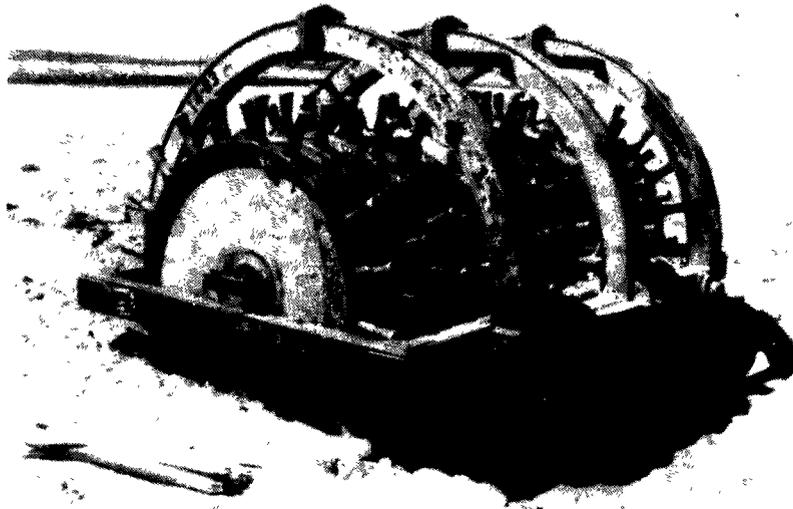


Figure 9-5. Equipment for compaction and fine finishing. The top photograph shows a sheep's foot roller; the bottom photograph shows a steel roller for fine finishing.

ensure adhesion of the overlying layer. Figure 9-6 shows a water vehicle used to add water to soil prior to compaction.



Figure 9-6. Water tank vehicle used to prepare the soil for compaction.

9.2.3 Construction of Embankments

The embankments are constructed in accordance with the design and with sufficient stability and strength to prevent their failure. Most of the operations carried on during the construction of the embankments are standard to earthworks in general. Compaction, which is of particular importance in constructing waste containment units, is discussed in the previous section. Embankments can serve as the support for a soil liner placed on the interior slope when the liner is placed in continuous lifts or part of the embankment can incorporate the bottom liner soil component when the soil liner is placed in horizontal lifts, as is shown in Figure 7-8. Thus, embankments can be constructed either as homogeneous or zoned embankments (Figure 7-9).

Before constructing the embankments, the foundation needs to be inspected to ensure that it has adequate bearing capacity to support embankment construction. Foundation soil analyses should include strength tests. The materials to be used for constructing the embankments should be inspected to ensure that all materials are uniform and as specified. If there is concern about meeting the design requirements with the soil and the equipment available, it may be desirable to construct a test fill, as is discussed in the next section, to verify that the specified soil density/moisture content/compactive effort/strength relationship developed by laboratory tests holds for field construction conditions and to determine whether the construction equipment is suitable. The inspection during construction is described in more detail in Chapter 10. Drainage systems are installed and erosion control measures are taken to ensure minimal erosion of the outer slopes of the embankments.

9.2.4 Construction of Soil Component of a Composite Liner

The soil liner used as the lower component of a composite liner serves as a protective bedding material for the FML upper component and minimizes the rate of leakage through any breaches that might occur in the FML upper component. The basic requirements of the soil liner are that it should have a maximum hydraulic conductivity of $1 \times 10^{-7} \text{ cm s}^{-1}$ and that it should serve as a long-term structurally stable base for all overlying components of the unit.

The soil material used in constructing the soil liner is selected after being tested for hydraulic conductivity and compatibility with the waste liquid or leachate to be contained. The soil should also have been tested in a laboratory for density/moisture content/compactive effort/hydraulic conductivity relations, particle-size distribution, Atterberg limits, and other properties as required for the specific design.

The soil used in constructing a liner must first be excavated either from a borrow source or from the site itself. If more than one soil is being excavated from the same source, the different materials can be blended at the excavation site. At the time of excavation, there may be a preliminary water content adjustment, particularly if large amounts of water are required. The soil is pulverized and stockpiled to allow it to hydrate before being transported to the construction area. The surface on which the soil is to be compacted is prepared by scarification with equipment such as a disk narrow or special rakes with short teeth. Care is taken in controlling the depth of penetration so that the integrity of previous compaction is ensured. The soil is distributed over the construction area evenly and to the thickness required so as not to exceed the thickness requirement for a compacted lift. Measures are taken to break down the clods, and the moisture content of the soil is adjusted so that the moisture content is within the required range. Mixing and allowing the soil to hydrate after spraying with water may be required to ensure that the soil has a uniform moisture content at the time of compaction. Once compaction is finished, the soil is tested in accordance with the QA/QC plan. If test results indicate the need, further compaction is performed. Construction continues in lifts until the required depth is reached.

In general, soil liners are compacted wet-of-optimum because of the lower hydraulic conductivity values that tend to result from compacting wet-of-optimum and because the higher moisture content will reduce the tendency of a soil to form clods. The requirement for compacting wet-of-optimum can pose construction problems if too much water gets into the soil, e.g. by rainfall. Removing water from a clay soil is very costly and can cause construction delays. The soil must be scarified and aerated in dry weather.

Due to the nonhomogeneity of soil materials and the potential effects of macrostructure deficiencies on the hydraulic conductivity of the in-place

liner, the hydraulic conductivity and other criteria for field construction that have been set as a result of laboratory testing may be difficult to achieve by field compaction, as is discussed in Section 7.5.3.1.5. Consequently, a test fill may be required using the same soil material, design specifications, equipment, and procedures proposed for the full-scale liner. An example of a test fill with a collection system is illustrated in Figure 9-7. Field hydraulic conductivity tests using an infiltrometer, such as the sealed double-ring infiltrometer described by Daniel and Trautwein (1986), can be performed. If field hydraulic conductivity testing of the in-place liner is required for regulatory acceptance, other soils tests which can be used as surrogate tests should be performed during construction so that the results of measuring the field hydraulic conductivity of the test fill can be used to estimate the field hydraulic conductivity of the full-scale liner, as is discussed in Section 7.5.3.1.5 and in Northeim and Truesdale (1986). Field variables (1986) that need to be carefully measured and controlled in both the construction of the test fill and the full-scale liner include the following Northeim and Truesdale (1986):

- Compaction equipment type, configuration, and weight.
- Number of passes of the compaction equipment.
- Method used to break down clods before compaction and the maximum allowable clod size.
- Method used to control and adjust moisture content, including equilibration time, and the quantity of water to be used in any adjustment.
- The speed of the compaction equipment traveling over the liner.

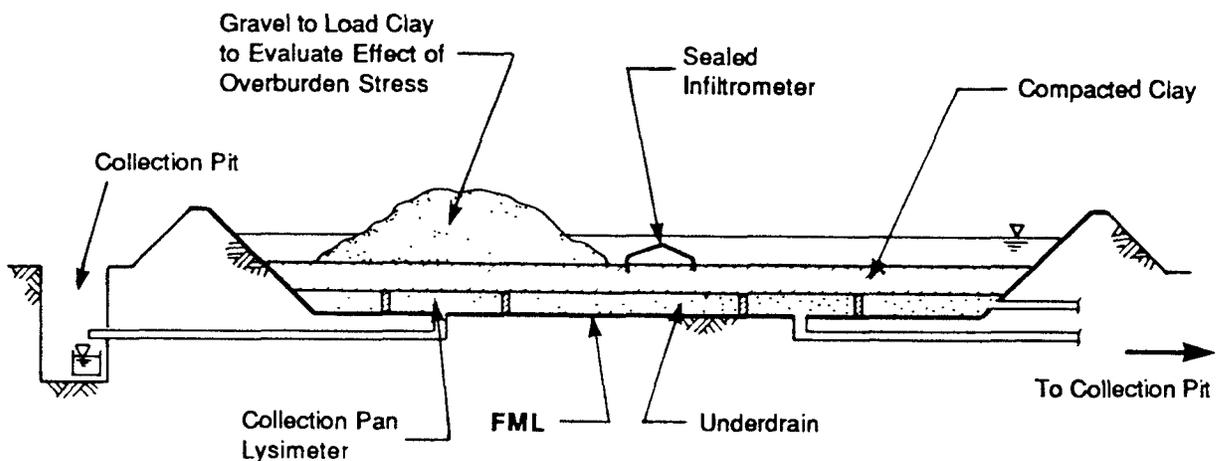


Figure 9-7. Schematic of a test fill equipped to allow quantification of hydraulic conductivity using a lysimeter and a sealed infiltrometer and to determine the effect of overburden stress on the hydraulic conductivity of the compacted liner. (Source: Northeim and Truesdale, 1986).

- Uncompacted and compacted lift thicknesses.
- Methods used to tie the lifts together.

If different soil materials are being used to construct the liner, the test fill can also be used to inspect the homogenization procedure.

Another important consideration is protecting the compacted soil liner from climatic effects during and after construction. Rainfall can result in erosion, in flooding of the site, or in over-moistening of the liner material. Desiccation and freezing can result in cracking of the compacted liner. To protect a site from the elements, inflatable domes have been installed over the site so that construction can proceed during inclement weather (Goldman et al, 1985). More frequently used measures include:

- Rolling the surface of the liner smooth with either a smooth drum or a wheeled roller to protect the surface from erosion. The site needs to be properly graded to ensure surface drainage to the lowest point of the site and to prevent puddling or ponding on the liner surface. Special measures may be required to remove water from the low point.
- Placing a plastic cover on the surface to prevent drying or wetting of the liner.
- Placing a loose soil cover on the surface to prevent drying or erosion of the liner.
- Placing a loose soil cover or a layer of organic mulch to protect the liner from freezing. All organic material will need to be removed before construction can continue.
- Spraying the soil surface with a soil sealant such as an asphalt emulsion.

If cracks develop in the liner, it is necessary to blade down to unaffected soil, disk the disturbed soil, and recompact.

Although much of experience has been accumulated in constructing similar structures, e.g. dams, canals, embankments, etc., relatively little is known about the construction of soil liners covering large areas; accordingly, quality control inspection work is an important element of construction. The effectiveness of the inspecting work will depend on the design of the quality control program (i.e. test methods, sampling strategies, etc.), the ability of the quality control team, its cooperation with the construction group, and the capacity of the contractor to "learn while doing" and improve his performance.

To assist in the inspection, there should be either an on-site laboratory or easy access to a qualified laboratory so that, at any time during

the construction of the soil liner, a clear and quick qualitative assessment can be made as to whether the work performed complies with specifications.

9.2.5 Fine Finishing of Soil Surfaces

After the compaction of the soil liner (which can serve as the bedding layer for the FML) or other subgrade on which the FML is to be placed has been completed, it is normal to fine finish the surface to avoid possible puncture of the FML. Depending on the design specifications, various techniques can be used. Often, teams of workers (generally from 2 to 10 depending on the size of the job) are assigned to scour the surface on both the base and sidewalls, looking for and removing rocks or debris. Workers are also encouraged to tamp down any soil which can be manually disaggregated and spread.

Requirements for a smooth surface on the bottom and sidewalls has resulted in drags being used to help form a regular, flat working surface. Usually, the fine finishing with vibrating rollers and drags will need to be performed on a slightly wet surface. Fine finishing with a smooth steel roller is sometimes required. Occasionally, in constructing the foundations for a nonhazardous waste containment unit, soil additions are required to bridge surface irregularities if the irregularities cannot otherwise be removed.

Figure 9-8 shows examples of subgrade that require additional work before an FML can be placed; Figure 9-9 shows scraper and roller being used to fine finish a subgrade, and Figure 9-10 presents examples of a suitable subgrade texture prior to placing an FML.

Vegetation at the site may need to be controlled to prevent damage to the FML, particularly if the FML is left uncovered or the unit is left unfilled for a while. In cases where the FML is to be installed directly on a foundation (i.e. in a containment unit for nonhazardous materials), unwanted grasses and other types of vegetation are controlled in the fine-finishing stage by removing of the layer containing the vegetation and/or applying a herbicide to the finished slopes and base. Selecting a proper herbicide is critical as some species of grasses found in western states are not killed by certain herbicides commonly used in the more humid eastern United States. In addition, application of the herbicide should not pose a long-term danger to human health and environment and should not interfere with the groundwater monitoring program for the facility. All fill obtained off-site should be inspected well to ensure that both germinating and inactive seeds and roots are killed by the application of herbicide.

Generally, if herbicide is applied, there is a delay of a few days before the FML installation begins so the herbicide is absorbed by the soil and so components that may react with the FML are allowed to volatilize. Figure 9-11 shows what can happen if an herbicide is not applied properly. The picture shows salt grass penetrating a 30-mil FML. When applying herbicides, proper protection against inhalation and skin contact should be taken.

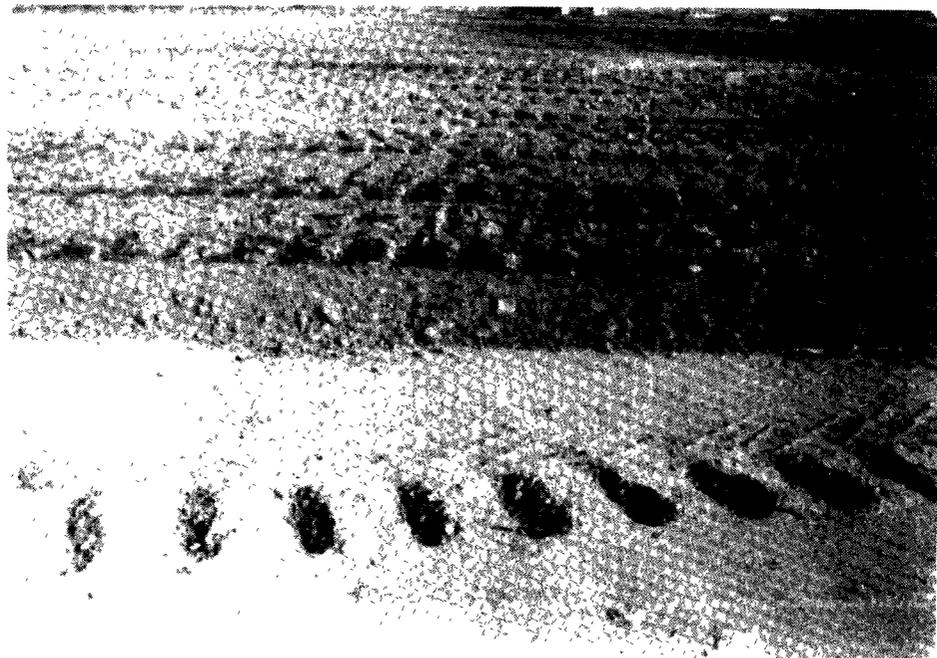
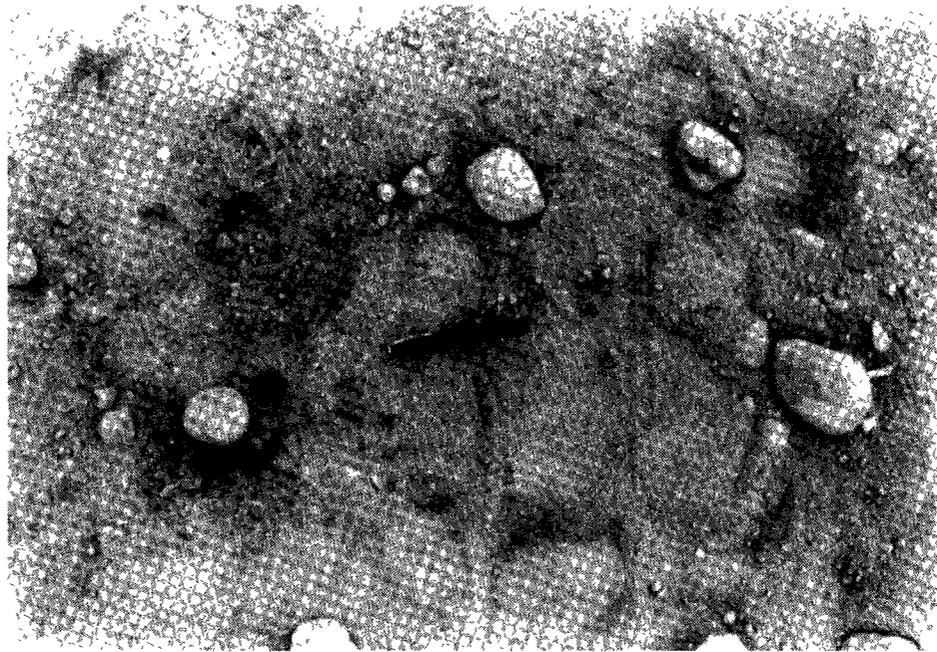


Figure 9-8. Photographs showing various stages of subgrade finishing. These subgrades require further work.

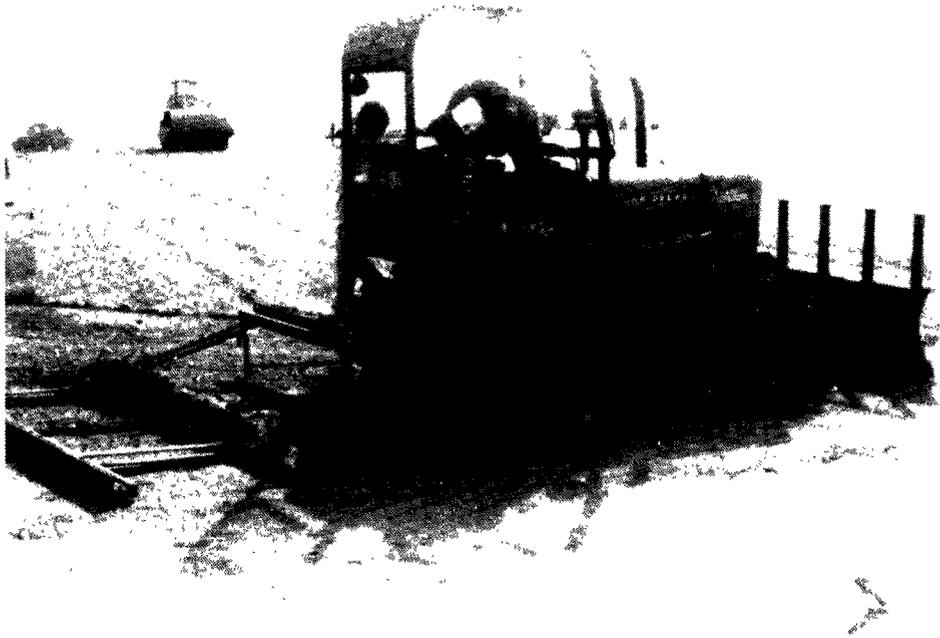


Figure 9-9. Scraper and roller being used to fine finish a subgrade.



Figure 9-10. Representative subgrade surface texture prior to placement of an FML.

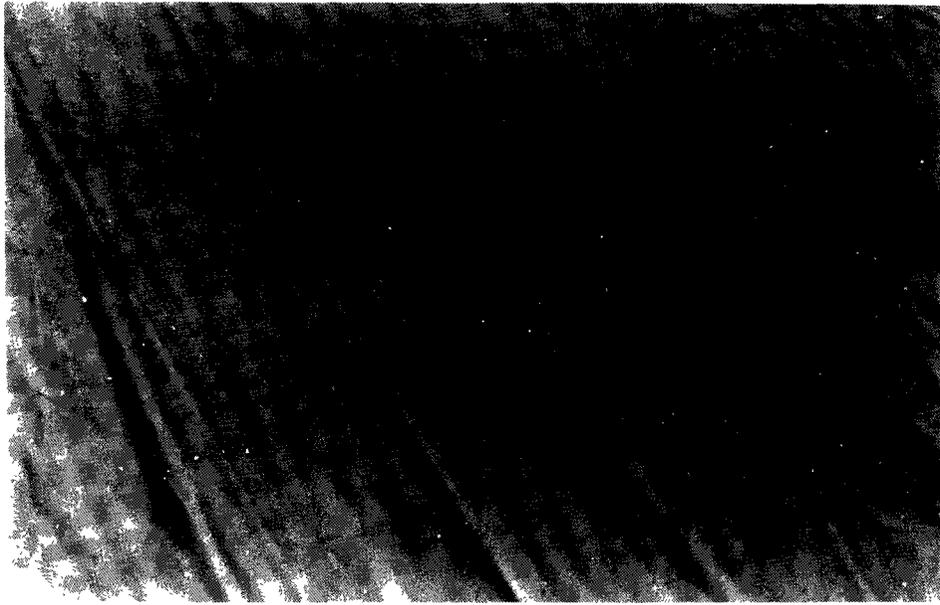


Figure 9-11. Salt grass penetrating a 30-mil FML. Soil sterilization is important prior to placing an FML liner.

The activities of excavation, construction, trenching, compaction, fine finishing, and liner installation are generally all progressing at the same time on larger jobs. It may be desirable during dry weather to sprinkle water or other dust control compounds on the prepared soil surface since seaming FMLs is best performed in a dust-free environment.

9.3 INSTALLATION OF FMLS

Installing an FML requires a significant amount of planning prior to construction. This planning must consider the storage and security of all necessary equipment, installation equipment, manpower requirements, the placement operation, field seaming, anchoring and sealing, construction quality control (CQC), construction quality assurance (CQA) inspection, and protection of placed liners. These considerations are discussed in detail in this section.

9.3.1 On-site Storage of Materials and Equipment

Items requiring storage will include the FMLs and all equipment necessary for installation. Figure 9-12 shows FMLs packaged and shipped to the site. Depending on the type, FMLs are packaged in folded panels or rolls which can weigh from 2,000 to 10,000 pounds each. All FMLs should be stored out of sunlight if possible to prevent degradation and, depending on the FML type, to minimize blocking, a phenomenon that occurs when an FML sticks to itself during shipping or storage, resulting in delamination or ripping when unrolled onto the subgrade. Figure 9-13 shows the result of blocking of a

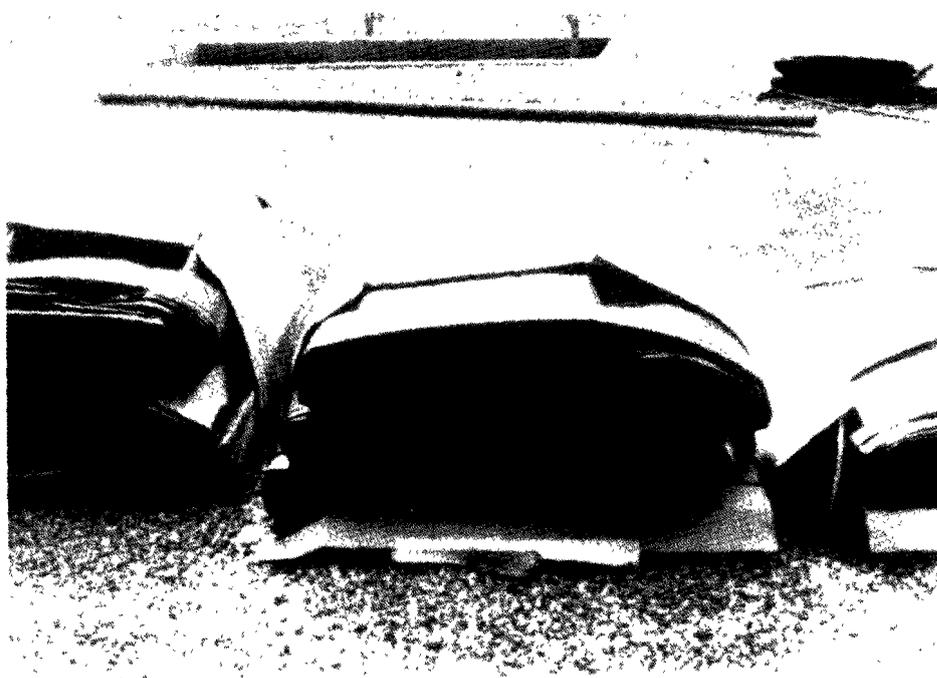


Figure 9-12. FML panels are shipped to the site on wooden pallets either rolled or accordion-folded.

reinforced FML, with the scrim exposed. This damage must be repaired. FMLs are shipped rolled or accordion-folded in cardboard boxes and placed on wooden pallets. The FML can thus be moved from the storage site to the construction site by means of a fork-lift truck, or some other suitable piece of equipment, without damage.



Figure 9-13. Damage to a fabric-reinforced FML caused by "blocking" of the sheeting. Blocking can occur during shipping or storage when the FML is rolled or folded and sticks together under warm conditions. The exposed fabric reinforcement must be repaired.

An important consideration in storing equipment and FMLs at a site is preventing of vandalism and theft. A temporary fence can be erected, or the FML can be stored in an existing secured area.

The need for an elaborate storage system can be minimized if the job is planned so that all equipment and materials necessary arrive at the site at the same time, and installation begins immediately after their arrival.

9.3.2 Equipment and Materials for Installing FMLs

The equipment needed to install an FML varies with depends the type of FML to be installed and the complexity of the job, which depends on factors such as size of the site, side slope steepness, the number of penetrations, the number of seals required, and the length of installation time anticipated.

The major types of equipment and materials needed for installing FMLs include:

- Equipment for transporting the FMLs to and on the construction site and for use in unrolling or unfolding the FML panels or rolls.
- Equipment and materials for holding the FML in position after it has been spotted.
- Equipment and materials necessary for seaming the FML.
- Equipment and materials for the safety of the work crew.

Some means of moving the FML from the storage area to the construction site and on the construction site is necessary. A forklift truck for moving FMLs placed on pallets can be used, though other pieces of equipment, such as a backhoe or front-end loader, can also be used. HDPE FMLs, which are brought to the site in rolls rather than on pallets, require a crane or front-end loader for moving to the construction site. These rolls can weigh up to 10,000 pounds, and special straps are used in moving them (Figure 9-14).

A backhoe may prove useful if touch-up work on subgrade preparation is required during installation. A backhoe or front-end loader can also be used to move sand to the top of the slopes so that sand bags can be filled to prevent the wind from damaging panels or rolls that are about to be seamed.

Once the panels or sheets have been laid out, an FML often needs to be moved across the subgrade by field crews. Wooden dowel rods can be used to help move panels without stretching the edges which will be seamed. These dowel rods are placed on the edge of the panel; the panel is then rolled onto the dowel rod. This provides a handle so that the panels can be moved without stretching and tearing the FML.

To control the effects of wind on FML panels or rolls that have been laid out, sandbags can be placed every 5 to 10 ft along unseamed edges. Figure 9-15 shows sandbags being used to prevent wind damage to an FML. Old tires have also been used. However, discarded steel-belted radials may have exposed wires that could damage the FML.

The type of equipment needed for seaming the FML will depend on the method by which the FML is seamed. The majority of FMLs are seamed in the field with either solvent-based or thermal-based techniques. Techniques for seaming FMLs are discussed in Section 4.2.2.3.

PE FMLs are heat-welded and require specialized equipment, some of which are proprietary and are used with a particular manufacturer's FML. Such equipment includes extrusion welders that can be raised or lowered along the sidewalls of the unit and others that can be hand-held. Figure 9-16 shows

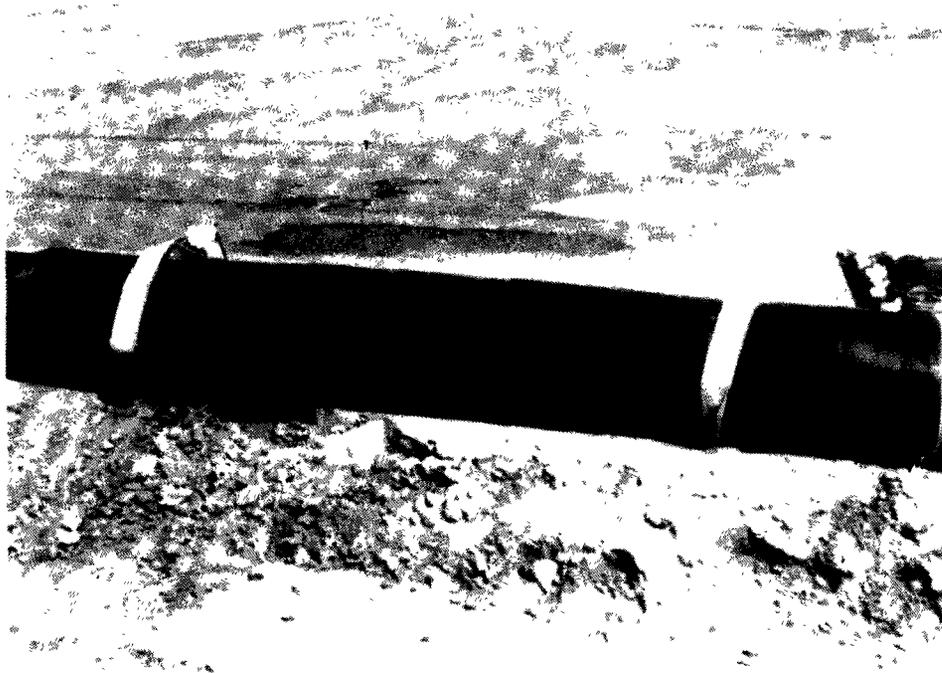
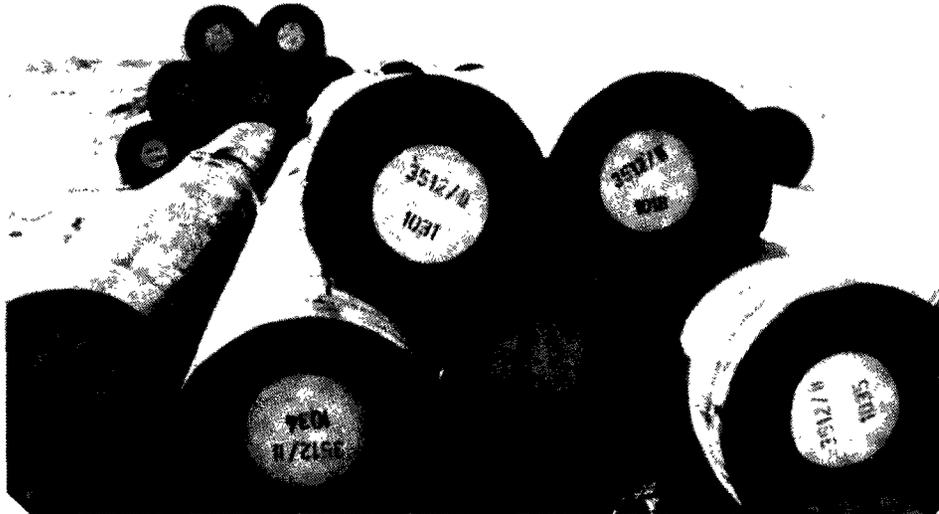


Figure 9-14. HDPE FMLs are shipped to the site rolled onto drums. Each roll may weigh up to five tons.

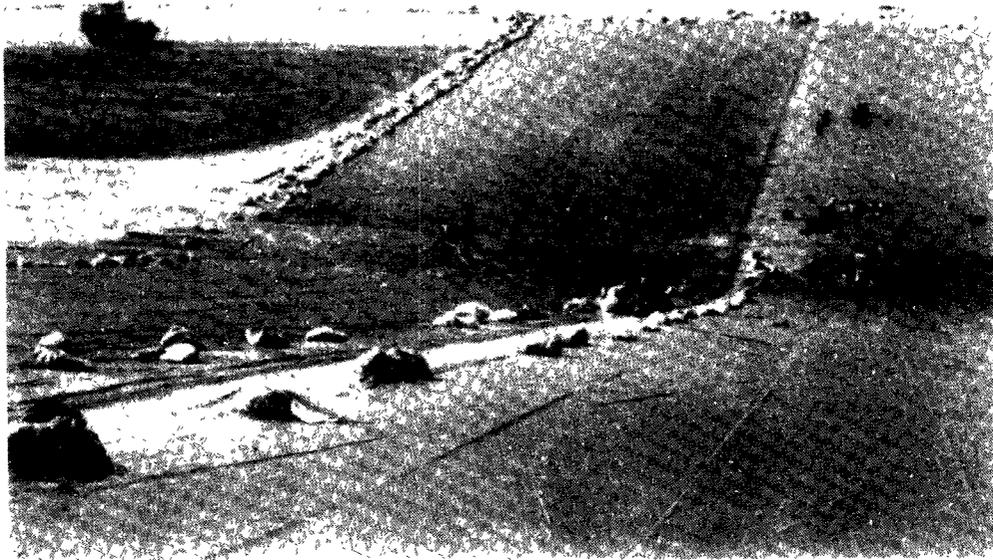


Figure 9-15. Use of sandbags to anchor unseamed sheets and unseamed edges of FMLs to prevent wind damage.



Figure 9-16. Hand-held extrusion welders for seaming HDPE FMLs. A fillet of molten HDPE is extruded over the edge of the overlap. (Top photo: courtesy of Gundle Lining Systems; bottom photo: courtesy of SLT North America, Inc.).

two hand-held extrusion welders, Figure 9-17 shows a partially-automated extrusion welder being lowered down a side slope by a winch, and Figure 9-18 presents a schematic of a hot-wedge welding device used in seaming PE FMLs.

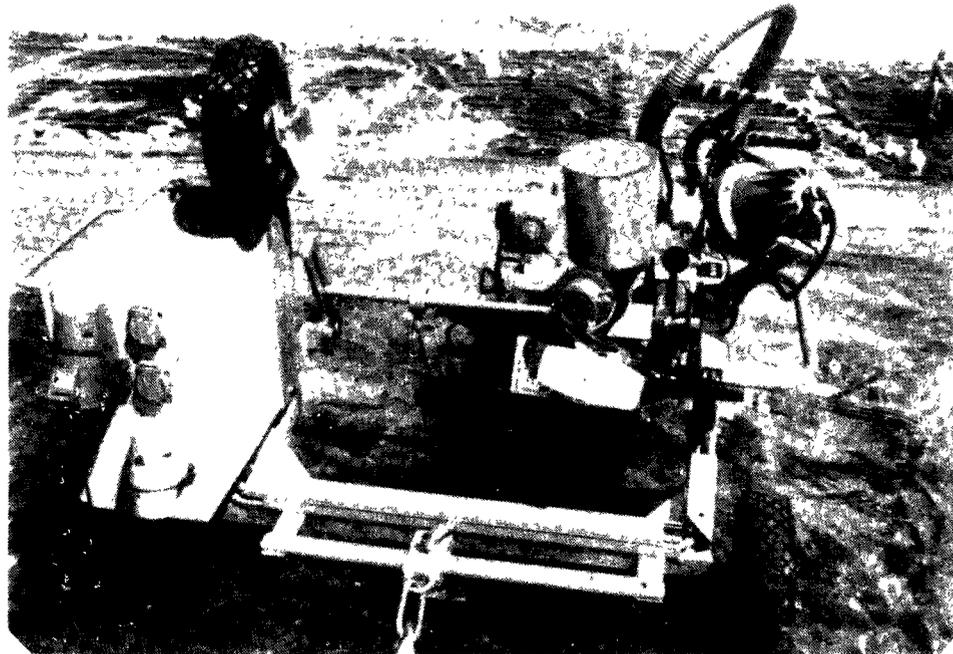


Figure 9-17. A partially-automated extrusion welder for seaming HDPE FMLs. Molten HDPE is extruded between the overlap of the two sheets being seamed. The welder is shown being lowered down a side slope by a winch.

FMLs seamed in the field with adhesives or by solvent-based techniques use hand rollers to ensure good contact between the surfaces being bonded. In addition, a board at least 1 in. thick, 12 in. wide, and up to 12 ft long should be available for each seaming crew to use. This board provides support during seaming and is placed under the overlap of the liner material. As seaming progresses, the board is slid along underneath the seam to provide a good seaming surface. These boards normally have ropes tied to the front so that they can be pulled along underneath the seam as the seaming crew moves from the middle of a panel to the ends. Figure 9-19 shows the rope attached to a seaming board placed underneath the seam.

Many FMLs require surface cleaning or treatment in the seaming area just prior to actual seaming. A sufficient supply of clean cotton rags needs to be available for wiping away moisture or dust and debris. Appropriate cleaning solvents may also be required. For seaming CSPE FMLs, means of scouring the FML surface, such as natural brushes or stainless steel scouring pads, may be needed to remove surface cure prior to seaming, particularly if the FML is installed too long after its manufacture.

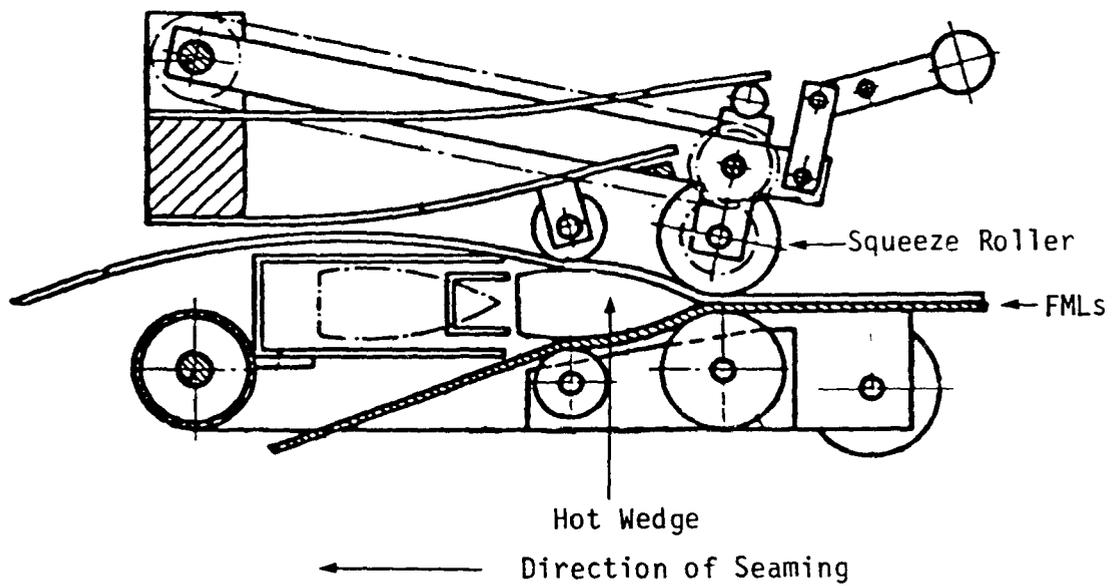


Figure 9-18. Schematic of hot-wedge welding device for seaming PE FMLs. [Based on U.S. Patent 4,146,419 (March 27, 1979)].



Figure 9-19. Field seaming operation using bodied-solvent adhesive. A board is being used for support under the area being seamed; the board is pulled along under the seam with the rope shown in the picture.

Heat guns should be available for solvent seaming operations. These guns can bring the FML to a suitable temperature if the ambient temperature is below 60°F. Figure 9-20 shows heat guns being used to warm an FML. If trichloroethylene is used in seaming, heat guns should be used with extreme caution, as toxic phosgene gas can be formed.

Additional equipment needed for installing FMLs can include caulking compounds and caulking guns, pails for washing solvents, paint brushes or other applicators, solvent resistant gloves, safety goggles for men working with solvents, knee pads, shoes with flat soles to prevent damage to the FML, scissors and a utility knife, hand-held earth tampers, hand rakes, shovels, and stakes and string to help in the spotting of the panels or rolls. Respirators are often needed, especially when solvent and solvent based adhesives are used and the work is performed in confined areas. If electrical equipment is being used during installation (e.g. heat guns and extrusion welding equipment), an electric generator and sufficient extension cords are necessary. A crayon should be available for marking the location of seams before solvents are applied and for use in identifying samples for QA/QC testing. Some methods of seaming HDPE require buffing of the edges to be seamed together. In this case, the proper buffing equipment is required.

A list of the equipment and materials often required for installing FMLs is presented in Table 9-2. Equipment used to test field seams is discussed in more detail in Section 9.3.6.

9.3.3 Manpower Requirements for Installing an FML

Installation of an FML requires a qualified contractor who has adequate experience with installing FMLs, particularly with the generic type of FML being installed. Some FML manufacturers have suggested that 1 million square feet of experience of adequately installed liner should be a requirement for being considered a qualified contractor. The installation contractor should plan and implement a quality control program which will help ensure that the FML meets material specifications and is installed in accordance with construction specifications. At the same time, the owner or his representative should plan and implement a quality assurance program. Inspection needs to be documented for review and record keeping.

The manpower requirements for installing FMLs are a function of the rate at which the installer wants to place panels and accomplish field seaming. Typically, installation contractors will have from five to ten people on site when placing one panel at a time. Generally, a crew foreman will direct the activities of the field crew. The foreman may not directly participate in the unrolling and spotting of panels or in field seaming; however, he must be experienced in installing the specific FML.

Crew size requirements also depend on the complexity of the installation and the experience of the field crew. If the majority of the crew members are recruited locally, they probably will require training during installation. At the present time, the trend is toward having installation contractors retain field supervisors who travel from job site to job site.



Figure 9-20. Heat guns being used to facilitate field seaming of FMLs.

TABLE 9-2. EQUIPMENT AND MATERIALS FOR INSTALLING FMLS

Item	Use
Fork lift or other lifting equipment	To move and aid in the placement of FML panels and rolls.
Sandbags	To anchor temporarily unseamed panels or rolls to prevent wind damage.
Proper adhesives	To make field seams and seal FML around concrete or steel penetrations.
Portable electric generator	To operate heat guns or lighting for working at night.
Seaming equipment	To seam the panels or sheets of FML.
Equipment for testing seams:	For QC testing of field seams.
- Air-lance	To test the continuity of field seams.
- Vacuum box	To test the continuity of field seams.
- Ultrasonic devices	To test the continuity of field seams.
- Spark tester	To test the continuity of field seams.
- Field tensometer	To test the strength of field seam samples.
Hand-held earth tampers	To smooth subgrade as necessary.
Miscellaneous materials:	For field seaming.
- Adhesive applicators (paint brushes, caulking guns, rollers, etc.).	
- FML preparation equipment: clean rags, scrub brushes, scouring pads, pails for solvent, hard surface rollers, seaming support board, heat guns, crayons for marking, dowels for pulling panels, stakes and chalk line, steel measuring tape, scissors and utility knives, electrical extension cords (for heat guns).	
Field crew equipment:	For field crew when making seams.
- Safety goggles, solvent resistant gloves, knee pads, respirators, soft-soled shoes.	
First aid kit	In case of accidents.
Air compressor	Supply air that might be needed when working with solvents, and for air-lance.

Large jobs where crews perform specific tasks may involve many people. This occurs where one crew unrolls panels, another crew spots the panels, and a third crew performs all field seaming. Crew sizes also depend on the number of structures or penetrations in the unit. For example, if three or four concrete pillars are located within the area of one panel or roll, this situation will require more manpower than if the FML is to be placed on a flat surface. In many instances, the owner of the unit may provide necessary manpower on an as-needed basis to the installation contractor. This arrangement will minimize the direct cost of installation to the owner, as excess work loads can be fulfilled with temporary labor.

9.3.4 Placement of an FML

An FML should be installed during dry, moderately warm weather. Installation during extremely cold, extremely hot, and/or wet weather can also be performed if it can be demonstrated that adverse weather conditions do not affect the integrity of the installed liner; a more rigid program for inspecting construction performed under adverse conditions should be formulated. Before the FML is moved from the storage site to the installation location, a number of tasks need to be performed, including:

- The anchor trench around the perimeter of the installation should be completed. The dirt excavated from the anchor trench should be raked smooth so that the FML can be unrolled along and parallel to the anchor trench in the width direction.
- The surface of soil subgrade should be inspected to make sure that it is firm, flat, and free of sharp rocks or debris. If inspection of the soil surface indicates the need for further fine finishing, this work should be performed as required.
- If standing water is present in the unit, it should be removed.
- Concrete structures that must be seamed around should be inspected to ensure that there are no sharp edges and that systems for anchoring the FML are prepared. If skirts are to be used around footings on concrete structures, these should be inspected to ensure that they are in place.
- All outflow or inflow structures or other appurtenances required by the designer should be inspected to ensure that they are in place.

Before placing the FML, the layout is consulted, and the rolls or folded panels are placed in the appropriate place indicated on the sheet layout, which will also indicate the direction in which the FML should be unrolled or unfolded. Instructions on boxes containing folded/rolled FML panels indicate the directions for unrolling and unfolding the FML so that it can be placed correctly (Figure 9-21). The FML is unrolled or unfolded lengthwise, as is shown in Figure 9-22. Depending on the FML type, it is then unfolded in the width direction, either down the side slope or across the floor (Figure 9-23). The field crew then begins to position or "spot" the FML into its proper location so that a sufficient overlap of adjacent panels or rolls is maintained for seaming (Figure 9-24). Generally, panels and rolls are placed

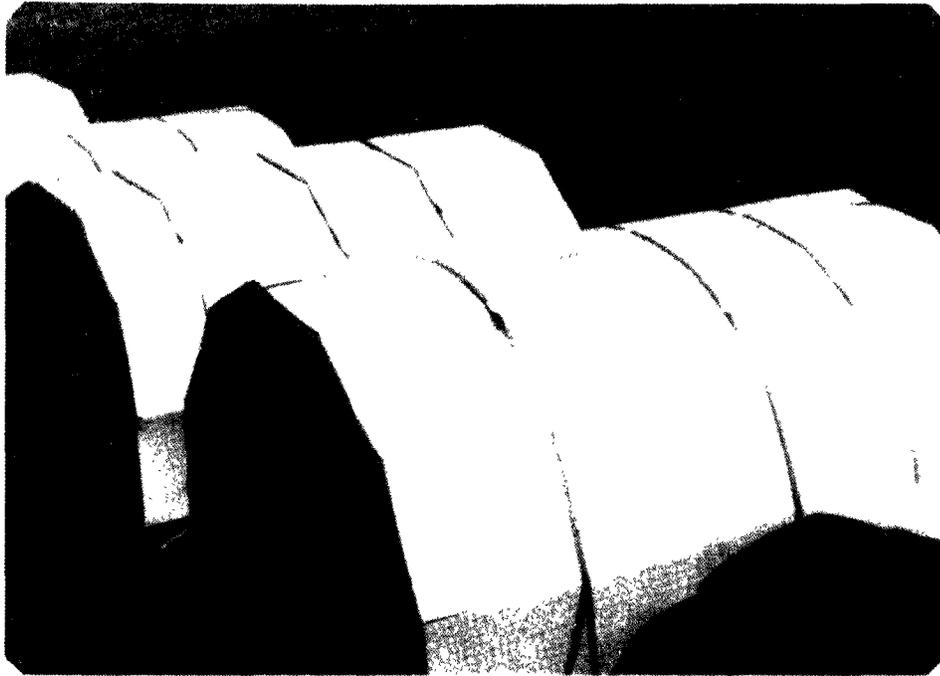


Figure 9-21. The instructions for unrolling FML panels are clearly shown on each container.



Figure 9-22. Panels of a fabric-reinforced FML being unfolded or unrolled.



Figure 9-23. Workmen "pulling" a panel fabricated from a fabric-reinforced FML across the subgrade. This step can be difficult to accomplish during windy conditions.

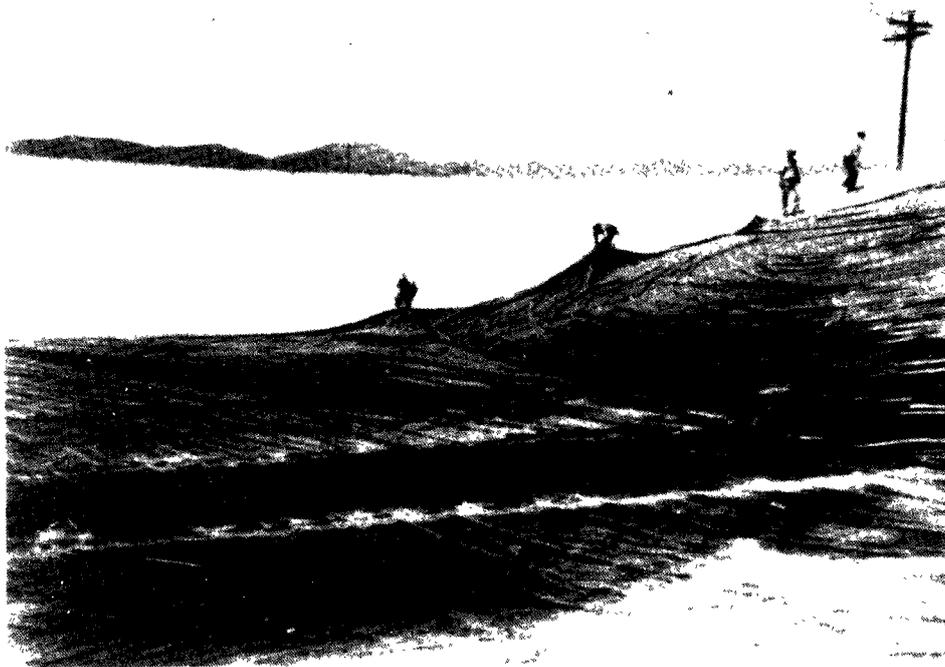


Figure 9-24. Spotting a panel fabricated from a fabric-reinforced FML. Once an FML panel has been unfolded, the crew "spots" or positions it in the proper location.

so that field seams will run perpendicular to the toe of the slopes; that is, the seams will run up and down rather than along the side slopes. This practice minimizes stress on field seams in the short run, while they are setting or curing and in the long run, while the FML is in service. As sheets or panels are spotted and seamed together, sand bags are placed on top of the FML, as is shown in Figure 9-15. The FML should be pulled relatively smooth over the subgrade (Figure 9-25). If the subgrade is smooth and compacted, then the FML should be relatively flat on the subgrade. However, sufficient slack must be left in the FML to accommodate possible shrinkage due to temperature changes which may result in tension in the FML.



Figure 9-25. Pulling an FML panel smooth. Each FML panel must be pulled smooth, leaving enough slack to accommodate anticipated changes in dimensions due to temperature changes.

It is important to make sure that no "bridging" occurs in the FML where angles are formed by the subgrade directly under an FML. Bridging is the condition that exists when the FML extends from one side of an angle to the other, leaving a void beneath the FML at the apex of the angle. Bridging occurs most often at penetrations and where steep sidewalls meet the bottom of the unit. Particular attention has to be directed to keeping the FML in contact with the subgrade at these locations and keeping it in a relaxed condition. It is also important to be sure that compaction of the subgrade in these areas meets design specifications to avoid localized stressing of the FML or the seams.

Depending on the location and the weather conditions, the number of panels or rolls placed in one day should not exceed the number which can be seamed in one day. This assures that, should bad weather conditions occur

overnight, the FML will not be left unseamed and subject to damage, especially from wind.

9.3.5 Field Seaming of FMLs

The success or failure of an FML installation depends to a great extent on both short-term and long-term integrity of all seams. Field seaming, which is performed under conditions that cannot be completely controlled, is a critical factor in FML installation. FML manufacturers recommend procedures and seaming systems for achieving successful field seams. If the manufacturer does not have a recommended seaming system, then the use of that FML should be questioned. During installation, the contractor should follow the manufacturer's recommended procedures for seaming and anchoring the FML to structures, etc., except in cases where it has been demonstrated that the procedure, technique, or equipment proposed by the installer results in seams of equal or higher quality.

FMLs are usually seamed in the field using either solvent-based or thermal-based techniques; the specific technique used during installation will depend on the FML type. Crosslinked FMLs, such as EPDM and neoprene FMLs, are usually sealed using gum tape and a two-part adhesive system. The reason for the general tendency in recent years to avoid using crosslinked FMLs is that there are many difficulties associated with forming a good bond between sheets of crosslinked FMLs. Uncured or unvulcanized FMLs, such as CSPE, CPE, and PVC FMLs, are usually sealed with solvents, bodied-solvent adhesives, or heat. Polyethylenes are sealed by various thermal methods, e.g. hot-air, hot-wedge, ultrasonic, or by one of several fusion extrusion methods. Using methods of joining FMLs that ensure molecular movement across the interface of the sheets and using FMLs containing no processing aid lubricants, such as those used to aid in extrusion, or other additives that may have exuded or "bloomed" to the surface of the sheets being joined help ensure good seam strength and durability. Methods of seaming FMLs are discussed in Section 4.2.2.3.

The long-term integrity of the field seam is determined by many factors. The most important factor is that the bonding system used must join the two FML surfaces on a molecular level under actual field conditions. It should be noted that differences between seaming equipment exist and that some equipment may be more appropriate for use under a wider range of conditions. The four basic conditions required for producing durable seams by thermal methods are cleanliness of the bonding surfaces, sufficient heat, sufficient pressure, and "dwell" time. In the case of an adhesive system, the basic requirements are the same except that the adhesive takes the place of the heat. Sufficient pressure and dwell time are necessary to create permanent bonding of the seam interface.

At present, most seaming techniques are manually controlled, i.e. they are not automated. Therefore, the success of a seaming operation for a given FML can be influenced by many job site factors including:

- The ambient temperature at which the seams are produced.

- The relative humidity.
- The amount of wind.
- The effect that clouds have on the liner temperature.
- The moisture content of the subgrade underneath the FML.
- The supporting surface on which the seam is bonded.
- The skill of the seaming crew.
- The quality and consistency of the adhesive, if an adhesive is used.
- Proper preparation of the FML surfaces to be joined.
- Sufficient overlap of adjacent panels or rolls to be seamed.
- The cleanliness of the seam interface, i.e. the amount of airborne dust and debris present.
- The ease in handling the seaming equipment.

Field seaming of FMLs during adverse weather conditions requires special considerations regarding the potential effect of these conditions on the particular bonding system. The adhesive system or specialized equipment used or recommended by the manufacturer or installer to seam the FML being installed can be affected by adverse weather. Cold weather seaming requires the field crew to exercise caution when making seams to make sure that the FML reaches a minimum temperature. Most solvent-based systems work best at ambient temperatures greater than 50°F. Temperature and wind velocity affect the rate at which solvents evaporate and thus the ability of the solvent-based adhesive to develop a sound bond between the sheets. Usually mixtures of solvents are used, the proportions of which can be varied in order to control evaporation rates at different temperatures. When the ambient temperature is below 50°F, the relative humidity is high, and a solvent-based system is being used, moisture condensation can take place due to the cooling effect of evaporation. Under such circumstances heat guns can be used to raise the temperature of the FML. However, extreme caution must be exercised when using heat guns around flammable solvents and chlorinated solvents which may generate the toxic gas, phosgene. For the same reasons, smoking should not be allowed on the job. Solvent seaming at high ambient temperatures can pose problems due to the volatility of the solvent which may not sufficiently dissolve the surfaces to be seamed before it evaporates. High ambient temperatures can also limit the ability of crews to work. Thermal and fusion systems for seaming HDPE FMLs have reportedly been used at temperatures as low as 25°F. External heat may need to be used to raise the FML temperature as required. Field seaming during precipitation should be avoided. A more rigid QA/QC program for inspecting seaming performed under adverse weather conditions needs to be formulated and implemented.

The method of applying pressure to the seam will vary with the type of seaming operation. Some thermal-based equipment for seaming FMLs have squeeze-rollers for pressing the two sheets together immediately after heating (Figure 9-18). FMLs seamed using solvent-based techniques need to be pressed together using hand rollers. Because these FML are usually fairly pliable, the seam needs to rest on a dry, hard, flat surface for rolling. Many installers use a board placed underneath the seaming area, as is described in Section 9.3.2. The boards are pulled along underneath the seam as the seaming operation progresses.

Seam overlap requirements vary with FML manufacturer, FML type, and seaming procedure. Recommended overlaps vary from 4 to 12 inches. Figure 9-26 illustrates typical factory and field seams for fabric-reinforced thermoplastic FMLs. Figure 4-12 schematically presents various configurations of FML seams. Overlap requirements for fabric-reinforced FMLs are often stated as a minimum bonded overlap of the reinforcing fabric. Figure 9-27 shows the overlap between panels being inspected.

The surfaces to be bonded need to be properly prepared, i.e. clean and dry, when the field seams are made. The presence of any moisture can interfere with bonding of the FML surfaces. The presence of any dirt or foreign material can jeopardize the seam integrity and provide a path for fluid to migrate through the seam. In the case of FMLs being seamed with an adhesive or a solvent, once the board is placed underneath the FML and the overlap is sufficient, then the top FML is peeled back and the surface prepared for the adhesive or solvent (Figure 9-28). In some installations, a solvent that will not inhibit bonding between the two surfaces can be used to clean the FML. In the case of some FMLs, e.g. aged CSPE, a cured or oxidized surface layer needs to be removed by careful buffing followed by a solvent wash prior to seaming. Field crews should wear suitable gloves to prevent skin irritation from the solvents (Figure 9-29). Respirators and eye protection may also be required. Once the surface has been cleaned with solvent, the adhesive is applied to the FML. Care needs to be taken to apply the adhesive uniformly. Figure 9-30 shows the application of adhesive with a squeeze bottle and with a paint brush. Generally, with a bodied solvent adhesive, the two surfaces should be placed together immediately (i.e. before the adhesive begins to "skin") and rolled with a steel or plastic roller (Figure 9-31). Initial rolling is performed perpendicular to the edge of the panel to ensure spreading of the adhesive across the width of the seam.

Some methods of seaming HDPE FMLs require buffing of the surfaces to be seamed together in order to present a fresh surface for bonding by removing a layer of oxidized material and compound additives that may have exuded to the surface of the sheeting. Surfaces can be buffed either parallel or perpendicular to the seam edge, as is shown in Figure 9-32. Some concern has been expressed over the possibility that parallel buffing may have a higher potential for initiating stress cracking in the field and causing loss of tensile strength. Therefore, even though buffing parallel to the seam is easier and quicker for the installer, perpendicular buffing is considered technically better. Care needs to be taken in all buffing operations to buff only those areas required for seaming and to prevent the grinder from digging too deep.

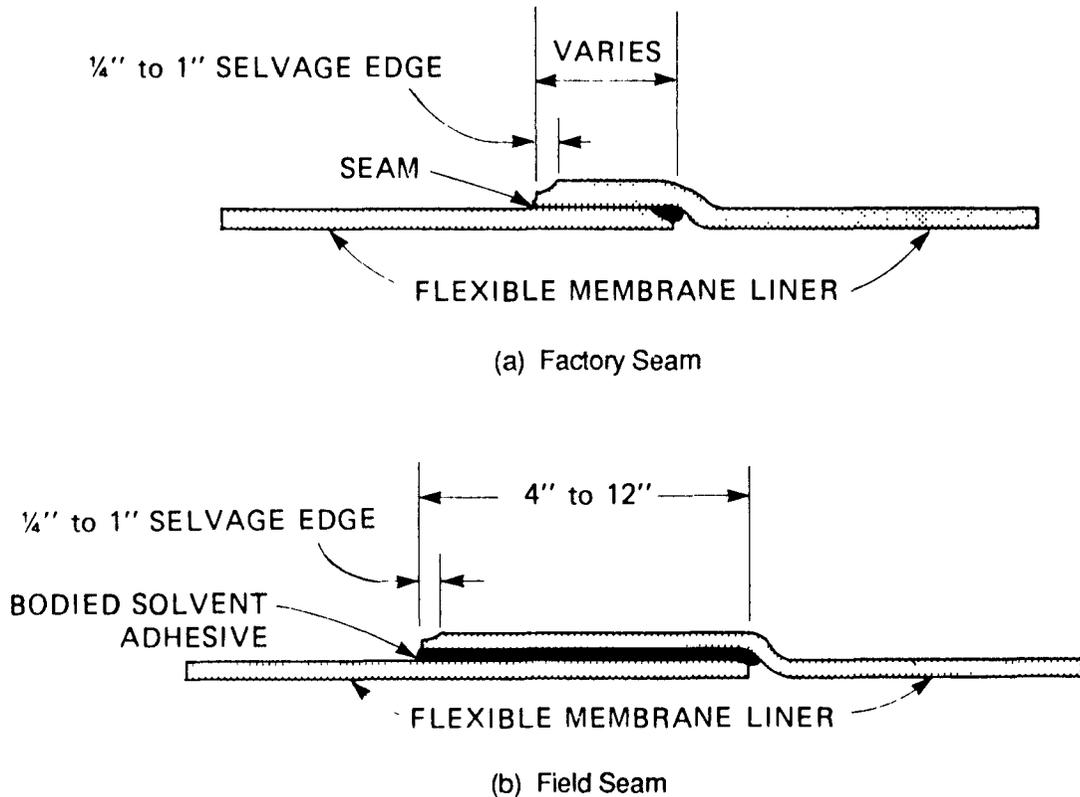


Figure 9-26. Typical lap seams for fabric-reinforced thermoplastic FMLs (Source: Small, 1980).

The crew should be careful not to allow any wrinkles to occur in the seam (Figure 9-33). Sheets should lie flat during seaming, with their surfaces contacting each other. Wrinkles can result in "fish mouths" which must be cut out and repaired. The sheets being joined need to be allowed to equilibrate to the same temperature and to flatten after being placed. Some sheets or panels may need some pulling to smooth them out; however, pulling the sheets smooth should not introduce stresses into the sheeting. Some installers of PE FMLs have found that seaming during cool weather or during cool parts of the day can greatly reduce the number and magnitude of problems (e.g. wrinkles or uneven shrinkage) caused by thermal expansion and contraction. Field seaming using solvent-based techniques normally begins at the center of a panel and continues to each end to minimize formation of large wrinkles which can occur if seaming begins at one end or the other.

If an electric generator is required during installation (e.g. for heat guns, seaming equipment, etc.), care needs to be taken to ensure that hot parts do not contact the FML and that gasoline does not spill onto the FML during refueling.



Figure 9-27. Inspecting overlap between panels of a fabric-reinforced FML. Sufficient seam overlap must be maintained. Manufacturers usually specify minimum overlap for field seams.



Figure 9-28. Cleaning the surface of a fabric-reinforced FML prior to seaming. The surfaces to be seamed must be cleaned to remove dirt. A solvent that will not inhibit bonding can be used to clean the FML surface.



Figure 9-29. Seaming crews working with solvents are advised to wear gloves for protection.

9.3.6 Field Testing of Seams

The quality of the seams made during installation is critical to the success of an FML-lined waste containment unit. Considering the great length of seams that may be made during the field installation of an FML liner for a single unit, and considering the variable and uncontrolled conditions that can exist during the seaming operations, it is essential to monitor the quality of the seams. The seams should be inspected and tested to determine whether they are continuous, i.e. whether there are gaps in the seams. One-hundred percent nondestructive testing of the seams is necessary as part of the quality control that must be performed by the installer. The seams should be first visually inspected and afterwards tested by one or more nondestructive techniques that are more objective. Table 9-3 lists and describes a series of nondestructive-type tests that might be performed on the seams. This table also indicates some of the limitations of the respective methods. The tests include the vacuum-box method, air-pressure method, ultrasonic tests, spark tests, air-lance tests, and a probe technique. Equipment for two of these methods used to assess the continuity of HDPE FML seams are shown in Figure 9-34. The ultrasonic shadow method is discussed further by Koerner et al (1987). However, none of the nondestructive test methods measure the strength of any given seam, nor the long-term chemical durability of that seam. At best, these test methods can only determine continuity of a seam.



Figure 9-30. Field seaming of a fabric-reinforced thermoplastic FML using a solvent-based technique. The bodied-solvent adhesive is applied using either a squeeze bottle or a paint brush.



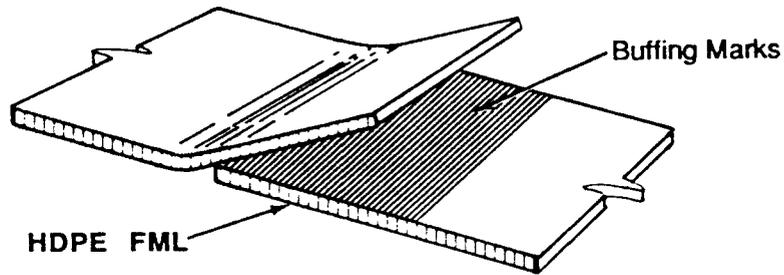
Figure 9-31. Rolling the seam of a fabric-reinforced thermoplastic FML. After the proper adhesive has been applied, the seam is rolled smooth.

Destructive tests, in which samples of the seams are cut and tested in shear and in peel, measure the strength of specimens of the seams. This testing, described in Chapter 4, is performed by both the installing contractor and the construction quality assurance organization. The validity of this testing depends to a large extent upon the sampling strategy and procedure that is followed. Destructive testing and its use in quality control and quality assurance of seams is discussed in Chapters 4 and 10, respectively.

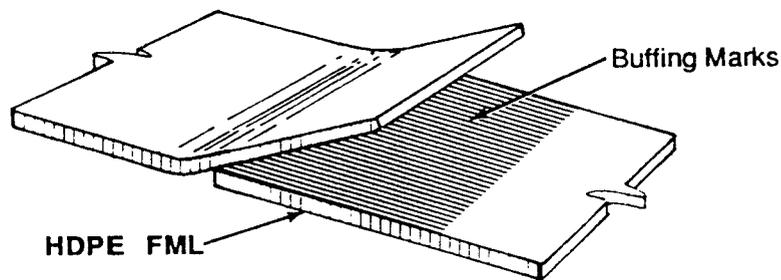
9.3.7 Placement of a Protective Soil Cover on an FML

If a protective soil cover has been specified in the design to protect an FML from weather conditions, equipment, and vandalism, it is placed as soon as scheduling permits. Generally, the FML is not covered until FML

installation is complete and has been accepted. However, on large projects, portions of the liner may be installed, accepted, and covered before the entire liner is installed.



(a) BUFFING PARALLEL TO THE SEAM EDGE



(b) BUFFING PERPENDICULAR TO THE SEAM EDGE

Figure 9-32. Parallel and perpendicular buffing of an HDPE FML. These marks should extend as little as possible outside the seam area.

During construction of the soil cover, particular care is taken to prevent damage to the FML. The cover soil should never be pushed down the slopes since the gravitational stresses may cause the FML to come out of the anchor trench or cause the liner to tear. Instead, once a ramp is built, placement of the cover usually proceeds from one end of the project to the other with soil being pushed up the slopes. Some FML manufacturers recommend that no bulldozer larger than a D-3 with wide tracks should be allowed for working around lining projects. Care needs to be taken to prevent operator error from damaging the FML (or underlying drainage layers). Operator errors can include allowing a dozer blade or the bucket of a front-end loader to go too low or allowing dozer tracks to spin. In addition, as placement of a soil cover progresses, care needs to be taken to prevent wrinkles from developing at the leading edge of the soil. Wrinkles can be trapped by depositing soil on the opposite side of the wrinkle using the bucket of a



Figure 9-33. Repairing a wrinkle in the seam of a fabric-reinforced thermoplastic FML. Wrinkles are also known as "fish mouths". The wrinkle is first preheated with a heat gun (top); after applying adhesive, the wrinkle is folded; the wrinkle has been rolled smooth and washed with a solvent; a patch is applied as a final step (bottom). Thicker sheeting, e.g. 45-mil, and stiffer sheeting, e.g. HDPE, may require slitting and use of a cover strip.

TABLE 9-3. NONDESTRUCTIVE TESTS USED TO EVALUATE SEAM CONTINUITY

Test	Description	Applicability	Comments
Vacuum box	A soapy solution is applied to the FML. A box with a transparent window is sealed against the FML and vacuum is established in the box. Soap bubbles will form if there is a leak.	Mostly for stiff FMLs.	Most commonly used test with stiff FMLs, such as HDPE, whose thickness exceeds 0.75 mm (30 mil). Cannot be used in corners or around small radii without special apparatus. Relatively slow process since testing area is limited by size of vacuum box.
Air pressure	A double seam with intermediate open channel is made. Pressurized air is blown into the channel. Leakage is detected if the air pressure cannot be kept constant.	Any type of FML if seamed with double seam with intermediate channel Underseam may fail, in which case seam may require capping.	Used only with double seams with intermediate open channel, i.e. seams made with double-hot-wedge or double-hot-air. More severe loading than vacuum test, but tests only a small fraction of seam strength. Causes some damage to FML because "leaking hole" must be cut. Quite efficient method since long sections of seam (up to 100 m) may be tested at one time. When defects are found, a vacuum box is often used to locate the defect.
Ultrasonic	Several types of ultrasonic techniques are used to assess the continuity of a seam: (1), the measured thickness of the seam can be compared to the thickness it should have; and/or (2), voids in the seam can be detected directly.	FMLs which may be fused.	Reliable test when conducted by very experienced operator over small areas. Difficult to interpret readout over long periods of time due to operator fatigue.
Spark testing	A conducting wire is placed in seam during seaming. A spark can be established between the wire and an electric device if the wire is exposed, i.e. if a portion of seam is missing.	All FMLs, but requires conducting wire inserted in seams.	Difficult to set up accurately over large areas. Applicable in areas where vacuum cannot be used (corners, etc.). Results not always reliable.
Air-lance	A pipe with a nozzle is used to blow pressurized air at the edge of a seam. If there is a lack of continuity in the seam air flows under the FML and inflates it or causes it to vibrate, often audibly.	Mostly for pliable FMLs.	Qualitative test only. Results not very reproducible.
Probe	A stiff probe, such as a blunt screwdriver, is used to verify mechanically if the seam is continuous.	All FMLs and all seams with well-defined edge.	Qualitative test only. Results not very reproducible.

Source: Based on Giroud and Fluet, 1986, pp 272-273.



Figure 9-34. Testing the continuity of HDPE FML seams. The upper photograph (courtesy of Gundle Lining Systems) shows the use of a "vacuum box" and the lower photograph (courtesy of Schlegel Lining Technology) shows the use of an ultrasonic technique.

wheel loader (Yamamoto, 1987). Once trapped, soil can be placed on top of the wrinkle. This method of trapping the soil prevents the wrinkle from folding over on itself. As the placement proceeds up the slopes, the leading edge can be wrapped with geotextile at the end of each day to minimize the effects of wind and rain.

9.4 CONSTRUCTION OF LEACHATE COLLECTION AND REMOVAL SYSTEMS (LCRSs)

In a waste containment unit there can be one or more LCRS. In a hazardous waste landfill there can be two systems: a primary LCRS above the top liner, which drains the leachate that may be generated within the waste being contained, and a secondary LCRS between the top and bottom liners which collects the leachate that might flow through a breach in the top liner. The latter system functions as a leak-detection system. In a hazardous waste surface impoundment there is only the secondary leachate collection and removal system or leak detection system to detect and collect liquid that may flow through a breach in the top liner. The number of LCRSs in nonhazardous units will depend on the type of unit, the design requirements, and regulatory requirements.

An LCRS typically is comprised of a number of subcomponents including:

- A drainage layer consisting of either granular or synthetic drainage media.
- A filter system to prevent clogging of the drainage layer and/or the pipe collection network.
- A strategically-placed network of perforated pipe for transporting leachate or a waste liquid from the drainage layer to the sump/manhole system.
- A bedding layer for the pipe network.
- A sump/manhole system which allows collection of the leachate or waste liquid and access to the pipe network for inspection and possible repairs through the operational and post-closure care periods.
- Mechanical and electrical equipment for conveying the liquid collected in the sump/manhole system to a separate storage or treatment area and (in the case of landfills and waste piles) for monitoring and controlling the level of leachate above the top liner.

Steps in installing an LCRS can include:

- Foundation preparation.
- Bedding layer placement.
- Pipe network installation.

- Drainage layer placement.
- Filter layer placement.
- Installation of sumps and associated structures.
- Installation of mechanical and electrical equipment.

Depending on the design, trenches may have to be constructed in which the pipe are placed. Details on the design of LCRSs are described in Section 7.5.

9.4.1 Construction of a Secondary LCRS

The secondary LCRS for a hazardous waste containment unit is constructed on top of a bottom liner. If the design calls for embedded pipe, the trenches in which the pipe are to be placed must be dug in the soil component of the composite bottom liner before the FML component of the composite liner can be installed. In digging the trenches, measures are taken to monitor the thickness of an underlying soil liner so that the required thickness is maintained. The edges of the trenches are rounded to prevent damage to the FML. The bottom liner is placed carefully so that there is sufficient material to line the trench. At the same time, care is taken not to damage the low-permeability soil liner and allow loose material to fall into the bottom of the trench. The pipe is then placed in these lined trenches and the necessary drainage material placed around the pipe. Geotextile can be used as a bedding material to prevent a granular drainage material from damaging the FML liner in the trenches. A procedure for lining an LCRS trench with a geotextile is presented in Figure 9-35.

If synthetic materials are specified in the design either for drainage or as bedding, the materials will need to be placed in accordance with a placement plan similar in form to an FML sheet layout. Before installing synthetic drainage media, the underlying FML needs to be swept clear of dirt and debris. The materials are placed to allow for sufficient overlap for seaming and so that the material is free from wrinkles and folds. Seaming is performed in accordance with the specified procedure. Geotextiles are usually seamed using portable sewing equipment; geonets can be "tacked" or "stitched" together using various mechanical means, e.g. plastic ties every 6 ft on center. An FML or geotextile should be placed on top of a geonet as soon as possible after it has been installed to prevent wind-blown dirt and debris from being deposited in the system.

If granular material is used in the drainage system, considerable care must be exercised with the equipment used in placing and compacting the granular material on top of the liner. Loose granules are removed from the surface of the liner in order to avoid possible puncture by traffic or personnel. Compaction of noncohesive soil materials is discussed in Section 9.2.2.

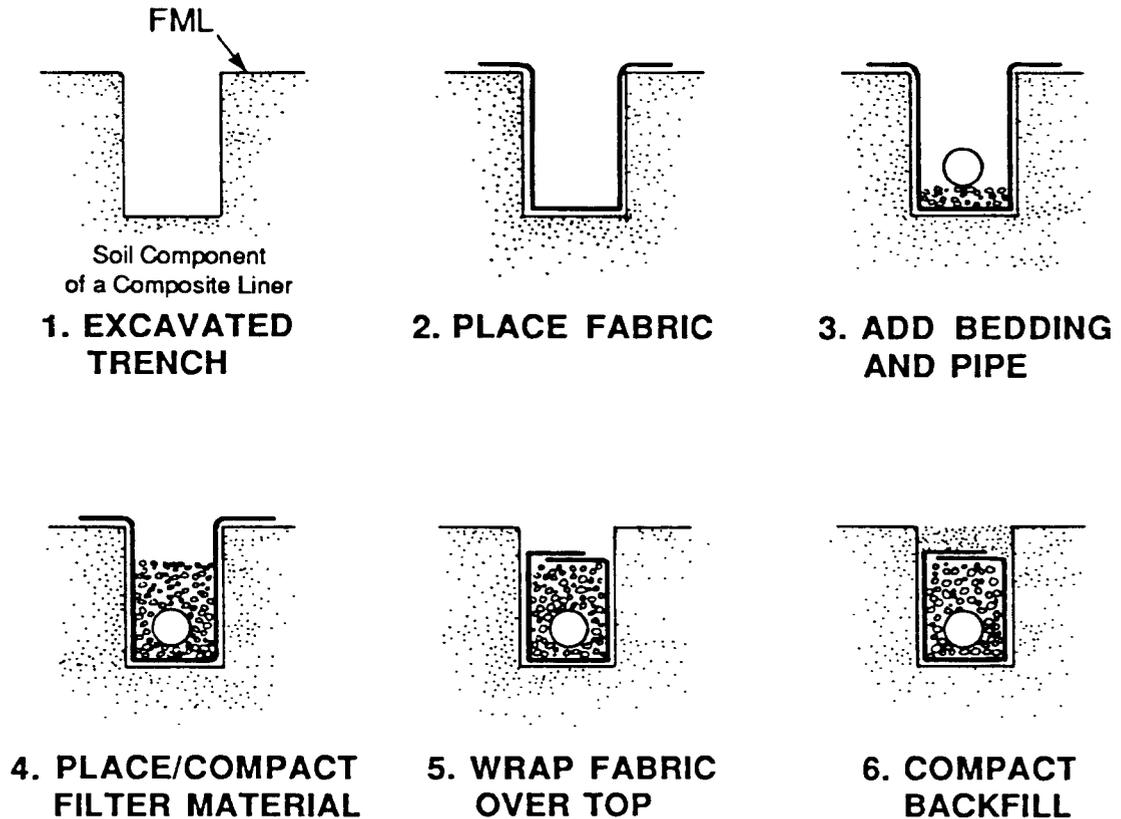


Figure 9-35. Schematic of sequential procedure for wrapping an LCRS trench with a geotextile. Actual trench design will probably have slopes less steep, and top edge of trench will be rounded.

If a composite liner is to be placed above the secondary LCRS, care must be exercised in placing the soil component of the liner. It is recommended that the first few lifts of soil not be compacted. Also, the succeeding layers should be lightly compacted until a sufficient bed has been formed that will allow full compaction. Specifications may require the top layer contacting the top FML to have a maximum hydraulic conductivity of $1 \times 10^{-7} \text{ cm s}^{-1}$.

9.4.2 Construction of a Primary LCRS

The primary LCRS is constructed above the top liner. Granular systems with perforated pipes can be built with the pipe network being placed on the liner, i.e. without the use of trenches. As in constructing the secondary LCRS, particular care must be taken while placing and compacting a granular drainage material above the pipes in order to avoid puncturing the FML and causing the pipe to collapse. It is recommended that the piping system be flushed out after installation to ensure that the pipes are clear.

9.5 ANCHORING/SEALING OF AN FML AROUND STRUCTURES/PENETRATIONS

Proper anchoring of the FML around the unit perimeter as well as conscientious tailoring and sealing the FML around penetrating structures are essential to satisfactory FML performance. Generally, in cut-and-fill type impoundments, the FML is anchored at the top of the embankment or berm using one of three ways:

- A trench and backfill method.
- A friction method.
- Anchoring to a concrete structure.

These different methods are presented schematically in Figure 7-30.

The trench and backfill method is the one recommended most often by FML manufacturers, probably due to its simplicity and economy. Excavation of the anchor trench in preparation for laying the liner is usually accomplished with a trenching machine such as a ditch witch or by using the blade of a bulldozer tilted at an angle. Using a trenching machine is generally considered more desirable because of the resulting trench geometry. Dirt from the excavation needs to be spread away from the slope and smoothed to facilitate unrolling and spotting of the FML.

While opening and spotting the FML, provisions are made for temporarily securing the edges of the rolls or panels in the anchor trench while the FML is seamed. After the seaming crew has completed the seams for a particular roll or panel, the trench is backfilled with earth that was excavated from the trench. The trench should not be backfilled until after the rolls or panels have been seamed so that they can be aligned and stretched, if necessary, for wrinkle-free seaming. In addition, it is generally recommended that FML seams be extended to the edge of the liner, including the bottom of the anchor trench. If the trench (and the edge of the liner) is to be capped with concrete curbing, it is desirable to position reinforcing rods vertically in the trench prior to backfilling. These reinforcing rods hold the FML in place during seaming.

The perimeter of the liner can be anchored to concrete structures along the berm or dike using anchor bolts embedded in the concrete and batten strips composed of a material resistant to attack by the chemical(s) to be stored in the unit. Concrete structures that come into contact with the FML should have rounded edges and be smooth and free of all curing compounds to minimize abrasion and chemical interaction with the FML. Anchor bolts should be positioned not more than 12-in. apart on centers. Concrete adhesive can be applied in a strip (minimum width 3 to 6 in., depending on the FML type) between the liner and the concrete where the batten strips will compress the liner to the concrete. A strip of FML (chafer strip) may be sandwiched between the FML liner and the concrete whenever the liner contacts an angle in the concrete structure to prevent abrasion. The batten strips are positioned over the liner and secured with washers and nuts to the anchor bolts.

Mastic should be used to effect a seal around the edge of the liner. Several alternative methods for anchoring to concrete structures are discussed by Kays (1986).

Depending on the design and purpose of the unit, one or more types of structures may penetrate the lining system. These penetrations can include inlet, outlet, overflow, or mud drain pipes; gas vents; level-indicating devices; emergency spill systems; pipe supports; or aeration systems. Penetrations can occur in the bottom or through one of the sidewalls, depending on their function and the design of the unit. Because tailoring and sealing the FML around structures can be difficult and offers a possibility for failure of the liner, several manufacturers have recommended that over-the-top pipe placement be used whenever possible.

Most manufacturers offer standardized procedures for installing (a) seals made in the plane of the lining system, and (b) boots to be used around penetrations. Construction around these penetrations needs to be performed carefully to avoid damage to the lining system after long-term service due to differential settlement, etc. If inlet or outlet pipes are introduced into the unit through a concrete structure, the seal can be made in the plane of the lining system. Pipe boots or shrouds are fitted over penetrating pipes and are seamed to the liner. These designs are discussed further in Section 7.5.7.2.

9.6 CONSTRUCTION OF THE FINAL COVER

At the end of its operational period, a landfill unit is closed by the placement of a final cover on top of the unit. The purpose of the final cover is to minimize the entrance of water into the unit and thereby minimize the generation of leachate. The construction of the final cover should meet the design requirements and criteria discussed in Chapter 7. As in the case of the liner system below the waste, the final cover is a multilayered system involving several different types of materials or components. As required by EPA guidance, the cover system should allow a transmission of liquids less than or equal to transmission through the liner system below the waste. Figure 9-36 presents a profile of a final cover system showing the subcomponents that might be required by a design. Actual covers are sloped to allow for drainage in the drainage layer and drainage of surface runoff. It should be noted that an FML may not be required in designs for closing nonhazardous waste landfills.

The construction of a final cover resembles the construction of the liner system and basically requires the same type of equipment. A significant difference between the construction of the cover system and that of the liner system is that the cover system is constructed on a foundation, i.e. the waste and the operational cover, that may not have the bearing strength of the native soil on which the bottom liner is constructed. Furthermore, the foundation for a final cover is more likely to settle unevenly.

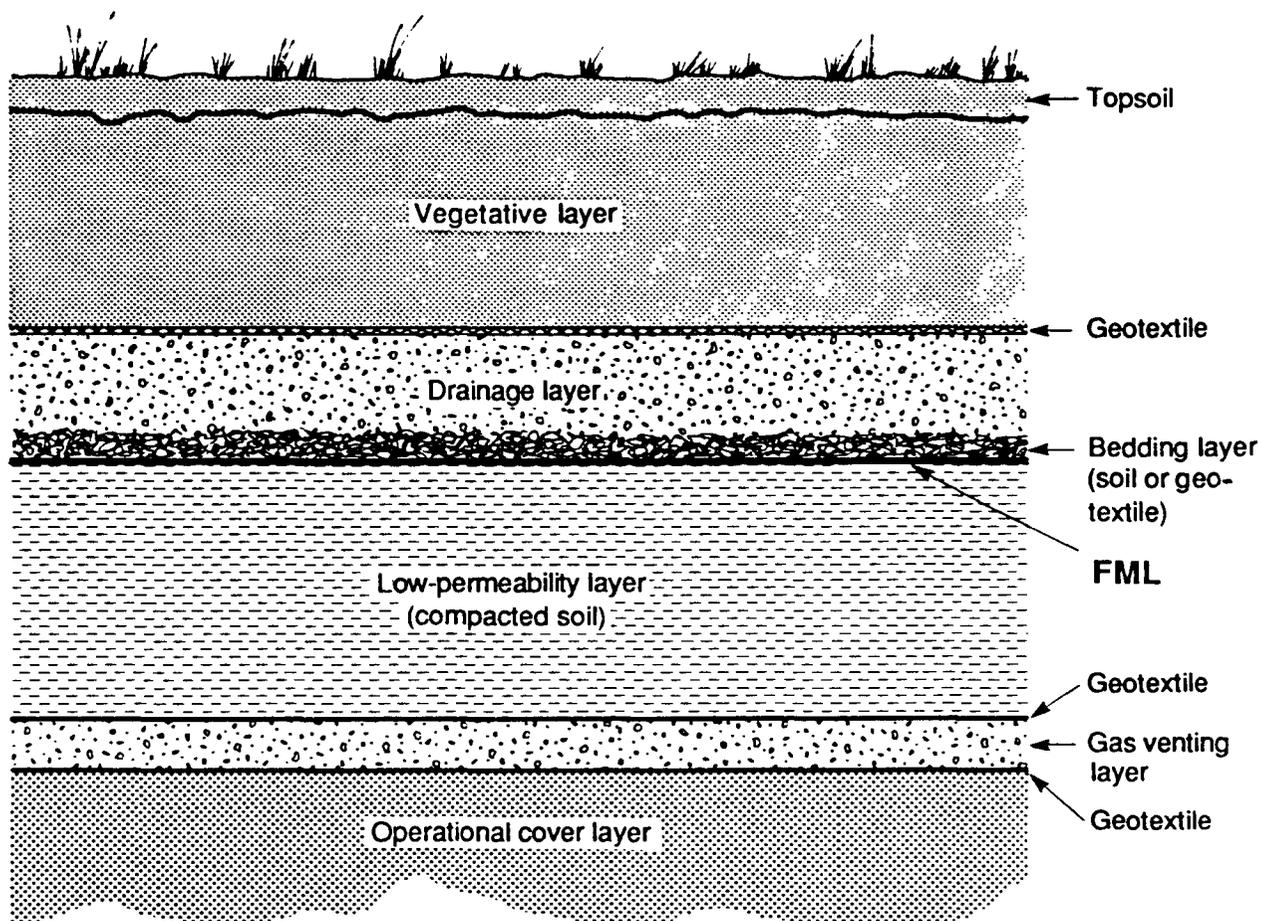


Figure 9-36. Schematic of a cover system showing the various layers that may require placement.

The equipment used in constructing final covers tends to be smaller than that used in larger projects such as dams and highways. Smooth rollers and tire rollers appear to be preferable to sheepsfoot rollers in constructing layered covers because they tend to cause less disturbance to underlying layers.

Because of the number of factors that contribute to the successful construction of the soil component of a final cover system, particularly the type of foundation on which the cover system is to be constructed (i.e. the landfill itself), construction of a test using the same materials, construction equipment, and design requirements that would be used in the full-scale cover construction may be required. The test section can be tested to determine whether the performance requirements for hydraulic conductivity and strength can be achieved given the materials, equipment, and construction procedures proposed in the design. Of particular interest is the vulnerability of the constructed section, e.g. to vehicular traffic.

Most final cover systems are constructed in layered increments, i.e. in layers at the time the unit is closed. However, cover systems can also be constructed in areal increments, as is presented schematically in Figure 9-37.

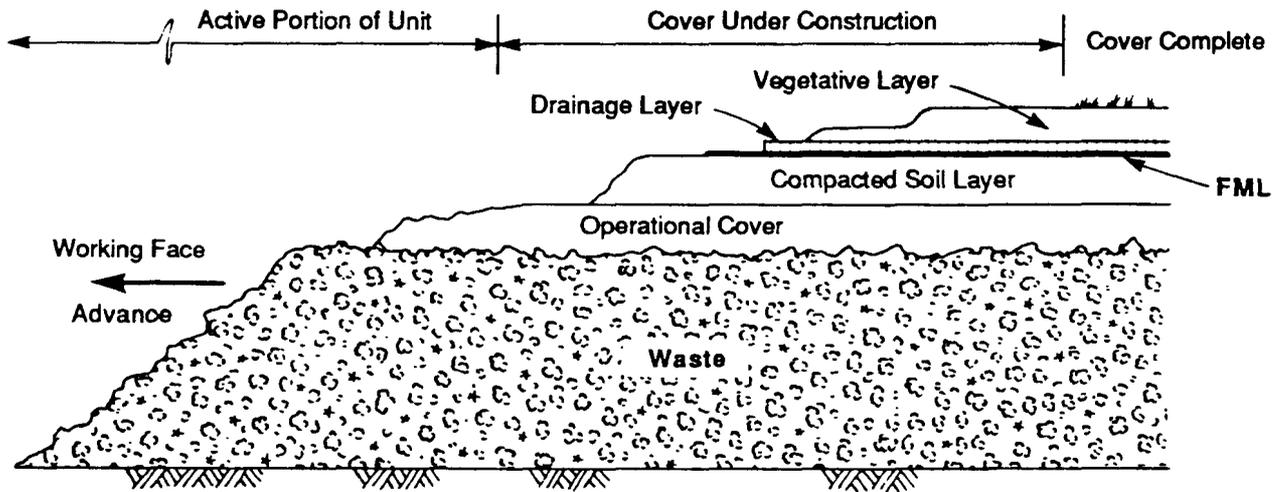


Figure 9-37. Construction of a final cover system in areal increments. (Based on Lutton, 1986, p 89).

In the layered-increment procedure, each layer is placed individually and completed before the next layer is added. The operational soil layer becomes the foundation for the cover system and probably requires further compaction before construction of the cover begins. The first layer may be a gas venting layer which may require geotextiles above and below. The low-permeability soil layer would be constructed in a manner similar to how the lower component of a composite liner was constructed, i.e. compacted to be less than or equal to a specified hydraulic conductivity value, which, in the case of a cover for a hazardous waste landfill, is $1 \times 10^{-7} \text{ cm s}^{-1}$. In order to avoid damaging the venting layer, the initial lift should not be compacted. Inasmuch as an FML in some designs would be placed on the low-permeability soil layer, the top of the soil layer will require fine finishing, as is described in Section 9.2.5. Subsequent layers can include a drainage layer of granular material followed by the top soil layer on which vegetation would be placed. Additional layers to protect the low-permeability layer may also be required in the design.

Construction in the areal method proceeds as the working face of the unit advances in subdivisions. Each layer is constructed as the fill subdivision closes and construction of the underlying layer within that subdivision is completed. Thus, in the areal method, the final cover system could be in all stages of construction at the same time. Such a method would probably provide more efficient use of the equipment, personnel, and material flow, particularly if the owner is constructing the final cover over time with his own personnel and equipment.

During construction of the cover system, particular attention must be placed on the workmanship around seals and penetrations of the cover system for vents, pipes, and risers penetration. Also, special attention must be taken in the construction around the perimeter of the cover where it joins the liner system of the unit. These are areas that have relatively high potential for leakage.

9.7 CONSTRUCTION OF ADMIX AND SPRAYED-ON LINERS

Admix liners refer to a variety of formed-in-place materials such as soil cement, concrete, and asphalt concrete. Although not suitable for use in the containment of hazardous wastes, these materials are still being used in the management of nonhazardous materials. Sprayed-on liners refer principally to liners made of catalytically-blown asphalt and asphalt-polymer compositions that can be sprayed on either a prepared earth surface or a geotextile placed on the ground. Both hot-sprayed asphalt and emulsified asphalt compositions are included. The characteristics of these materials are discussed in Chapter 4. Constructing liners based on these materials is discussed in the following subsections.

9.7.1 Asphalt Concrete

Asphalt concrete for hydraulic structures such as a pond or landfill is similar to paving-grade asphalt concrete, but, to reduce air voids in the concrete, well-graded aggregate with high percentages of mineral fillers and higher asphalt content are used. Side slopes are generally 2:1. As the mix is not subject to automotive traffic it does not need the very high stability of paving asphalt concrete but should be stable on the side slopes when hot (Asphalt Institute, 1976).

The foundation on which the asphalt concrete liner is constructed should be smoothed by rollers after compacting the top 6 in. to at least 95% of maximum density by ASTM D1557. Initially, the subgrade is treated with soil sterilant to prevent weed growth. A prime coat of hot liquid asphalt is then applied to the surface and allowed to cure before paving. The hot asphalt concrete mix should be placed by spreaders equipped with hoppers and strike-off plates or screeds. They should be capable of producing courses 10 to 15 ft wide, free from grooves, depressions, holes, etc. Ironing screeds used with strike offs and screeds on the spreader need to be heated to at least 250°F before starting operations to prevent sticking or tearing of the surface. Placement is planned to minimize the number of cold joints. Figure 9-38 shows a two-inch thick asphalt concrete liner being placed with road paving equipment.

The edges of spreads are smooth and sloped for 6 to 12 in. to provide a bonding surface with the adjacent spread. Cold surfaces are heated with an infrared heater just before forming joints. Asphalt concrete mixtures should be applied to slopes from bottom to top (Day, 1970). Generally, best results are obtained when the side slopes are paved before the floor (Asphalt Institute, 1976). The asphalt concrete liner needs to be compacted as soon after



Figure 9-38. A 2-in. thick asphalt concrete liner being applied using road paving equipment and methods. After the surface cools, a seal coat is applied (Source: Shultz, 1982).

spreading as possible. Ironing screeds, rollers, vibrators or tampers may be used for compaction (Day, 1970). In order to achieve a permeability coefficient of less than 1×10^{-7} cm s⁻¹, a voids content of 4% or less is required (Asphalt Institute, 1976). When a liner thickness greater than 3 inches is required, multiple courses should be applied. All joints should be staggered in the overlying course to ensure strength and low permeability for the liner as a whole (Day, 1970, pp 56-59).

9.7.2 Soil Cement

Soil-cement liners can be made from standard or plastic soil-cement mixes. The latter contain more cement and water than the former. Best results are obtained when the cement is mixed with a well-graded sandy soil (maximum size = 0.75 in.) as the cement is the minor ingredient. Type V sulfate-resistant cement is recommended when the soil contains sulfate as determined by laboratory tests. The design mix should be tested by the moisture-density relations test (ASTM D558), wet-dry test (ASTM D559), and freeze-thaw test (ASTM D560), and be tested for permeability [e.g. Bureau of Reclamation Test Method E-13 (Bureau of Reclamation, 1974)].

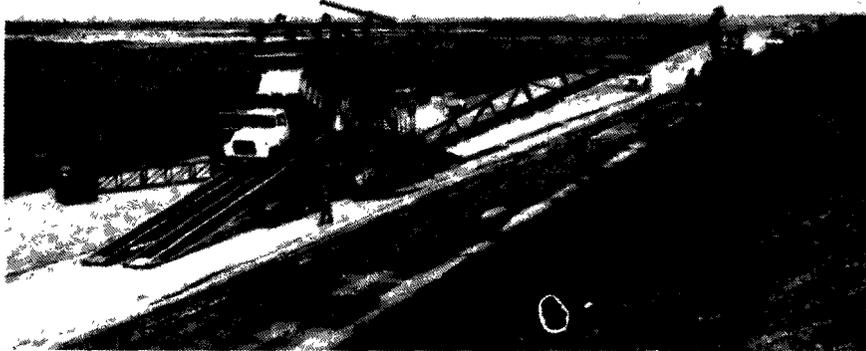
Soil cement is placed using road paving methods and equipment, but it should not be placed when air temperatures are below 45°F. The compacted density should be 98% of the laboratory maximum density. The compaction should proceed so that no more than one hour elapses between the spreading and compacting of a layer. Several stages of the installation of a soil-cement liner are shown in Figure 9-39. The surface of a compacted layer needs to be kept moist by fog spraying if another layer is to be applied. The finished liner should be allowed to cure for seven days. Soil cement must be sealed with compounds such as bituminous liquids and emulsions. These compounds are sprayed onto the soil-cement surface after it has been sprayed with water so that the liner reaches its maximum water absorption level. The surface of the liner should be sealed as soon after compaction as practical (Day, 1970).

9.7.3 Concrete and Cement

The details of procedures for construction, subgrade preparation, placing and curing of cement concrete liners may be obtained from the Bureau of Reclamation's Concrete Manual (1975), and from consulting engineers in this field. However, some considerations and procedures are presented below.

Subgrade preparation is particularly important if there is a possibility of high hydraulic pressures against the liner. A layer of gravel or drainage system should be placed beneath the liner. The subgrade should be well moistened just before placing the concrete. This will help prevent the liner from drying too quickly (Bureau of Reclamation, 1963).

Concrete mixes for pond liners need to be plastic enough to consolidate well and stiff enough not to slip on side slopes. A concrete mix with a slump of 2 to 2.5 in. is usually satisfactory. It is important to control



Placing machine is custom built to handle 10,000 cu yd of soil-cement a day



Conveyor boom extends 100-ft to dump soil-cement mix that is



compacted by rollers in stepped lifts of 9-in

Figure 9-39. Steps in the installation of a soil-cement liner (Source: Brown and Root, Inc., 1978).

the workability and consistency of the concrete carefully; a change of one inch in slump will interfere with the quality and progress of the work. The maximum recommended size of aggregate is 0.75 in. or less for a liner 2.5-in. thick. The inclusion of air-entraining agents is strongly recommended in areas where the liner will be exposed to freezing temperatures (Bureau of Reclamation, 1975).

Placement of the concrete may be done by slip form or the use of a screed. Surface finishing is not necessary since it is of little useful value in this type of situation. Curing is important. The use of accepted sealing compounds on the exposed surface is recommended to produce satisfactory results.

Shotcrete or gunite is cement mixed with sand of maximum size of 0.188 in., although 0.75-in. aggregate is used for some structural shotcrete. The relatively dry mix is "shot" through a large flexible hose by pneumatic pressure. Moist curing or use of a curing compound is necessary for shotcrete. Gunite may be used as a liner by itself, but generally requires an asphaltic or membrane seal to attain the required permeability (Bureau of Reclamation, 1963).

9.7.4 Sprayed-on Liners

A basic problem in placing a sprayed-on liner is to prevent pinholes from forming. Sprayed-on liners require a more carefully prepared subgrade than types of admix liners. The subgrade is dragged and rolled to produce a smooth surface free from rough, irregular, and angular projections. If the surface cannot meet the above criterion, a fine sand or soil padding may be necessary for proper membrane support. Geotextiles have also been used. The site should be excavated or over-excavated and side slopes flattened to allow for any padding necessary before liner application and for 1 to 3 ft of cover over the membrane (Bureau of Reclamation, 1963, pp 80-82).

Catalytically-blown asphalt is heated to 200-220°C (392-428°F) and applied at a rate of 1.5 gal yd⁻² measured at 60°F to form an asphalt membrane. The high softening point asphalt should not be overheated since high temperatures may lower the softening point and change other properties of the material. The spray bar is usually set off to the side of the distributor so that the heavy equipment does not travel over the subgrade or newly applied membrane. To eliminate pinholes, it is recommended that three passes be made at a rate of 0.5 gal yd⁻² each for a cumulative application of 1.5 gal yd⁻² (Asphalt Institute, 1976). The final membrane is usually about 0.25-in. thick. Sections of membrane should be overlapped 1 to 2 feet. The newly applied hot asphalt melts the underlying layer and both cool to form one continuous liner. The asphalt cools quickly and the next pass with the spray bar may be made immediately after finishing the previous layer. Care should be taken to avoid the accumulation of sand, silt, dust, or gravel on the asphalt between applications. Foreign materials on the membrane prevent proper bonding of layers and may cause pinholes to form.

The property of rapid cooling and hardening also presents some problems in applications. Skill and organization are required to prevent freezing of asphalt in the lines. Spray bars should not be turned off for more than one or two minutes at a time. All pumps, lines and bars should be cleaned with air or distillate after each spraying operation (Day, 1970). Figure 9-40 illustrates large scale spraying equipment and the spraying of an asphalt-rubber membrane.

Asphalt membranes can also be constructed by spraying asphalt emulsions at ambient temperatures greater than freezing onto a prepared subgrade, usually a supporting fabric of jute or glass fiber or a geotextile. A continuous membrane forms after the emulsion breaks and the water evaporates. Several light applications are used, not only to avoid pinholes, but to allow drying between coats to avoid porosity due to entrapped water.

Asphalt membranes are usually covered to protect them from mechanical damage. Cover materials are usually earth or graded earth and gravel. Membrane damage and leaks can occur from poor application or choice of cover material. Blading the cover frequently folds the top of the membrane and should be avoided. Rocks can tear or gouge the liner. Cover materials should not be applied if the temperature is below 32°F since the membrane may rupture from the operation (Day, 1970). Placement of a fine grained soil cover by draglines should be done on the floor first then from bottom to top of the side slopes. Coarser materials may then be applied. (Bureau of Reclamation, 1963, pp 82-83).

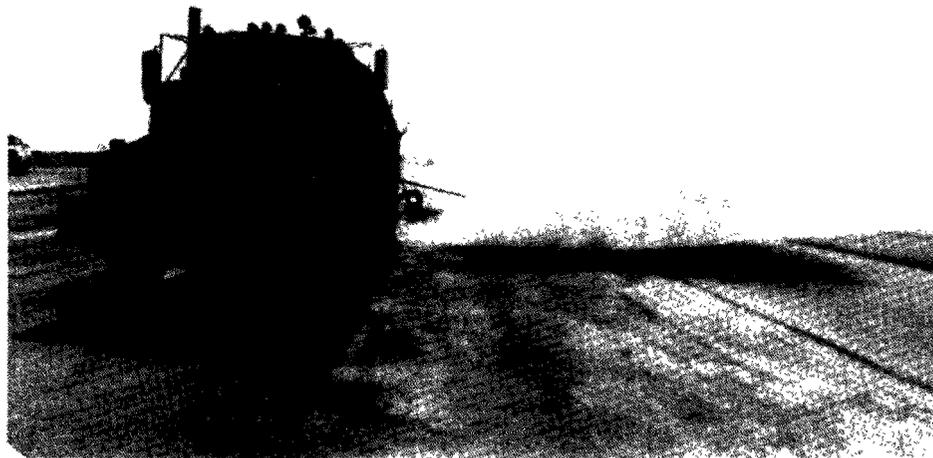
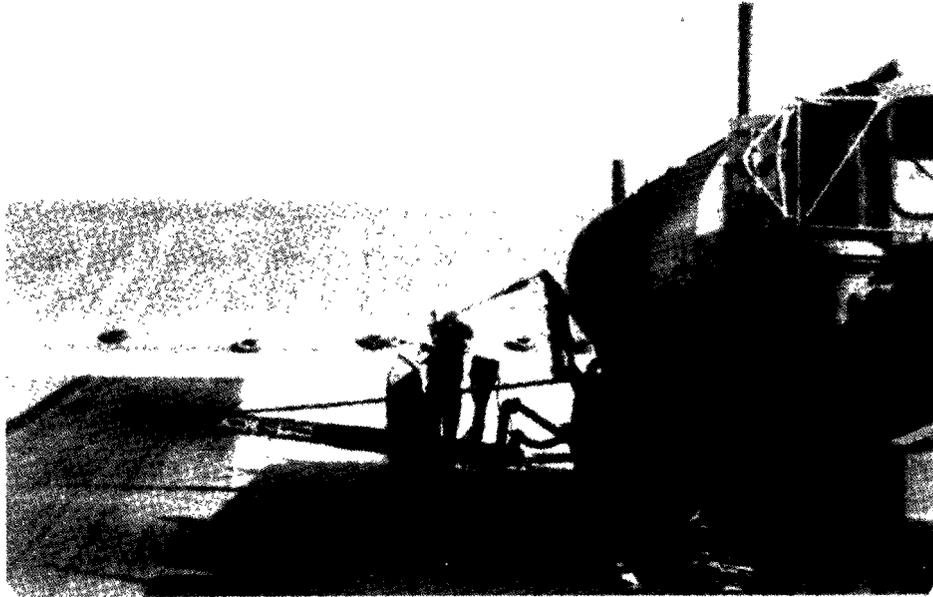


Figure 9-40. Placement of sprayed-on liners. The upper photograph shows a spray bar attached to a tanker truck and the lower photograph shows the spraying of an asphalt-rubber membrane (courtesy of Arizona Refining Company).

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CHAPTER 10

QUALITY ASSURANCE FOR THE CONSTRUCTION OF FML LINER SYSTEMS

10.1 INTRODUCTION

As is discussed in Chapter 6, strict conformance to a well-planned quality assurance plan for the construction of a waste containment unit has been found by experience to be an important factor in the success of such units. Rigorous quality assurance may make the difference between a unit that functions with a minimum number of problems throughout its service life and one that falls short of its minimum performance goals.

Construction quality assurance (CQA) in the context of constructing a storage or disposal unit is a planned system of activities that provides assurance that the unit is constructed as specified in the design (Norheim and Truesdale, 1986, p 3). Thus, CQA refers to those activities initiated by the facility owner that ensure that the construction of the entire facility, including manufacture, fabrication, and installation of the various components of the lining system, meets design specifications and performance requirements. CQA activities include inspections, verifications, audits, and evaluations of materials and workmanship necessary to determine and document the quality of the constructed facility. These activities are often performed by a third-party quality assurance team that is independent of the designer, manufacturer, fabricator, installer, and owner/operator to ensure impartiality.

CQA activities should be differentiated from construction quality control (CQC) activities which include those activities initiated by the designer, manufacturer, fabricator, installer, or construction contractor(s) necessary to control the quality of the constructed or installed component and to ensure that specifications are being met. Even though the CQC activities will overlap with those performed in fulfillment of the CQA plan, CQC and CQA activities are ultimately independent of each other.

The CQA plan is the facility owner's site-specific written response to the EPA's CQA program and is submitted as part of the permit application. It should include a detailed description of all CQA activities that will be performed to manage construction quality in order to document the owner's approach to CQA. The plan is developed, usually by the design engineer, in such a way that the focus of quality assurance will be on those elements of

the design that are critical to the function of the facility. Nevertheless, the facility owner is ultimately responsible for the CQA plan and its implementation, just as he is responsible for all elements of the design, construction, and operation of a disposal facility.

It is assumed that at the time the CQA plan is implemented the site has been characterized adequately and that a site-specific facility design has been evaluated and accepted by the facility owner/operator. It is also assumed that at this time the FML and other materials to be used in the lining system have been selected. The CQA plan covers the period beginning with construction at the site or the manufacture of components of the lining system, whichever is earlier, and ending with acceptance of the site by the owner/operator. Quality assurance activities involved in ensuring the adequate performance of a unit once it is placed in service are considered part of management and are discussed in Chapter 11.

This chapter reviews the guidelines for CQA plans set forth in the EPA's Technical Guidance Document, "Construction Quality Assurance for Hazardous Waste Disposal Facilities" (Northeim and Trusdale, 1986), which discusses the elements of a CQA plan in detail. In particular, this chapter emphasizes the inspection activities involved in the CQA of the different components of a completed containment unit.

10.2 THE ELEMENTS OF A CQA PLAN

The CQA plan is a written document, the exact content of which will depend on site-specific conditions for each proposed facility. Each element of the plan should be treated comprehensively. Even though the plan is site-specific, at a minimum, the following elements should be included:

- Delineation of responsibility and authority.
- Statement of qualifications of CQA personnel.
- Design specifications.
- Inspection activities to be performed.
- Sampling requirements of the inspection activities.
- Acceptance/rejection criteria and corrective measures.
- Documentation requirements.

Each of these elements is discussed briefly in the following paragraphs.

10.2.1 Delineation of Responsibility and Authority

The permitting, designing, and construction of a disposal facility involves a large number of organizations. Those organizations involved

directly in CQA include the permitting agency, the facility owner/operator, the design engineer, the CQA personnel, and the construction and installation contractor(s). The FML manufacturer may also be directly involved. These organizations are not necessarily completely independent of each other. For example, the facility owner/operator may also be the construction contractor. The CQA personnel may be employees of the facility owner/operator, of the design engineer, or of an independent firm. The installer could also be the FML manufacturer or fabricator. Regardless of the relationships among the organizations, the areas of responsibility and the lines of authority for each organization need to be clearly delineated in a CQA plan. Northeim and Truesdale (1986) list the basic responsibilities of the various parties involved in CQA. Giroud and Fluet (1986) also discuss the roles and responsibilities of the parties involved.

Periodic meetings and visits are necessary to ensure good communication between all parties (Northeim and Truesdale, 1986; Giroud and Fluet, 1986). Project meetings will benefit all those involved with the facility by ensuring familiarity with facility design, construction procedures, the requirements of the CQA plan, and any design changes. Examples of the types of meetings that may be held include the following:

- A preconstruction CQA meeting to resolve any uncertainties about the design, the CQA plan, etc. This meeting should be held following the completion of the facility design, completion of the site-specific CQA plan, and award of the construction contract. This meeting should be attended by the facility owner/operator, design engineer, CQA personnel, construction contractor, and the installer, if one has been selected.
- Daily meetings to review progress.
- Problem or work deficiency meetings to be held as the need arises.

These meeting should be documented.

10.2.2 Statement of Qualifications of CQA Personnel

The CQA plan should identify the qualifications of the CQA officer and the CQA inspection personnel in terms of the training and experience necessary to fulfill their assigned responsibilities.

10.2.3 Design Specifications

Insofar as the purpose of a CQA plan is to verify whether or not the various components of the facility and the completed facility itself meet the design specifications, these specifications are a necessary part of the CQA plan. Specifications for materials and construction are discussed in more detail in Chapters 7 and 8.

10.2.4 Inspection Activities to be Performed

The inspection activities to be performed in the implementation of a CQA plan include observations and tests that ensure that the materials of construction, the construction itself, and the installation of the various components of the lining system meet or exceed all design criteria, plans, and specifications. The wide range of materials of construction and the number of different construction activities involved in constructing a disposal facility is reflected in the number of different inspection activities that are involved in implementing a CQA plan. The areas for CQA inspection include the earthworks (including the foundation, the embankments, and a low-permeability soil liner in composite double-liner systems), the FML liner (from inspection of the raw materials up through inspection of the installed liner), and the different components of the leachate collection systems. Each of these areas is discussed separately in Sections 10.3 through 10.5.

It is important that appropriate tests are selected for inspecting the quality of the construction materials and the workmanship and that the exact procedures to be used to test the materials are well defined. For example, some ASTM standards, such as ASTM D638* which describes methods for testing the tensile properties of plastics, include a range of alternative testing procedures. Citation of the number of a standard in a CQA plan may not be enough to define the exact testing procedure to be followed.

Ideally, CQA inspections and tests should meet the following criteria (Spigolon and Kelley, 1984):

- A CQA inspection test should be a good indicator of a design quality.
- A CQA inspection test or observation should be accurate and precise. The test results or observations should be documentable, i.e. the results or observations should be numbers or well-defined terms or phrases.
- The results of a CQA inspection should be available within a short period of time so that acceptance decisions can be made without causing interference with contractor performance.
- A CQA inspection test should be easy to run using simple, rugged equipment.
- Preferably, a CQA inspection test should be nondestructive, i.e. should not damage the integrity of any component of the installed lining system.

*The references at the end of this chapter list the ASTM standards cited in this chapter and their titles.

The data that results from CQA inspection testing will be one of two types: attribute-type data or measurement-type data. The type of data that will be reported will depend on the test method, the design specifications, and on how the acceptance/rejection criteria are stated. Attribute-type data can be based on dichotomous classifications, e.g. pass/fail, acceptable/defective type classifications, or, in the case of FML destructive seam testing, classifying the results of testing seams as a film-tearing bond break or a non-film-tearing bond break. The criterion distinguishing between classifications should be clearly stated. In the case of FML seam testing, a schematic of the different ways in which tested specimens can break could be included as part of the design specifications or the CQA plan. Measurement-type data are test values which can be used to compute summary statistics such as means, variances, and ranges. In cases in which there are alternative means of calculating test values, the precise method for calculating should be stated.

10.2.5 Sampling Requirements

Since it is neither possible nor economically feasible to perform 100% inspection of many materials and construction processes, the quality of the material or process must be estimated from the results of inspecting a representative sample of the total material or constructed facility. Examples of this situation include estimations of the integrity of FML seams by destructive testing and assessments of the characteristics of the soil liner in an FML/composite double liner. For all types of QA testing, the sampling requirements need to be stated.

Inspection and sampling requirements should include statement of the sampling strategy, the size or the definition of the unit to be sampled, the size of the sample itself, the sampling procedure, and the number of specimens to be tested per sample. There are three basic types of sampling strategies: 100% inspection, judgmental sampling, and statistical sampling. One hundred percent inspection means that inspection is made continuously on every unit of a product being manufactured or fabricated.

Judgmental sampling refers to any sampling procedure in which decisions concerning sample size, selection scheme, and locations are based on considerations not derived from probability theory. The objective of such sampling may be to test typical samples that represent the whole, to test zones of suspected quality, or a combination of the two. Thus, in sampling FML seams, samples could be taken at a minimum frequency per unit of seam length from locations assigned by the CQA inspector before seaming is started and also from locations that are of suspected quality. The success of a judgmental sampling plan is dependent on the knowledge, capability, and experience of the design engineer, the CQA inspection personnel, the CQA officer, and the project manager. Organizations that construct large numbers of similar projects, such as the U.S. Army Corps of Engineers or the U.S. Bureau of Reclamation, often employ judgmental sampling plans using sampling frequencies based on years of construction experience. For example, more intensive sampling may be required in areas where design specifications are more difficult to meet (e.g. field seaming operations on the slopes of a

unit). The potential weakness of judgmental sampling is that such methods are subject to biases and sampling errors.

Statistical sampling methods are based on principles of probability theory and are used to estimate selected characteristics (e.g. means, variance, percent defective) of the overall material or construction process. These methods are more rational, calculable, and documentable than judgmental methods and are recommended whenever feasible and applicable. An important element of all statistical methods is knowledge of the inherent variability of the specified characteristic to be measured. This variability can be a function of material quality, construction operations, measurement techniques and instrumentation, and the skill of the CQA personnel. The weakness of specific statistical sampling methods depends on the applicability of the theoretical assumptions to the population to be sampled; for example, whether the probability distribution of sample test measurements is normal.

Knowledge about the applicability of statistical sampling methods for the CQA of constructing a waste containment unit is not well-developed. In practice, a balanced CQA program uses both judgmental and statistical approaches to take advantage of the lack of bias in statistical sampling methods and the experience and judgment of qualified CQA personnel.

Sampling strategies are discussed in more detail by Northeim and Truesdale (1986, pp 54-69). Additional information on sampling and sampling procedures can be found in ASTM E105 and E122 and in texts by Beaton (1968), Burr (1976), Deming (1950), Dixon and Massey (1957), Duncan (1959), Grant (1964), Kish (1967), and the U.S. Department of the Army (1977).

10.2.6 Acceptance/Rejection Criteria and Corrective Measures

The acceptance or rejection criteria for the inspection activities should be stated. The type of criteria will depend on the type of data resulting from the inspection testing. If the data being collected are attribute-type data (e.g. film-tearing bond break/non-film-tearing bond break for reporting the results of destructive testing of FML seams), the maximum percentage of specimens that are unacceptable per tested sample or the maximum percentage of unacceptable samples per sample block should be stated. If the data being collected are measurement-type data, acceptance/rejection criteria are based on whether a nominal level (e.g. mean, median, variance) meets the design specification value(s) for a specific measurement (e.g. FML seam strength). The nature of the nominal level, e.g. whether it is a median or a mean, should be stated in the specifications.

The criteria for accepting or rejecting measurements that appear to be atypical or in error should be stated. This type of datum, called an outlier, may be an extreme manifestation of the random variability inherent in data resulting from testing a specific material or process, or it may be a result of a gross deviation in the test procedure or an error in calculating or recording the numerical value. For further discussion of outliers, see ASTM E178 or texts by Barnett and Lewis (1978) and Dixon and Massey (1957).

When material or work is rejected because the CQA inspection activities indicate that it does not meet the design specifications, corrective measures must be implemented. The types of corrective measures that should be taken and the requirements for inspecting these measures should be stated.

10.2.7 Documentation

Thorough documentation is an important part of the implementation and success of a CQA Plan. The documentation requirements for all CQA activities should be described in detail in the plan. These requirements should include such items as daily summary reports, inspection data sheets, problem identification and corrective measure reports, block evaluation reports, acceptance reports, and the final documentation, which is submitted to the permitting agency. Provisions for final storage of the CQA records should also be included in the CQA plan. Recordkeeping documentation of geotechnical work is discussed in detail by Spigolon and Kelley (1984).

10.3 CQA INSPECTION OF EARTHWORKS AND SOIL LINER COMPONENT(S) OF COMPOSITE DOUBLE LINERS

The importance of CQA inspection of the construction of the earthworks which will support an FML cannot be overstressed, since FMLs are not themselves structural materials. Case histories on liner failures indicate that many have occurred due to engineering and construction failures in the earthworks rather than due to failures in the FMLs themselves (Giroud, 1984), as is discussed in Chapter 6. Quality assurance for earthworks and embankments should focus on two areas:

- Tests/observations for evaluation of soil materials.
- Tests/observations for evaluation of workmanship.

This section briefly discusses the CQA inspection activities that are appropriate to the construction of the foundation, the embankments, and the soil liner component of a composite double liner. Specific test procedures that can be used and types of observations that can be made during CQA inspection are listed in Appendix M.

10.3.1 Inspection of the Foundation

The purpose of the foundation is to provide structurally stable subgrades for the overlying facility components and to provide satisfactory contact with the overlying liner and other system components. The foundation should also be resistant to settlement, uplift, and compression, which could distort or rupture the liner or its subsystems. The U.S. Department of the Army (1977) recommends the following inspection activities for constructing the foundation of hydraulic structures:

- Tests and observations to ensure the quality of compacted fill. These tests should include index property tests that indicate or correlate with engineering properties including, tests of weight-volume relationships, soil classification tests, and laboratory compaction tests.

- Observations of soil and rock surfaces for adequate filling of rock joints, clay fractures, or depressions, and removal and filling of sand seams.
- Measurements of the depth and slope of the excavation to ensure that they meet design requirements.
- Observations of stripping and excavation to ensure that there are no moisture seeps and that all soft, organic, and otherwise undesirable materials are removed. Proof-rolling with heavy equipment can be used to detect soft areas likely to cause settlement and the consistency of the foundation soil may be checked with a penetrometer or similar device.

Construction observations should be continuous and the type of compaction equipment and compaction methods used should be noted. Surveying will be necessary to ensure that facility dimensions, side slopes, and bottom slopes are as specified in the design. Further information on the CQA of foundations, including discussions of specific inspection procedures and sampling techniques, can be found in Spigolon and Kelley (1984), Bureau of Reclamation (1974), and U.S. Army (1977).

10.3.2 Inspection of the Embankments

The purpose of embankments in waste containment facilities is to function as retaining walls that resist the lateral forces of the stored wastes and to provide support to the overlying facility components. Embankments must be constructed with sufficient structural stability to prevent massive failure throughout the lifetime of the facility. Embankment design and construction focuses on strength and stability and, in most cases, embankments are constructed from excavated fill material. Recently, geogrids have been used to reinforce the soil to steepen embankment slopes (see Sections 4.2.4. and 7.5.2).

CQA inspection requirements are similar to those for inspecting the foundations. It should be noted, however, that the soil material for embankments is compacted for strength and not necessarily for low permeability. Preconstruction inspection activities can include evaluation of excavated fill materials (which should continue throughout construction), evaluation of the suitability of the construction equipment to perform the required level of compaction, and construction of a test fill. Inspection activities that should be carried out during construction include the following (Northeim and Truesdale, 1986):

- Testing of fill material characteristics.
- Measurement of compacted lift thickness.
- Observation of clod-size reduction and material homogenization operations (if applicable).
- Tests to verify water content (if applicable).

- Observations of the number of passes by the compaction equipment, and the uniformity of compaction coverage.
- Tests to verify the density of the compacted fill.
- Observations of scarification and connection between compacted fill lifts (if applicable).
- Measurement of the embankment slopes.

Embankments can be constructed either with a zoned cross section (i.e. with a core and shells that support the core in position and give it strength to resist lateral forces) or with a homogeneous cross section. If the embankments are constructed with a zoned cross section, the required CQA inspection activities for each zone are the same as those listed above.

Additional information on the CQA of embankments, including the discussion of specific inspection procedures and sampling techniques, can be found in Spigolon and Kelley (1984), Bureau of Reclamation (1977), and U.S. Army (1977).

10.3.3 Inspection of Soil Liners

The purpose of a low-permeability soil liner depends on the overall liner system design. In the containment of hazardous wastes, soil liners are presently being used as the soil component of a composite liner in a double liner system which serves as a protective bedding material for the FML component and which is compacted to achieve a specified hydraulic conductivity.

CQA activities prior to construction include inspection of the soil materials to be compacted to be sure that they are uniform and as specified in the design. If the soil materials need to be amended with other materials (e.g. bentonite), CQA personnel should inspect the additional materials to ensure their quality and make observations and tests to ensure that the specified amount is added and that the materials are mixed uniformly with the natural soil. Initial inspection of the soil can be largely visual, although such inspection requires CQA personnel to be experienced with visual-manual soil classification techniques. In addition, samples of the liner material should be tested for the following properties:

- Hydraulic conductivity.
- Soil density/moisture content relationships.
- Maximum clod size.
- Particle size distribution.
- Atterberg limits.
- Natural water content.

Tests for these properties are listed in Appendix M. Inspection of the soil materials should continue throughout the construction process. The recommendations of Gordon et al (1984) for the construction documentation of clay liners are given in Table 10-1.

The EPA presently recommends the construction of test fills to verify the adequacy of the materials, design, equipment, and construction procedures proposed for the soil liner. Several studies have indicated that field (in-place) hydraulic conductivity of a compacted soil liner may be much greater than would be predicted from laboratory hydraulic conductivity tests (Herzog and Morse, 1984; Gordon and Huebner, 1983; Daniel, 1984; Boutwell and Donald, 1982). Unfortunately, field hydraulic conductivity tests conducted on the full-scale liner can cause substantial delays in construction and result in other problems caused by the prolonged exposure of the soil liner (e.g. desiccation, erosion, etc.). Determining the hydraulic conductivity of a test liner compacted of the same soil materials in accordance with the same construction procedures in conjunction with a strict CQA plan should allow the performance of the full-scale liner to be predicted with the highest degree of confidence presently available. Ideally, the test fill can also be used to establish a correlation between index property tests (e.g. hydraulic conductivity of laboratory compacted samples, Atterberg limits, particle-size distribution, etc.) and field hydraulic conductivity tests, thus eliminating the need for field hydraulic conductivity testing of the full-scale liner. Guidelines for the construction and CQA of test fills are presented by Norheim and Truesdale (1986). See also Section 7.5.3.1.5.

During construction, CQA personnel should observe the compaction process (including estimating the compactive effort) continuously and test the compacted liner in accordance with a specified sampling strategy using specified test procedures. Tests for the CQA inspection of low-permeability soil liners are listed in Appendix M. Further information on the CQA of compacted soil liners can be found in Spigolon and Kelley (1984) and Goldman et al (1985).

Since the top surface of the compacted soil liner can also serve as the bedding layer for an FML, CQA of the finished soil liner should include (Norheim and Truesdale, 1986):

- Observations to ensure the removal of objects such as roots, large clods and rocks that could penetrate the FML.
- Observations to ensure uniform application of herbicides, when required.
- Observations and tests to ensure that the surface is properly compacted, smooth, uniform, and free from sudden changes in grade.
- Observations to ensure that any recessed areas in the subgrade are properly placed.

TABLE 10-1. SAMPLE RECOMMENDATIONS FOR CONSTRUCTION
DOCUMENTATION OF CLAY-LINED LANDFILLS

Item	Testing	Frequency
1. Clay borrow source testing	Grain size	1,000 yd ³
	Moisture content	1,000 yd ³
	Atterberg limits (liquid limit and plasticity index)	5,000 yd ³
	Moisture-density curve	5,000 yd ³ and all changes in material
	Lab hydraulic conductivity (remolded samples)	10,000 yd ³
2. Clay liner testing	Density (nuclear or sand cone)	5 test/acre/lift (250 yd ³)
	Moisture content	5 test/acre/lift (250 yd ³)
	Hydraulic conductivity (undisturbed soil sample)	1 test/acre/lift (1,500 yd ³)
	Dry density (undisturbed soil sample)	1 test/acre/lift (1,500 yd ³)
	Moisture content (undisturbed soil sample)	1 test/acre/lift (1,500 yd ³)
	Atterberg limits (liquid limit and plasticity index)	1 test/acre/lift (1,500 yd ³)
	Grain size (to the 2-micron particle size)	1 test/acre/lift (1,500 yd ³)
	Moisture-density curve (as per clay borrow requirements)	5,000 yd ³ and all changes in material
3. Granular drainage blanket testing	Grain size (to the No. 200 sieve)	1,500 yd ³
	Hydraulic conductivity	3,000 yd ³

Source: Gordon et al, 1984.

- Observations to ensure the uniform application of the protective soil bedding layer should one be required, as well as observations to ensure the proper placement of geotextiles which may be used to protect the FML.

Wright et al (1987) discuss the CQA inspection of the supporting surface for an FML in detail.

10.4 CQA INSPECTION OF FMLS

At the present state-of-the-art of FML technology and the design and construction of hazardous waste storage and disposal facilities, it is not feasible to set specifications for ultimate performance which can be tested to assure the construction of a sound facility. Such specifications can be used for manufactured products. For example, the long-term performance of an automotive tire, which is a complex polymeric product, can be measured by such relatively rapid tests as tread wear, skid resistance, and various wheel tests for durability. No short-term tests are available at present to determine the long-term performance of a disposal facility. At the present time, owners and designers of waste disposal and storage facilities must depend on methods that have developed as conventions for setting specifications, quality assurance programs to cover both materials and construction, and materials that have demonstrated the best performance.

The five basic steps from the manufacture of an FML through its installation as a liner for a waste storage or disposal facility are as follows:

- Manufacture of the raw materials.
- Manufacture of the FML.
- Fabrication of the FML into panels (if necessary).
- Transportation, handling, and storage of the FML.
- Installation of the FML, including seaming.

Each of these steps requires CQA inspection to ensure the quality of the installed lining system.

Specific laboratory test procedures for the CQA inspection of FMLs are discussed in Section 4.2.2.5. Methods for the nondestructive testing of seams are discussed in Section 9.3.6.

It is assumed that at the time the CQA plan begins to be implemented, compatibility tests were performed if they were required as part of the permitting process. This type of testing is necessary to ensure the site owner that the FML to be used is compatible with the waste liquid or leachate

to be contained. As part of compatibility testing, the FML being tested should have been fingerprinted so that it is possible to show that the FML that was tested is equivalent to the one being installed at the facility site. Fingerprinting of FMLs is discussed in Section 4.2.2.6.

10.4.1 Control of Raw Materials used in the Manufacture of FMLs

To assure the production of an FML of uniform and reproducible quality, the raw materials of which it is made must also be of uniform quality. In many situations the FML manufacturer depends upon the supplier to furnish the proper raw materials so that the manufactured FML can meet the design specifications. Thus, the FML manufacturer will have a set of specifications that are agreed to by the raw material supplier to ensure a proper and consistent level of quality. The raw material supplier can issue a certificate of conformance with the agreed specifications for each lot of material. However, the manufacturer should still perform quality control testing on the incoming raw materials, particularly the critical materials used in the FML compound to determine whether they meet the appropriate specifications.

Of the various raw materials that are incorporated into a polymeric FML, the polymer is the most critical. The ultimate user of the FML, i.e. the owner/operator of the facility to be constructed, should know that a manufacturer of FMLs has a quality control program to ensure uniformity of the materials. For rubbery polymers, viscosity, molecular weight, and cure rates are typical of the properties that must be controlled. For thermoplastics, the viscosity and molecular weight are of particular importance. In the case of semicrystalline polymers such as polyethylene, it is important in the production of the base resin to control the density, level of crystallinity, melt index and composition, i.e. the ratio of ethylene to other olefins in the polymer and the molecular weight distribution. In view of potential batch-to-batch variation, Knipschild et al (1979) recommend that HDPE suppliers test each batch of resin and report the following values to an FML manufacturer: density, percent carbon black, melt index, relative solution viscosity, stress-crack resistance, and percent volatiles. Knipschild et al (1979) also suggest that the HDPE FML manufacturer, in turn, test at least the melt index and percent volatiles of the base resin since these two properties can affect processing. Cadwallader (1985) suggests that an HDPE FML manufacturer should test the melt index, density, and oxidative induction time of the raw resin.

In addition to the polymer, the FML compound will contain other ingredients, each of which will be produced to specification and will be selected based upon experimental testing in the formulated compound by the manufacturer. In most cases, there will be several suppliers of the auxiliary ingredients; the suppliers are selected by the FML manufacturer. Among the auxiliary materials that are of particular importance are the fillers and processing aids for the rubbers, the carbon black used with polyethylene for ultraviolet protection, the plasticizers for some thermoplastics, and the various antioxidants and antidegradants used in all materials. For fabric-reinforced FMLs, specifications should be set by the manufacturer to ensure

strength and proper pretreatment of the fabric. Composition and strength of the fabric should also be specified.

CQA inspection of this step of FML manufacture can involve inspection of the manufacturer's quality control program for ensuring the uniform quality of the raw materials including inspection of any certificates furnished by the raw material supplier and inspection of the FML manufacturer's testing of the raw materials. If there are areas where the CQA officer feels the manufacturer's quality control program is weak, he may request the manufacturer to conduct additional testing. The CQA officer may also conduct additional testing to verify the manufacturer's product specifications or his test results.

10.4.2 Inspection of the Manufactured FML Sheeting

FML compounds are mixed in various types of equipment depending on the type of polymer; for example, rubbers and thermoplastics are generally mixed in internal mixers and on mills. Polyethylenes are mixed on mills and in extruder mixers. The ingredients are dispersed and the mass becomes thermoplastic and processable on calenders and in extruders used to manufacture the FML. The rheological properties, e.g. viscosity of the mixed compound, must be controlled within specified limits in order to assure uniform shaping. If the FML is to be exposed to the weather, particular attention must be paid to the dispersion of the ultraviolet screen, e.g. carbon black and the antioxidants.

The three basic methods used in the manufacture of FMLs are calendering, extrusion, and spread coating. Calendering is used in forming both unreinforced and fabric-reinforced FMLs, whereas extrusion is only used in making unreinforced FMLs, e.g. polyethylene. Spread coating is used usually for making fabric-reinforced FMLs in which the fabric weave is comparatively tight, i.e. the number of thread ends per inch is greater than 20. These manufacturing processes are discussed in more detail in Chapter 4. Each process requires a different quality control plan, and each manufacturer should have an appropriate quality control manual that is available to a CQA officer.

CQA testing of the manufactured FML will depend on the type of FML being tested and the specifications which the manufactured FML has to meet. Most of these specifications give minimum values for the FML. Testing can include measurements of the following properties:

- Analytical properties:
 - Volatiles.
 - Ash content.
 - Extractables.
 - Specific gravity/density.

- Crystallinity content (if FML is semicrystalline).
- Carbon black content (if FML is semicrystalline).
- Carbon black dispersion (if FML is semicrystalline).
- Melt flow index (if FML is semicrystalline).
- Physical properties:
 - Thickness (a minimum thickness at all points across the roll width should be met).
 - Tensile properties.
 - Modulus of elasticity (if FML is semicrystalline).
 - Hardness.
 - Tear resistance.
 - Puncture resistance, including impact puncture.
 - Hydrostatic resistance.
 - Scrim characteristics (if FML is fabric-reinforced).
 - Ply adhesion (if FML is fabric-reinforced).
- Permeability characteristics:
 - Water vapor transmission.
 - Solvent vapor transmission.
 - Gas permeability.
- Tests that measure environmental and aging effects:
 - Resistance to ozone-cracking.
 - Resistance to environmental stress-cracking (if FML is semi-crystalline).
 - Low-temperature properties.
 - High-temperature properties.
 - Air-oven aging characteristics.
 - Dimensional stability.

--Water absorption.

--Resistance to soil burial.

These properties and specific tests for measuring them are discussed in Chapter 4.

For calendered FMLs, the important features of inspection include measurement of thickness and visual inspection of the surface to ensure that a minimum thickness in the specification is met and that the FML is free of pinholes and surface irregularities. For fabric-reinforced FMLs, ply adhesion and thickness of the coating over the scrim should be measured as the FML is being manufactured. The distance from the selvage edges of the fabric with respect to the edge of the sheeting should be inspected during manufacture to make sure it meets specification. Also, during the processing a visual inspection must be maintained to avoid deformation of the fabric. Measurements of ply adhesion are particularly needed on FMLs manufactured with fabrics with high thread end counts, due to the reduced area for strike through.

The manufactured FML should be fingerprinted by the CQA laboratory and the results compared with the fingerprint of the FML tested in the compatibility study to ensure that the FML used in the final construction is of the same composition.

An important aspect of CQA inspections of manufactured FMLs is the level of sampling. There are two types of sampling to consider: (1) the level at which samples can be taken from the manufactured FML, i.e. the number and size of sample removed per FML roll, and (2) the level of testing to perform per sample. At this time most sampling is performed on a judgmental basis. The sampling of the rolls for property testing is often coordinated with the manufacturer's quality control sampling which usually occurs either at the beginning or end of a roll and sometimes somewhere in the middle, depending on production procedures. In the case of FMLs that are fabricated into panels, the FML can also be sampled during fabrication so that samples can include factory seams. The level of testing and the type of tests to perform on the sample will depend on the type of FML and the production process. CQA testing should concentrate on testing those properties which are important to FML performance and those which are subject to variability due to variations in production conditions or compound composition. For example, the most frequently performed testing will probably be measurements of thickness. In the CQA inspection testing of a fabric-reinforced CPE FML, the Bureau of Reclamation performed a clearly defined level of testing per sample of the CPE liner installed at the Mt. Elbert Forebay Reservoir, as is shown in Table 10-2 (Morrison et al, 1981). The samples taken during fabrication of the panels were perpendicular to the factory seams. Each sample, which measured approximately 1 x 70 or 140 ft depending on panel design size, was long enough to include all the factory seams in that panel. One out of every 10 panels was sampled out of an estimated 1,000 panels that were required for the entire project. The required level of sampling and testing should be stated in the CQA plan.

TABLE 10-2. SPECIFICATIONS AND THE NUMBER OF SPECIMENS TESTED PER SAMPLE OF A CPE FML USED IN CONSTRUCTION OF MT. ELBERT FOREBAY RESERVOIR

Property	Test Method	Minimum requirement	Number of specimens tested per panel ^a sample
Thickness	ASTM D751	1.04 mm (0.041 in.)	(Random readings)
Breaking strength, each direction	ASTM D751, Grab Method A	8.90 N (200 lbf)	5 (warp direction) 5 fill direction)
Tear strength, each direction	ASTM D751, Tongue Tear Method B	334 N (75 lbf)	5 (warp direction) 5 (fill direction)
Bonded seam strength, in shear	ASTM D751, Grab Method A	Equals parent material breaking strength	5
Bonded seam strength, in peel	ASTM D1876	No specification requirement	5
Dimensional stability (percent change, maximum)	ASTM D1204, 1 hour at 100°C (212°F)	2%	2
Low temperature bend	ASTM D2136, 3-mm (1/8-in.) mandrel; 4 hours at -40°C (-40°F)	Pass	5
Hydrostatic resistance	ASTM D751, Method A	2.07 MPa (300 lb/in. ²)	5
Ply adhesion	ASTM D413, Machine Method Type A specimens	1400 N/m (8 lb/in.)	5
Infrared spectroscopy	Manufacturer laboratory procedure	Matching IR scan	2
Total specimens per panel			49

^aPanels were supplied in two shapes: (1) 200 x 70 ft, containing 14 seams, or (2) 100 x 140 ft, containing 29 seams. One out of every 10 panels was sampled out of an estimated 1,000 panels that were required for the entire project.

Source: Morrison et al, 1981, p 21.

A CQA officer should visit the FML manufacturing plant prior to or during manufacture of the FML rolls for the specific project. During this visit the CQA officer should review the manufacturing process and the quality control and testing procedures and make arrangements to coordinate CQA inspection activities with the manufacturer. Some CQA plans have required the manufacturer to submit laboratory test reports on physical properties (including copies of appropriate stress-strain curves) for each day's production. An important part of such a requirement is the inspection and approval of the manufacturer's testing procedures and facilities. The CQA officer should also inspect documentation so that it is possible to coordinate inspection test results with the FML being installed at the site.

Criteria for the rejection of FMLs should be set in the design step as part of the specifications. For example, FMLs could be rejected on the basis of not meeting the specifications for physical properties, composition, and thickness. Polyethylene FMLs should be rejected on the basis of inadequate thickness and carbon black content and dispersion; fabric-reinforced FMLs should be rejected for inadequate ply adhesion and insufficient thickness of coating over fabric.

10.4.3 Inspection of Fabricated Panels

To reduce the amount of field seaming to a minimum, narrow-width FMLs are fabricated into panels under factory conditions. Each panel is made according to a design layout for the liner and is numbered and identified for installation. The size of the panels is limited by weight, and the ability of a crew to install them in the field. These panels range from 2,000 to 5,000 lbs and up to 100 x 200 ft (30 x 60 m). It is desirable to reduce the amount of field seaming because seaming procedures and conditions can be controlled more precisely in a factory. Methods of seaming FMLs are discussed in Section 4.2.2.3. It should be noted that PE FMLs are brought to the site in rolls rather than panels and require a crane or front-end loader for moving to the installation site. These rolls may weigh up to 10,000 pounds.

CQA inspection of panel fabrication should concentrate on the inspection of the seams which should be 100% nondestructively tested for continuity. Methods for the nondestructive testing of seams are described in Section 9.3.6. A CQA officer should visit the fabrication site to review the fabricator's quality control procedures and facilities for testing. In particular, he should review:

- The levels of inspection of the FML for pinholes and other surface imperfections during fabrication of the panels.
- The nondestructive testing of the panel seams, e.g. by air-lance.
- Quality control procedures involving destructive testing of seams.

- The handling of the fabricated FMLs as they are prepared for shipment.
- The clarity of the directions for placement of the panels or rolls at the job site and the directions for unfolding or unrolling of each individual panel.
- The document control.

The quality control procedures involving destructive testing of seams can include testing of samples removed from fabricated panels and testing of prestart seam samples, i.e. samples that are made at the beginning of a shift on extraneous pieces of FML to test the fabricating personnel and their equipment. Heat-sealed seams can be tested almost immediately. For CQA testing, specifications may require conditioning of seam samples for 24 hours at 23°C (73.4°F) before testing. Seams fabricated using solvent-based methods must wait until the solvent has evaporated. NSF (1985) specifies that adhesive-seamed samples (including those seamed with bodied solvents) should be conditioned for a minimum of 12 days at 23°C (73.4°F); at the end of this period if the seam does not appear dry or suitable for testing, the seam samples can then be conditioned in an air-circulating oven at 70°C (158°F) for 3 hours and allowed to rest at 23°C (73.4°F) for 48 hours before testing. The hole remaining from sampling a fabricated panel must be patched, generally with a bodied-solvent adhesive for noncrystalline thermoplastic or by fillet-extrusion welds for PE FMLs.

The level of sampling for the CQA destructive testing of seams will depend on the CQA planner's judgment about the level of variation inherent in the seaming procedure and on the size of the entire job. As is described in the previous subsection, the Bureau of Reclamation took a 1-ft wide sample that ran perpendicular to the seam from an edge of one out of every 10 panels used in constructing a reservoir (Morrison et al, 1981). In this way, each sample had a section from every seam in the sampled panel. At the CQA laboratory, each sample was visually inspected for:

- Sufficient seam overlap to ensure specified scrim-to-scrim bonding.
- Sufficient adhesion of the overlap to ensure that the selvage was fully bonded to the adjacent panel.

Five specimens were randomly cut and tested for shear and five for peel from each sample. For jobs in which the size and shape of the panels varies, sampling can also be performed on the basis of a specified number per linear foot of seam, e.g. one destructive sample per 1,000 ft of seam. Wright et al (1987) report that one factory seam sample per 1525 m (5,000 ft) of factory seam is normally required.

10.4.4 Inspection of Transportation, Handling, and Storage of FMLs

FMLs are usually shipped and stored at the site before being installed. The basic function of CQA inspection at this stage is to ensure that no

damage occurs to the FML and to ensure that what damage does occur is noted and eventually repaired. In particular, the CQA officer inspects the storage facilities and the conditions under which the FML is transported. Depending on the FML type, the CQA officer may need to pay particular attention to high temperature and other environmental conditions during storage prior to shipment, during shipment, and at the site prior to installation. Some FMLs, e.g. those based on CSPE and CPE, are sensitive to moisture and heat; these FMLs can partially crosslink (making the FML more difficult to seam) or block (a phenomenon that occurs when an FML sticks to itself while being stored rolled or folded, resulting in delamination or ripping when the FML is unrolled) under improper storage conditions before being installed in the field. A CQA officer should inspect all facilities intended for storage of FMLs. In cases where the FML will be stored in direct contact with the ground, the CQA officer should inspect the ground surface to ensure that it is relatively level, smooth, and free of rocks, holes, and debris.

The CQA officer should inspect the manufactured rolls or fabricated panels to ensure that their identification labels include the following, depending on the type of FML:

- Name of manufacturer/fabricator.
- FML type, including polymer type and details of construction (e.g. number of plies, type of scrim, nominal thickness, etc.).
- Manufacturing batch code (of rolls).
- Panel number or placement according to the design layout pattern.
- Date of manufacture (of rolls) or date of fabrication (of panels).
- Physical dimensions (length and width).
- Directions for unrolling or unfolding of the FML.

For FMLs that have been fabricated into panels, documentation identifying the rolls used in a specific panel may also be required so the results of CQA inspection testing of the rolls can be correlated with the panels being installed in the facility.

Once the FML is received at the job site, all documentation should be checked to verify receipt of the FML. The FML should be inspected to ensure that it is not damaged and that any damage that has occurred is noted and corrected. In addition, the auxiliary materials that are used in the seaming, e.g. adhesives or welding materials, should be visually inspected to ensure that the correct materials are on hand as required by specifications.

Other considerations in the CQA of on-site unloading and storage of FMLs are discussed by Wright et al (1987).

10.4.5 Inspection of FML Installation

Installation of the FML involves bringing the FML to the site, unrolling or unfolding it, seaming the adjacent panels or sheets together, anchoring the FML in trenches or attaching it to a structure, and finally covering the liner with an upper bedding layer as required by the design. CQA activities involved in each of these steps are discussed in detail by Wright et al (1987). CQA inspection of the leachate collection and removal systems is described in Section 10.5.

10.4.5.1 Inspection of FML Placement--

Placement of the FML at the job site involves:

- Transporting the rolled or folded FML to the work area.
- Removing the FML from the packaging.
- Spreading the FML over the subgrade in accordance with the design layout pattern.

CQA inspection of the placement of the FML should include:

- Final inspection of the subgrade surface and the anchor trenches.
- Inspection of the equipment for unloading the FML, including making sure that it is of the appropriate type and that an appropriate quantity is available at the site.
- Checking the number and qualifications of the personnel involved in laying out the FML and the appropriateness of their clothing (e.g. gloves, footwear, etc.).
- Making sure that proper procedures are followed during FML layout, including making sure that the FML is laid out under the proper weather conditions.
- Confirming that placement of panels or rolls is in accordance with the design layout plan. In cases in which specific rolls are not assigned specific placement in the plan, the "as built" drawings should identify the actual placement of individual rolls.
- Visually inspecting the entire surface of each roll or panel for tears, punctures, etc., as it is placed. Any defects that are noticed should be marked for repair.
- Cutting out a sample of the FML and giving it to the owner/installer for future reference.

- Confirming that the overlap between adjacent rolls or panels meets specification and making sure that there is proper temporary anchorage of the FML prior to seaming and covering.
- Keeping a daily record of weather conditions and other factors, such as those indicated in the next section.

In addition, photographing the critical steps in the liner installation is also recommended.

10.4.5.2 Inspection of FML Field Seams--

The success or failure of the liner installation depends to a great extent on the integrity of the field seams. As is discussed in Section 9.3.5, job site factors have been found to influence field seaming operations, which are largely manually controlled (i.e. they are not automated) include:

- The ambient temperature at which the seams are produced.
- The relative humidity.
- The amount of wind.
- The effect that clouds have on the FML temperature.
- The moisture content of the subgrade underneath the FML.
- The supporting surface on which the seam is bonded.
- The skill of the seaming crew.
- The quality and consistency of the adhesive, if an adhesive is used.
- Proper preparation of the FML surfaces to be joined.
- The cleanliness of the seam interface, i.e. the amount of airborne dust and debris present.
- The ease in handling seaming equipment, if seaming equipment is used.

Inspection activities that should be documented during field seaming operations include (Northeim and Truesdale, 1986):

- Observations to ensure that the FML is free from dirt, dust, and moisture.
- Observations to ensure that the seaming materials and equipment are as specified.
- Observations to ensure that a proper foundation is available for seaming.

- Observations of weather conditions (e.g. temperature, humidity, wind) to ensure that they are acceptable for seaming.
- Measurements of temperatures, pressures, and speed of seaming, when applicable, to ensure that they are as specified (e.g. gages and dials should be checked and readings recorded).
- Observations to ensure that the FML is not damaged by equipment or personnel during the seaming process.

All seams should be subjected to 100% visual inspection and to non-destructive testing in accordance with the CQA plan. Methods of non-destructive testing are discussed in Section 9.3.6. These methods are basically to measure the continuity of the seams and include vacuum box, air pressure, ultrasonic spark, and air-lance, and probe methods. Depending on the method of seaming and the type of testing, seams may need time to develop strength before being tested.

Since nondestructive tests only measure seam continuity and not seam strength, seam samples should also be subjected to destructive testing. Samples should be taken on a frequency basis. The minimum number of samples per seam length per seam crew and the procedures for determining sample locations should be stated in the CQA plan. For example, Wright et al (1987) report that one destructive seam sample per 152.5 m (500 ft) of field seam is normally required. Additional samples may also be required at the discretion of the CQA officer due to suspicions about contamination by dirt or moisture, variations in appearance, changes in seaming materials, an increase in failures resulting from nondestructive testing, etc. The level of sampling ultimately should depend on the level of variability in the seaming procedure. Thus, different seaming procedures may require different levels of sampling. In addition, the level of sampling may also depend on the location of the installed liner. For example, more samples may be required on the slopes where more difficulties in seaming arise than on the level part of the liner at the bottom. As field seaming techniques become more automated, the required level of sampling may decrease.

There are two types of samples that can be tested destructively: samples that are cut directly out of the installed liner (destructive samples) and samples that are made separately alongside the actual seam at the time the seam was made (nondestructive samples). Nondestructive samples include both field-fabricated start-up seam samples and random field-fabricated samples, as required in the specification. Start-up samples are made at the beginning of a shift using the same methods and equipment as those used to seam the installed liner. Random field-fabricated samples can be made either on a frequency basis (i.e. one per unit length of actual installed seam) or at the discretion of the CQA inspector. These seams should be made by the same personnel under the same conditions using the same techniques and equipment as those used in seaming the actual liner at the time the sample is requested. The limitation of nondestructive sampling is that the test results give only a partial indication of the quality of the actual seam. They

indicate whether the personnel or seaming equipment performed adequately at the time and under the conditions of sample fabrication.

On the other hand, destructive sampling, which allows testing of the actual fabricated seam, results in damage to the liner in the process of taking the sample which must be repaired. Because of this damage to the liner, Wright et al (1987) recommend nondestructive sampling over destructive sampling of field seams except in the following situations:

- When there is an insufficient number of CQA inspectors to observe each seaming crew full-time.
- When the results of testing nondestructive samples indicate poor seam quality.

Nevertheless, they recommend testing a minimum of one destructive sample per seaming crew per day per day. Most specifications covering liner installation and seam testing require some destructive sampling.

In fabricating nondestructive samples, care should be taken so that there is sufficient free overlap to allow peel testing of the seam. At the time a destructive sample is taken, or a nondestructive sample is fabricated, its location in the liner or in relation to the actual seaming should be indicated on the "as-built" drawing.

The required size of the seam sample for destructive testing will depend on the number of parties involved in testing that particular sample. Samples can be tested in the field by a field tensometer, tested by the CQA laboratory, and tested by the installer's laboratory. In addition, a portion of the sample may be retained for the facility owner's archives for future reference. For full testing by a single laboratory (five specimens in peel and five in shear), an 18-in. length of seam is needed for unreinforced FMLs and a 30-in. length for fabric-reinforced FMLs. The minimum width is 6 in. of FML on both sides of the seam plus the seam width (i.e. 1 ft plus the seam width).

Identification of samples sent to a QC/QA laboratory should include the following:

- Type of FML, including thickness.
- Project name.
- Cell identification, if a liner is being installed in more than one cell at a particular facility.
- Seam identification or identification of adjacent panels and location on seam so that the location from which the sample was taken can be easily identified on the site layout pattern.
- Crew identification.

- Machine identification (if applicable).
- Date of fabrication.

The date of fabrication is particularly important in testing seams made with adhesive- or solvent-based methods so that the samples can be tested after the correct amount of time.

For the purposes of CQA testing, the test area of the seam may need to be precisely defined. For example, in the seaming of HDPE FMLs using fillet-weld techniques, the two sheets to be seamed together are sometimes tacked together by thermal means. Since the hot-tack operation is usually a relatively uncontrolled operation, the hot tack area should not be considered part of the seam and should be delaminated prior to testing, when possible.

In performing CQA destructive testing of field seam samples, laboratory testing of the samples is ultimately preferred over field testing because of the greater control over the testing conditions that is possible in a laboratory. Variations in test conditions could significantly affect test results. CQA inspection testing of seams will always ultimately rely on laboratory results.

The criteria for passing or failing a seam sample should be stated clearly. Examples of criteria include:

- The average of all test values for a sample has to be greater than or equal to specified values in both peel and shear modes.
- The median of the test values for a sample has to be greater than or equal to specified values in both peel and shear modes. In the case where the number of specimens tested per sample per test equals five, at least three specimens would have to have test values greater than or equal to the specified value.
- Specifying a minimum number of specimens per sample that must result in test values greater than or equal to specified values in both peel and shear modes.
- Specifying a minimum number of specimens per sample that must result in the type of break required in the specifications, e.g. a film-tearing bond break, in both peel and shear modes.

The specific pass/fail criteria stated in the CQA plan will depend on how the specification requirements for the field seams are stated, i.e. on whether they are stated as minimum values, a type of break, or both.

Information about the specific ways in which specimens broke during destructive testing has been found to be valuable in determining whether a specific break is acceptable. As an aid to classifying the various types of breaks that occur in testing individual specimens, a series of locus-of-break

codes are presented in Appendix N for various types of seams. It is suggested that the appropriate group of locus-of-break codes be incorporated in the specifications along with a minimum stress-at-break value for both peel and shear modes.

Documentation of the seam test results (both destructive and nondestructive) should show that all field seams meet design specifications (Section 8.5.4). In case of any test sample failure, either by destructive or non-destructive testing, the procedures for performing the necessary corrective measures on the installed FML, e.g. capping, should be stated in the CQA plan. These corrective measures may depend on the type of sample failure. In the EPA Policy Directive on the CQA of hazardous waste land disposal facilities, Norheim and Truesdale (1986) state the following:

For field seams that fail [the test], the seam can either be reconstructed between the failed and any previous passed seam location or the installer can go on either side of the failed seam location (10-ft minimum), take another sample, test it and if it passes, reconstruct the seam between the two locations. If it fails, the process should be continued. In all cases, acceptable seams must be bounded by two passed test locations (p 36).

The repair of all seam failures should be documented.

10.4.5.3 Inspection of FML Anchors and Attachments--

All FMLs will need to be anchored in place around the perimeter of either the site or the specific cell. Failure of a perimeter anchor can lead to the collapse of a major portion of an FML installation. CQA personnel should observe anchor excavation and anchoring of the FML to ensure the following (Wright et al, 1987):

- Trench depth and width (and distance from slope, if applicable) meet specifications.
- The leading edge of the trench is smooth and free of sharp or jagged edges.
- Temporary anchoring methods (sand bags) do not damage the FML.
- FML is properly installed in the trench.
- Earth fill for the anchor trench is free of sharp rocks.
- Final backfilling and compaction operations do not damage the FML.

When a design requires penetrations through the FML (e.g. structures and pipes), CQA personnel must ensure that the attachments to the penetrations

are of sufficient strength and form liquid-tight seals. Inspections that also should be made on all attachments include:

- Observations to ensure that the materials (e.g. the pipe boots or the sealing compounds) are compatible with the waste liquid and are as specified.
- Observations to ensure that all objects placed adjacent to the FML are smooth and free of objects or conditions that may damage the FML.

10.4.5.4 Large-Scale Hydrostatic Leak-Detection Test of Installed FML--

Though a performance specification is not part of the overall specification, ultimately the operator/owner of a waste impoundment facility needs to be assured that the facility he is accepting and placing into service is liquid-tight and that the leak detection and drainage systems perform satisfactorily. None of the tests that are performed during the course of the quality assurance testing from the design through the final construction of the containment unit indicates the final performance of the liner. They indicate the compatibility of the liner with the waste, that the composition is satisfactory, and that the seams have passed inspection and destructive tests. The ultimate test is when the site is placed in service and monitored for a period of time. An actual measure of the performance of a containment unit is desirable and is a long-term goal of the liner industry.

The performance of a liner for a lined waste containment unit can, in some situations, be assessed before actual wastes are placed. For example, before a protective cover is placed on the liner (if required), the completely lined unit can be partially filled with water and observations made as to whether losses exceed evaporative losses. An electrical leak location method such as the one described by Darilek and Parra (1988) can also be used to detect and locate leaks. This technique is described in more detail in Section 11.5.3. If a leak-detection system underlies the liner, as is the case of a top liner in a double liner system, a leak could be detected by the presence of water in the sump. As the bottom liner in a double liner system will probably not have a leak-detection system below it, the evaporative method or the electrical leak location method might be used to indicate possible leakage.

To avoid false-positive results when partially filling a lined impoundment to detect leakage, it may be desirable to introduce a tracer in the water above the liner under test to ensure that the water that is observed in the leak-detection system in reality came from the test water. It would, of course, be more desirable if a facility could be filled with the test water to ascertain if there are any leaks in the system, especially in the slopes where most seaming problems occur.

The limitations of this procedure include the costs for pumping water, both in and out of the unit, and the delay in the construction schedule.

10.4.5.5 Inspection of the Placement of a Protective Cover Over the FML--

Depending on the type of liner, containment, or disposal facility and its design requirements, a layer of soil may be placed on top of the FML to protect it from weather conditions, equipment, and vandalism. Prior to placement of the soil cover, the liner should be inspected for any damage that occurred during installation. Any damage that is found should be corrected by the specified patching procedure, and the patch should be nondestructively tested. Ideally, the FML should not be covered until the FML installation is completed and accepted. However, on large jobs, portions of the liner may need to be accepted and covered prior to completion of the entire liner.

CQA inspection activities during placement of the soil cover should include:

- Observations and tests to ensure that the cover material meets specifications (e.g. as defined by the soil index tests. See Spigolon and Kelley, 1984).
- Observation to ensure that the cover material is free of rocks, sticks, and other items that could damage the FML.
- Observation of the use of equipment to unload and spread the cover material to ensure that the equipment does not damage the FML.
- Measurements to ensure that the entire liner is covered with the specified thickness of material (e.g. using grade sticks, marked measuring staffs, surveying techniques, etc.).

In cases in which other types of protective covers are used (e.g. geotextiles or portland cement concrete), or if the soil protective cover is placed on top of a leachate drainage and collection system, these inspection activities will have to be adapted accordingly.

10.5 INSPECTION OF THE INSTALLATION OF THE LEACHATE COLLECTION AND REMOVAL SYSTEMS

The purpose of a primary leachate collection and removal system (LCRS) in a landfill is to minimize the hydraulic head on the top liner during operation of the unit and to remove liquids from the unit up through the end of the post-closure care period. The purpose of a secondary LCRS (also known as a leak-detection system) between the two liners of a landfill or surface impoundment is to rapidly detect, collect, and remove liquids entering the system up through the end of the post-closure care period.

An LCRS is comprised of a number of subcomponents including:

- A drainage layer.

- A filter layer.
- A pipe network for collecting leachate or waste liquid from the drainage layer and transporting it to the sump/manhole system.
- A bedding layer for the pipe network.
- A sump/manhole system which allows collection of the leachate or waste liquid and access to the pipe network for inspection and possible repairs throughout the monitoring periods.
- Mechanical and electrical equipment for conveying the leachate from the collection system to a separate storage or treatment area and for monitoring and controlling the level of leachate above the liner.

The CQA inspection plan for each site will be site-specific because of the number of options that are available to the facility designer. Nevertheless, CQA inspection will still include observation and testing of the various materials used in constructing the collection system(s) to ensure that they meet or exceed design specifications. It is assumed that the materials that are being installed have been tested for compatibility with the waste liquid or leachate to be contained. It is also assumed that, in the case of the polymeric materials, the materials have been fingerprinted so that it can be shown that the materials being installed are equivalent to those that were tested for compatibility. In addition, CQA inspection should be performed throughout the construction of the LCRS to ensure that materials were installed according to specification. Steps in the installation of an LCRS include:

- Foundation preparation.
- Bedding layer placement.
- Pipe network installation.
- Drainage layer placement.
- Filter layer placement.
- Installation of sumps and associated structures.
- Installation of mechanical and electrical equipment.

Foundation preparation is critical. The horizontal and vertical alignment of the foundation should be measured prior to placement of drainage materials to ensure that the leachate will be able to flow toward the sump (Bass, 1986). All granular materials that will contact the FML should be inspected to

ensure they do not contain objects that would damage the FML. In addition, all granular materials used in the LCS should be inspected for fines which could clog the system.

When the pipe network is installed, the layout should be observed by CQA personnel to determine whether it conforms to the design drawings, and observations and tests should be made to ensure that all pipes are joined as planned. Integrity of all joints should also be determined. Television equipment mounted on skids can be used to verify that the alignment and overall condition of the line is satisfactory. If the pipes were not adequately protected from soil fines during construction, the pipe network may need to be flushed to remove any debris that may have accumulated and to verify that the lines are open. Standard sewer cleaning equipment can be used to determine if any pipe segments have been crushed or damaged during placement of bedding and drainage materials. Backfilling and compaction over the the collection network must be observed by CQA personel to ensure that damage to the pipe network has not occurred. Bass (1986) recommends a second inspection of the liner using photographic or television equipment after compaction of the first layer of waste or soil. When manufactured materials such as geosynthetics and geonets are used, they should be inspected to ensure the overlaps and field seams or other joining methods have been performed as specified. If geonets are included in the design, the placement of the layer directly above the geonet should be observed to ensure that debris does not enter the drainage system.

All electrical controls within the LCRS should also be inspected. All pumps must be tested to ensure that they are operating at rated capacity, and any monitoring equipment must be thoroughly checked out to determine conformance with specifications.

Appendix M lists CQA activities for the placement of leachate collection systems.

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CHAPTER 11

MANAGEMENT, MONITORING, AND MAINTENANCE OF LINED WASTE STORAGE AND DISPOSAL UNITS

11.1 INTRODUCTION

Proper management of the operation of a lined waste containment unit is necessary if the unit is to perform properly and the design criteria and the maximum life of the liner system are to be realized. In managing lined containment units it is necessary to:

- Protect the integrity of the containment unit and the lining system.
- Develop standard operating procedures and define them in an operations and maintenance manual.
- Monitor the overall performance of the lining system to determine whether it is operating within the design criteria and is not failing, i.e. by monitoring the groundwater, the leachate collection and removal system (LCRS) between the liners, etc.
- Inspect the condition of the liner to determine if any abnormal swelling, degradation, or changes in properties have occurred.
- Inspect periodically other critical components of the containment unit, e.g. the LCRSs, the embankments, etc.

The operational period of a containment unit can last less than 1 year up to approximately 10 years. During this period, management focuses on the following areas:

- Control of incoming wastes into the containment unit.
- Monitoring the performance of the liner system, its components, and the earthworks, including the condition of the in-place liner.
- Maintaining and protecting the liner, the earthworks, and subsystems such as the LCRSs.
- Training of personnel.
- Maintaining a logbook of incoming wastes, repair and maintenance activities, etc.

Following the operational period, a landfill is closed by placing a final cover over the landfill in accordance with regulatory requirements, e.g. 40 CRF 264, Subpart G for the closure and post-closure of hazardous waste containment units (EPA, 1986a). The maintenance of the landfill must continue during the construction of the final cover and through the post-closure care period (PCCP), which lasts a minimum of 30 years. During this period, the owner/operator must:

- Maintain the integrity and the effectiveness of the final cover, including making repairs to the cap as necessary to correct the effect of settling, subsidence, erosion, or other events.
- Continue to operate the LCRSs until no leachate is produced.
- Monitor the condition of the components of the liner system.
- Maintain and monitor the groundwater monitoring system.
- Maintain the vegetative cover and prevent run-on and runoff from eroding or otherwise damaging the final cover.
- Protect and maintain surveyed bench marks.
- Continue to document maintenance, problems, and corrective measures taken during the PCCP.

This chapter describes measures that need to be taken in managing landfills and other containment units from the time operations commence through the operational and post-closure care periods. These measures include the standard operating procedures that must be developed at the time the permit application is prepared. These operating procedures include control of the incoming waste; monitoring the overall performance of the waste containment unit; monitoring, maintaining, and repairing the components of the lining system, including the LCRSs, the in-service liners, and the earthworks; and maintenance of the final cover system.

11.2 STANDARD OPERATING PROCEDURES FOR A WASTE STORAGE AND DISPOSAL UNIT

The three basic types of containment units are:

- Surface impoundments.
- Solid waste landfills.
- Waste piles.

Some standard operating procedures are applicable for all three types of containment units; other procedures are specific to a single type. For instance, all units designed and constructed with double liners will have leak-detection systems between the two liners which must be monitored

and maintained. Surface impoundments generally are storage units and are all open to the atmosphere, though the top FML liner may or may not be exposed to the weather depending on whether the liner is protected by a soil or other type of cover. In the case of landfills, the liners will be buried for most of their service lives.

Several standard handbooks and manuals are available on operating MSW containment facilities (EPA, 1978; ASCE, 1976; EPA, 1973); however, particularly in the case of lined containment units, additional information should be incorporated in the standard operating procedures manual for the specific facility. The additional requirements and procedures in an operating manual should reflect the specific types of materials that were used and "as-built" construction details.

The operating and procedures manual for a specific unit should be prepared by the design, construction, and operations team and should include, as a minimum, the following:

- Operation and maintenance staff requirements and structure.
- Facility description and design parameters with "as-built" drawings.
- Response action plans, including emergency shutdown procedures.
- Operation variables and procedures, including methods of placing materials into the unit and inspection schedules.
- Facility troubleshooting procedures.
- Preventive maintenance and requirements.
- Specialized maintenance and monitoring procedures, e.g. after a storm.
- Plant personnel safety requirements and procedures.
- Equipment maintenance records.
- Site inspection records.
- List of permissible wastes.
- List of unacceptable wastes.
- Master file noting changes such as additions, revisions, or deletions to procedures.

Certain operational procedures are not acceptable if the integrity of the lined containment unit is to be maintained. These procedures include, but are not limited to, the following:

- The discharge of high-temperature waste liquids onto exposed or

unprotected FMLs, i.e. FMLs with no soil cover or with insufficient standing liquid levels.

- The passage of any vehicle over any portion of an exposed FML.
- The discharge of incompatible wastes into the unit.
- The discharge of wastes directly onto an FML without adequate provision for energy dissipation, e.g. a splash pad, splash tubes, etc.
- Unauthorized modifications or repairs to the unit.

Preventing damage to the liner is extremely important since reliable repair of a waste exposed FML, in almost all cases, is not feasible (Haxo, 1987).

Inasmuch as the technology for lining waste containment units is relatively new and basic experience is limited, good records need to be kept of the performance of a unit. Problems and difficulties as well as the results of routine inspections should be noted.

11.3 INFORMATION ON DESIGN, CONSTRUCTION, AND MATERIALS OF CONSTRUCTION

Detailed information regarding all of the components of the liner system should be available to the operating personnel during the operational period and to caretaker personnel of a closed landfill during the PCCP. Availability of copies of the "as-built" drawings of the containment, detailed information on the liner system, i.e. the FML and all components of the leachate drainage, collection, and leak-detection systems, is particularly important. This information should include data on the original characteristics and properties of all components, and the reports of the compatibility tests, e.g. those performed in accordance with Method 9090 (EPA, 1986b). This information should be supplied by the designer of the unit as a package from data he has developed in his investigation of the site and from data furnished by the manufacturer of the liner, the installer, and the construction contractor. This information should include the data generated during the implementation of the construction quality assurance plan, which is discussed in Chapter 10.

Samples of the liner material and other components of the lining and leachate collection and removal systems should be retained for possible use in case the containment unit malfunctions. A full discussion should be included in the package as to the compatibility limitations of the liner material. The material was selected on the basis of its compatibility with the wastes which it will contain; consequently, deviations in the waste composition from the anticipated composition should be avoided. Information of this type should be incorporated into the operating manual and into the operator training program.

11.4 CONTROL OF INCOMING WASTE

As indicated in the above section, the composition and character of the waste needs to be controlled to avoid possible damage to the liner system. Legal restrictions mandate that control must be maintained of the hazardous materials placed in a containment unit to prevent improper disposal of a waste. However, materials that are potentially aggressive to the lining system also need to be controlled. Analyses should be performed on incoming wastes to determine whether these wastes meet regulatory criteria for land disposal or disposal at the particular containment unit and whether the wastes contain constituents that may be aggressive to the lining material. It should be noted that present EPA regulations require waste generators to test their waste to determine whether it is restricted [40 CFR 268.7 (EPA, 1986c)]. However, as is discussed in Chapter 2, this testing may not be sufficient for determining whether or not constituents that may be aggressive to lining materials are present. Compatibility of the incoming waste with the wastes already in the containment unit should also be assured. The added waste may have a synergistic and damaging effect on the materials of the liner system. Reference should be made to the analysis of the leachate or waste liquid used in performing the compatibility tests during the design and permitting stage. The operator should develop a knowledge of the types of industries in the area to be aware of those materials that he may be asked to dispose of.

According to current RCRA regulations [40 CFR 264.314 (1986 ed)], wastes containing free liquids including those placed in drums, can no longer be placed in a hazardous waste landfill. The absence of free liquids has to be demonstrated by the "Paint Filter Liquids Test," EPA Method 9095 (EPA, 1986b). All free-standing liquid needs to be removed from the waste or solidified and stabilized by soil, by a suitable dry absorbent, or by addition of selected chemicals before disposal in a hazardous waste landfill.

The effects of EPA regulations and current and future waste management practices on the composition of wastes and waste liquid that are stored or disposed of on land are discussed in Chapter 2.

In order to know the contents of a hazardous waste containment unit at any given time, records need to be kept of the particular wastes placed in the unit, as is required by EPA regulations [40 CFR 264, Subpart E (1986 ed.)]. In addition, the organic and inorganic constituents that are aggressive toward liners should also be recorded, and significant amounts in the landfill should be avoided.

The waste leachate or waste liquid should be analyzed periodically in order to determine the current composition. Chemical reactions and volatilization of the constituents within the unit will probably cause continual change in the composition of the contained liquid in direct contact with the lining system.

Adequate procedures for placing wastes in the unit should be incorporated in the design. Over-the-edge dumping of wastes should be avoided, as should the addition of hot wastes, particularly liquids, directly on a

liner. "Sacrificial" covers made of the same material as the liner have been used on slopes to protect a liner from damage when wastes are dumped over the edge. These covers can be inspected regularly and replaced when they have deteriorated, but they must be replaced with a sheeting of the same composition as the liner or one that is known to be compatible with the liner. For example, ingredients from one type of FML can migrate and damage a second type with which it is in contact. Specially designed covers and troughs have also been used for protecting the main liner during addition of waste to a lined unit. Designs for placing liquid wastes in surface impoundments are discussed in Chapter 7.

11.5 MONITORING THE PERFORMANCE OF THE WASTE CONTAINMENT UNIT

The principal purpose of a lined containment unit is to contain a waste and control the escape of pollutants from the unit. The performance of such a unit is measured by its ability to prevent uncontrolled migration of waste constituents into the environment, particularly the groundwater. Although performance monitoring for the lifetime of a containment unit is relatively new and no method has been proven 100% effective in detecting leaks, techniques are available that can increase confidence that a unit is functioning as designed. These techniques range in complexity from groundwater monitoring with monitoring wells to "high tech" geophysical systems that can determine the point source of a leak.

Monitoring techniques can be divided into four types:

- Generalized leak-detection techniques based on observation of the leak detection and drainage system constructed between the liners of a double-liner system.
- Areal monitoring techniques which monitor the soil and groundwater in the containment area.
- Point source leak-detection techniques which can detect a leak and locate its source.

11.5.1 Leak Detection by a Secondary Leachate Collection and Removal System (LCRS)

Present EPA regulations require an LCRS between the two liners of a hazardous waste containment unit (40 CFR 264). This system, also known as a secondary LCRS, is designed to intercept any liquids that may bypass the top liner system and remove them for treatment and/or disposal. Thus, the secondary LCRS monitors the performance of the top liner. Insofar as a secondary LCRS not only detects leaks but collects and removes the liquids present in the LCRS, it is also an integral part of the lining system as a whole which is designed to control the migration of waste constituents. The design of secondary LCRSs is discussed in Section 7.5.4.

In recently proposed regulations, the EPA proposes requiring the owner/operator of a hazardous waste containment unit to develop site-specific

response action plans (RAP) which establish operating procedures given a rate of leakage through the top liner system (EPA, 1987a). The objectives of the proposed regulations in combination with the double-liner design are:

- To detect leaks in the top liner at the earliest possible time.
- To contain the leakage within the engineered structure of the unit.
- To prevent groundwater contamination when technically feasible and thereby obviate the need for corrective action.

The EPA considers a secondary LCRS the best available system for monitoring the performance of a lined containment unit and for detecting and collecting leakage through a top liner. An RAP goes into effect when a site-specific action leakage rate (ALR) has been exceeded. The ALR constitutes a trigger for initiating interaction between the owner/operator and the EPA. The ALR is based primarily on leakage rate rather than leachate/waste liquid quality because:

- Leakage rates allow for faster processing of data.
- Changes in rates of leakage are more indicative of progressive changes in the condition of the top liner.
- Leakage rates are more indicative of the severity of a breach in the FML.

The EPA has proposed an ALR of 5 to 20 gal per acre per day, which the EPA believes is representative of a high level of CQA at a hazardous waste containment unit. The EPA also proposes allowing an owner/operator to develop a site-specific ALR value.

In the proposed regulations, RAPs are required for at least two leakage rates:

- Rapid and extremely large leakage (RLL), which is defined as the maximum design leakage rate that the secondary LCRS can remove under gravity flow conditions.
- Leaks less than rapid and extremely large but greater than the ALR.

For leaks that exceed the ALR but are less than rapid and large, the EPA considers acceptable responses to include:

- Terminating receipt of waste and closing the unit (or part of the unit).
- Repairing any leaks expeditiously.
- Instituting operational changes to reduce leakage into the secondary LCRS.

- Increasing the pump capacity to allow more rapid collection and removal of leachate, and, in addition, increasing groundwater monitoring.
- Maintaining current operating procedures (including the collection and removal of leachate).

Different responses can be established for different bands of leakage rates. The range of appropriate responses to rates greater than or equal to an RLL rate can be the same as those in response to leakage rates less than RLL. Appropriate responses include:

- Terminating receipt of waste and closing the unit.
- Repairing the leaks expeditiously, including possibly retrofitting another liner on top of the existing system.
- Instituting operational changes to reduce leakage into the secondary LCRS.

Elements of an RAP include:

- General description of unit.
- Description of waste constituents.
- Description of all events that may cause leakage.
- Discussion of factors affecting amounts of leakage entering LCRS.
- Design and operational mechanisms to prevent leakage of hazardous constituents.
- Assessment of effectiveness of possible response actions.

11.5.2 Areal Techniques

11.5.2.1 Monitoring Wells--

By far the most common areal tool for monitoring a waste containment unit is the monitoring well. This tool is considered by many to be indispensable, since it ultimately provides "ground truth" as to the presence of waste constituents in the groundwater. Typically, water samples are drawn from the wells at some set interval and analyzed for the presence of contaminants. Construction details for a single well are presented in Figure 11-1. Multilevel well nests can be used to sample the groundwater flow at several distinct levels, as is shown in Figure 11-2.

Monitoring wells have certain limitations, however. Placed in the groundwater, a well does not reveal the presence of contaminants until they have migrated from the unit through the underlying soil to the groundwater itself; this process can take extensive periods of time, since groundwater

moves very slowly. By the time contamination is detected, a significant amount of damage may have occurred, which can mean that a significant amount of cleanup is required, and potential liability has been incurred. Furthermore, the information resulting from a monitoring well only pertains to the conditions of the groundwater that has contacted that particular well and may not actually represent conditions even a few meters away. A schematic of the limitations of a single monitoring well screened through a large vertical section of a thick, uniform aquifer is presented in Figure 11-3. Ultimately, the effectiveness of a groundwater monitoring plan is dependent on the accuracy of the geohydrologic studies performed during the site investigation and design phases (see Section 7.4), together with assumptions about the effects of locating the containment unit in the geohydrologic regime and potential location of leaks in the lining system.

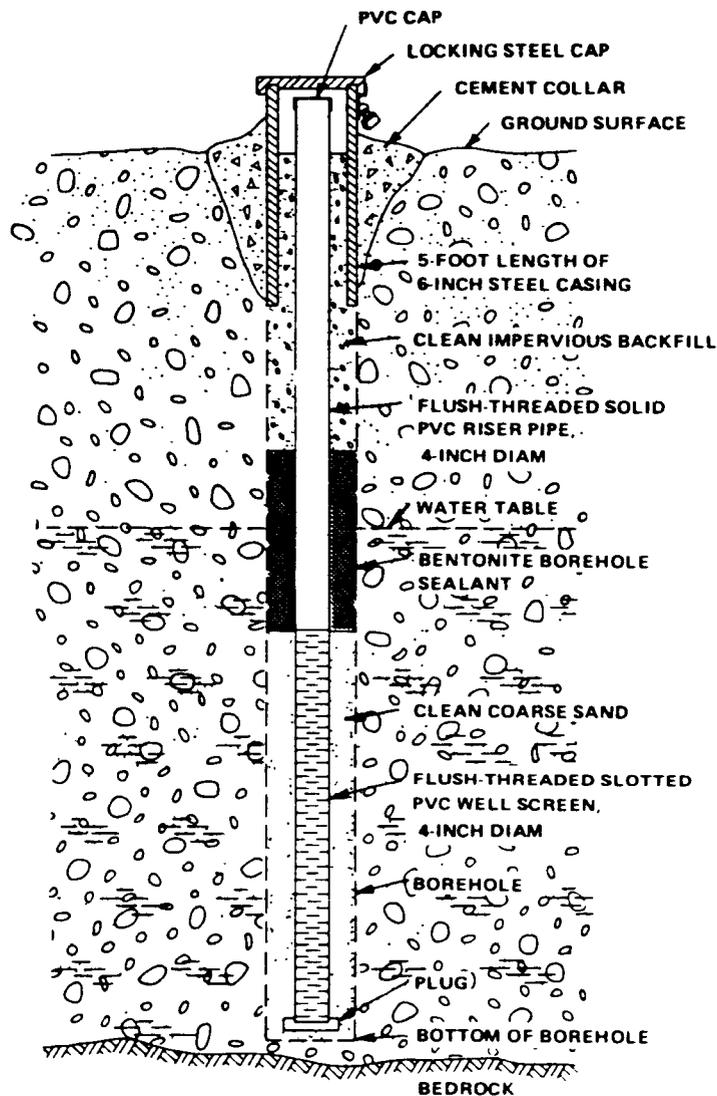


Figure 11-1. Construction details for a sample monitoring well in which the screen is located entirely within an unconsolidated aquifer of sand and gravel. (Source: EPRI, 1985, p 5-28).

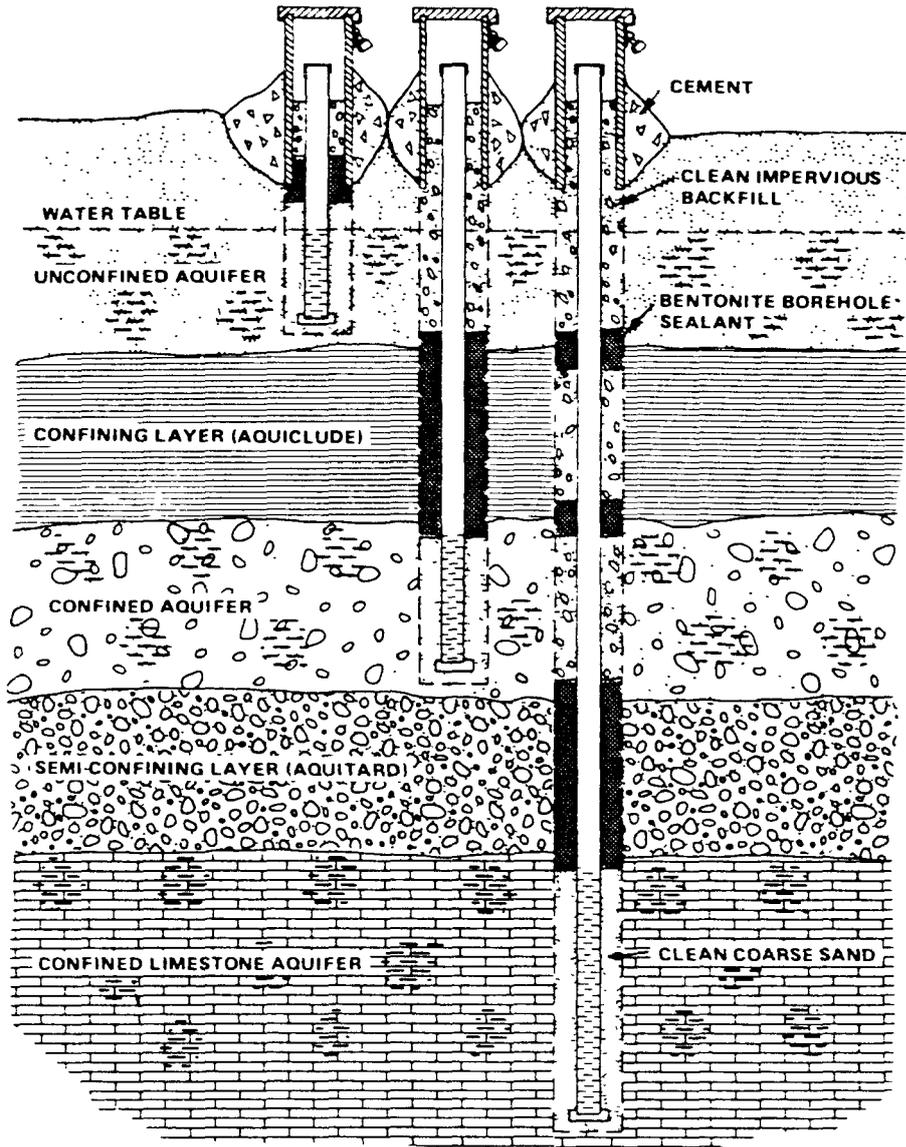


Figure 11-2. Multilevel sampling wells installed in individual, small-diameter boreholes for monitoring groundwater quality in three distinct aquifers. Well construction details are presented in Figure 11-1. (Source: EPRI, 1985, p 5-33).

In designing a groundwater monitoring plan, an engineer must include the following elements (Boutwell, 1988):

- The well system design, including the location of the wells, the depth at which the wells are screened, the method of constructing the wells, and the materials out of which the wells are to be constructed.
- A plan for sampling the wells and analyzing the samples.

- A plan for assessing the data from analyzing the monitoring well samples.

Ideally, wells are located such that the concentrations resulting from a leak anywhere in the lining system will be detectable at one or more monitoring wells. A plan for placing the wells is developed using available equations or computer models to optimize proximity to the regulated unit and proximity to major flow path in order to achieve a minimum probability that a leak will be detected. The depth of an individual well depends not only on the depth of the aquifer to be monitored but also on the depth within the target aquifer to be screened. The vertical placement of well screens should be based on a calculated vertical distribution of the contaminants that potentially may leak from the containment unit and appear in the aquifer at the well site. Elements in the design of a single well are discussed in Section 7.5.7.8. Further discussion on the design and construction of monitoring well systems, plans for sampling the wells and analyzing the well samples, and methods of assessing data from monitoring wells can be found in Sanders et al (1983), EPRI (1985), EPA (1986d), Barcelona et al (1987), U.S. Army Toxic and Hazardous Materials Agency (1987), Nielsen (1987), and Keely and Boateng (1987a and 1987b).

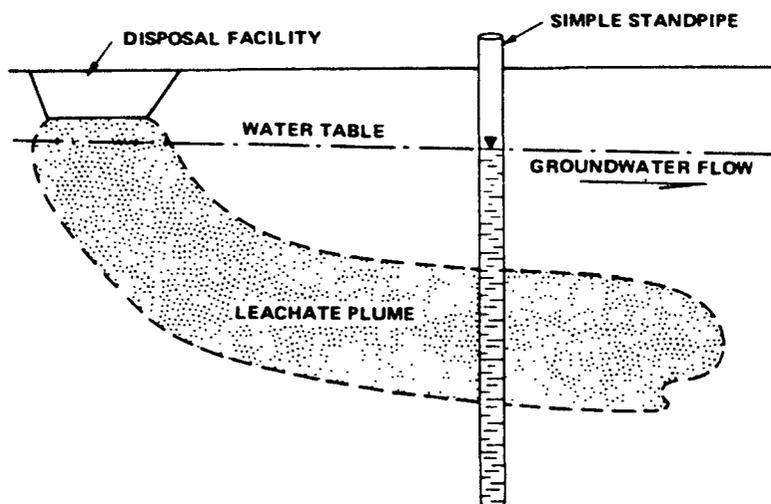


Figure 11-3. Illustration showing a disadvantage of using a single monitoring well screened through a large vertical section of a thick, uniform aquifer. A water quality sample from this well would not accurately represent concentration levels of contaminants in the thin leachate plume due to dilution with uncontaminated groundwater. (Source: Fetter, 1983, p 63).

Monitoring the soil gas and soil pore water in the unsaturated (or vadose) zone is highly desirable because it can allow the detection of contaminants, particularly volatile organic compounds in the case of soil gas, prior to groundwater damage (Kirschner and Bloomsburg, 1988). One device used to sample soil pore water is a suction or pressure-vacuum lysimeter which consists of a porous cup attached to tubing that runs to the

soil surface. By creating a vacuum from the surface in the tubing, liquid can be pulled from the surrounding soil through the porous cup and then removed and analyzed (Figure 11-4). Like monitoring wells, lysimeters only sample a very localized point, and the contaminant must intersect the lysimeter in order to be detected. One potential difficulty with lysimeters is that they have been found to plug readily. Further information on monitoring in the unsaturated zone can be found in Everett (1981), Wilson (1981, 1982, and 1983), Marrin (1988), and Kerfoot (1988).

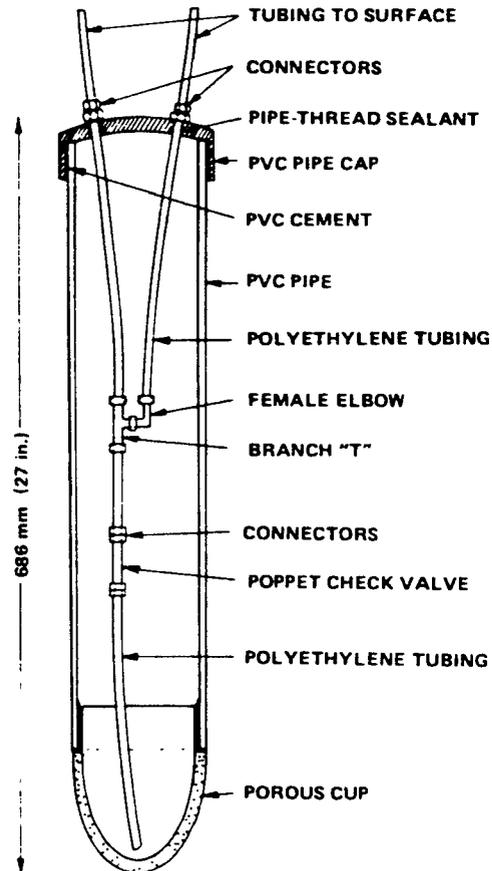


Figure 11-4. Pressure-vacuum lysimeter is installed in a borehole for collection of water samples from the zone of aeration. (Source: Woods, 1973).

11.5.2.2 Electrical Conductivity Surveys

A geophysical technique that has been used to monitor the unsaturated zone and the groundwater is the conductivity survey using electromagnetic induction methods. In this type of survey, an electromagnetic field is transmitted into the subsurface, and the generation of a secondary electromagnetic field resulting from the presence of contaminant plumes, buried metallic objects, bedrock fracture zones, etc., will be indicated by variations in the subsurface conductivity. Figure 11-5 schematically presents a

two-coil electromagnetic induction apparatus. The transmitter coil induces an electromagnetic field of known strength, and the receiving coil detects distortions in the primary field resulting from a secondary field generated by transmitting the primary field through an anomalous conducting body. Of particular interest is the possibility that this technique can be used to detect changes over time in the electrical conductivity of the soil pore water resulting from an increase in the water content of the soil or changes in the ionic content of the soil pore water, both of which could result from the escape of constituents from a waste containment unit. The type of instrument selected for use will depend on the range of subsurface depths of interest.

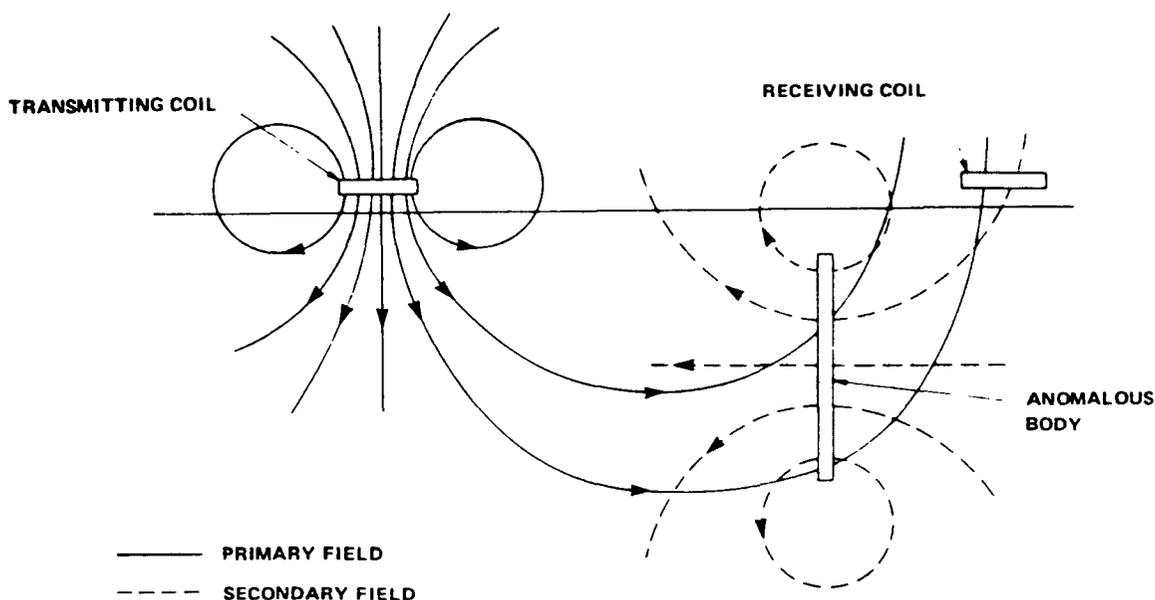


Figure 11-5. Two-coil electromagnetic induction apparatus. (Source: Griffiths and King, 1981)

Using a conductivity meter, or electromagnetic induction apparatus, one or two operators walk the site taking conductivity readings over a previously defined grid pattern. If liquids of higher or lower conductivity than the in situ pore water have entered the soil this will be indicated by a change in conductivity values. A wide area can be profiled almost as fast as an inspector can walk. Furthermore, with selection of correct instrumentation it is possible to use one instrument to monitor the unsaturated zone and a second instrument, designed for greater depths, to monitor the groundwater. If questionable areas develop, one can decide to profile at deeper depths or to zero in on a specific area more intensively with additional instrumentation. Griffiths and King (1981), Waller and Davis (1983), E.C. Jordan (1984), and EPRI (1985), discuss this type of site surveying in detail.

Ideally, electrical conductivity surveys of the site should be performed prior to unit construction and again immediately after construction to determine background levels. The site can then be surveyed every three to six months to compare new data with the original background values. If changes or trends develop in the unsaturated zone they can be watched and investigated further.

At the present time, this type of survey probably offers the quickest and least costly method available and provides the most readily interpretable areal data. The effectiveness of this type of survey, however, depends on certain site-specific conditions. If the site is highly conductive to begin with (as most appear to be), large anomalies in conductivity will be necessary before a leak will be detected.

11.5.3 Point Source Leak-Detection Techniques

So-called point source methods are techniques that can determine the existence of a leak and zero-in on its location so that the leak can be repaired. Two undergrid systems, one of which uses acoustical emission monitoring (AEM) techniques and another which uses time-domain reflectometry (TDR) techniques, and a pole-dipole electrical resistivity (ER) technique have been evaluated (Waller and Singh, 1983; Shultz et al, 1984). The undergrid systems must be designed and built into a site, and can potentially be used with any type of liner. These systems cannot be retrofitted, except possibly where an existing lining system is overlain by another liner. The ER technique can be used in an existing site, but requires the insulating properties of an FML in order to pinpoint the site of a leak.

AEM techniques have been successfully used to detect instabilities in dams and slopes, retaining walls, footings, and underground mines, etc. by detecting subaudible sound waves caused by the release of stored elastic-strain energy in stressed materials. AEM has been suggested as a method of detecting leaks based on that fact that transducers (e.g. microphones, piezoelectric sensors) can be used to detect and monitor low frequency vibrations caused by turbulent flow (velocity greater than 0.04 in. s^{-1}) through soil. Thus, AEM can be used to detect and monitor the sound of waste liquid or leachate moving through drainage media or leaking from the containment unit (E. C. Jordan, 1984; Davis et al, 1984; Koerner et al 1984). A schematic showing AEM equipment with a single sensor is presented in Figure 11-6, and a schematic showing the installation of an AEM sensor between the two liners of a double-lined surface impoundment is presented in Figure 11-7. AEM as a technique for leak detection has had only limited field testing. Potential drawbacks of AEM techniques for use in detecting leaks include:

- Sensors and lead wires may corrode during the active life and the post-closure care period of the unit.
- AEM may not detect small leaks or low velocity leaks where flow is not turbulent.

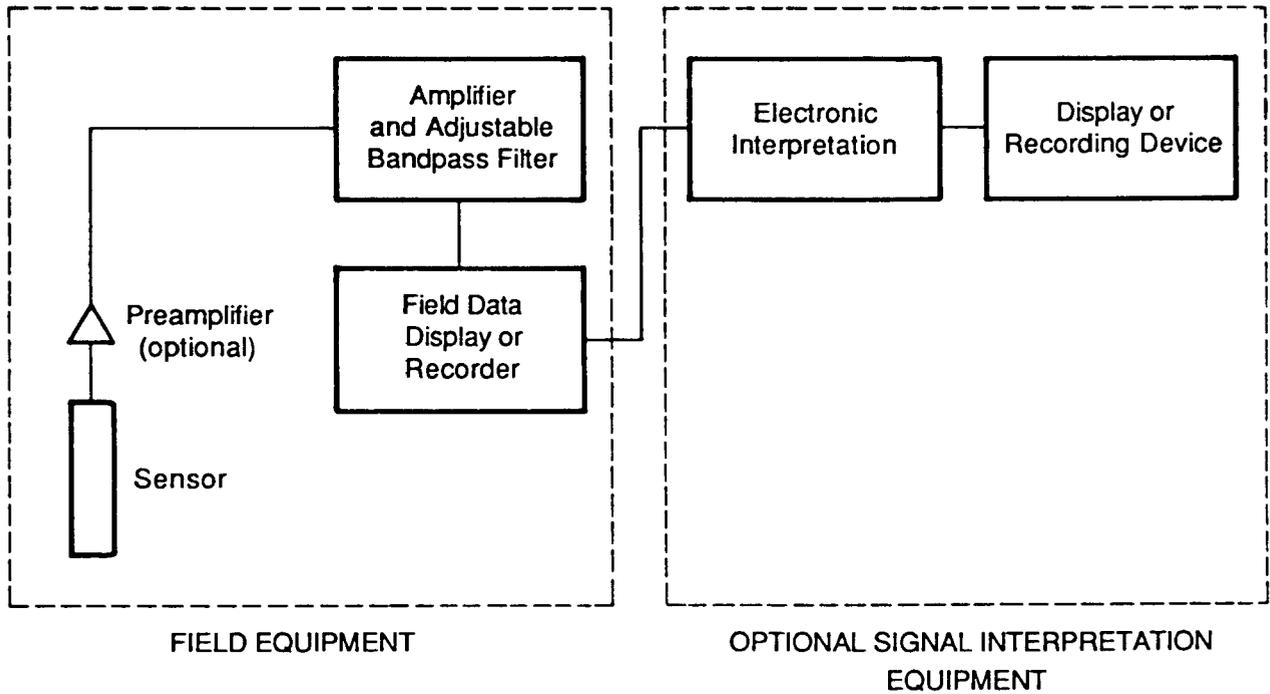


Figure 11-6. Schematic of single channel AEM equipment. (Based on E. C. Jordan, 1984, p 82).

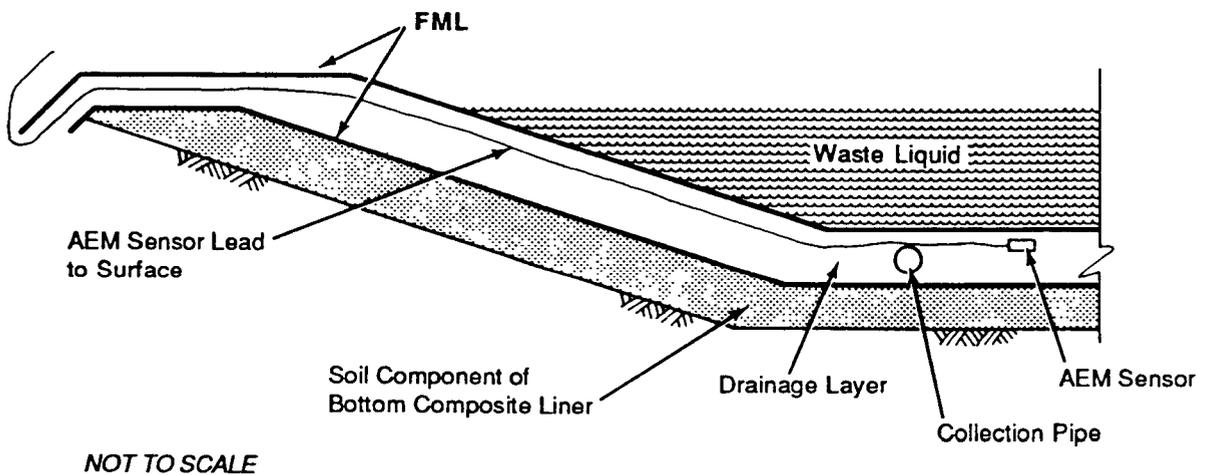


Figure 11-7. Schematic showing installation of an AEM sensor below the top liner in a double-lined surface impoundment. (Based on E. C. Jordan, 1984, p 85).

- AEM is sensitive to background noises, e.g. nearby equipment or machinery.
- The AEM system must detect a leak within a few minutes of occurrence before the sound intensity diminishes to threshold values. Because of this, continuous monitoring is required.

TDR techniques measure the electrical property variations in a material along a pair of parallel transmission line conductors. Because TDR is sensitive to soil moisture, it is attractive for leak detection. A conceptual illustration of a TDR installation is presented in Figure 11-8. Potential drawbacks of TDR techniques include:

- The wires must be installed in sand with a moisture content low enough to provide an adequate contrast between unwetted and wetted sand.
- The wires may corrode.
- Although a drainage layer of well-compacted medium-to-fine grained sand increases horizontal dispersion of a leak, thus increasing the TDR response, too much fine sand rapidly attenuates the TDR signal and is not desirable for drainage.

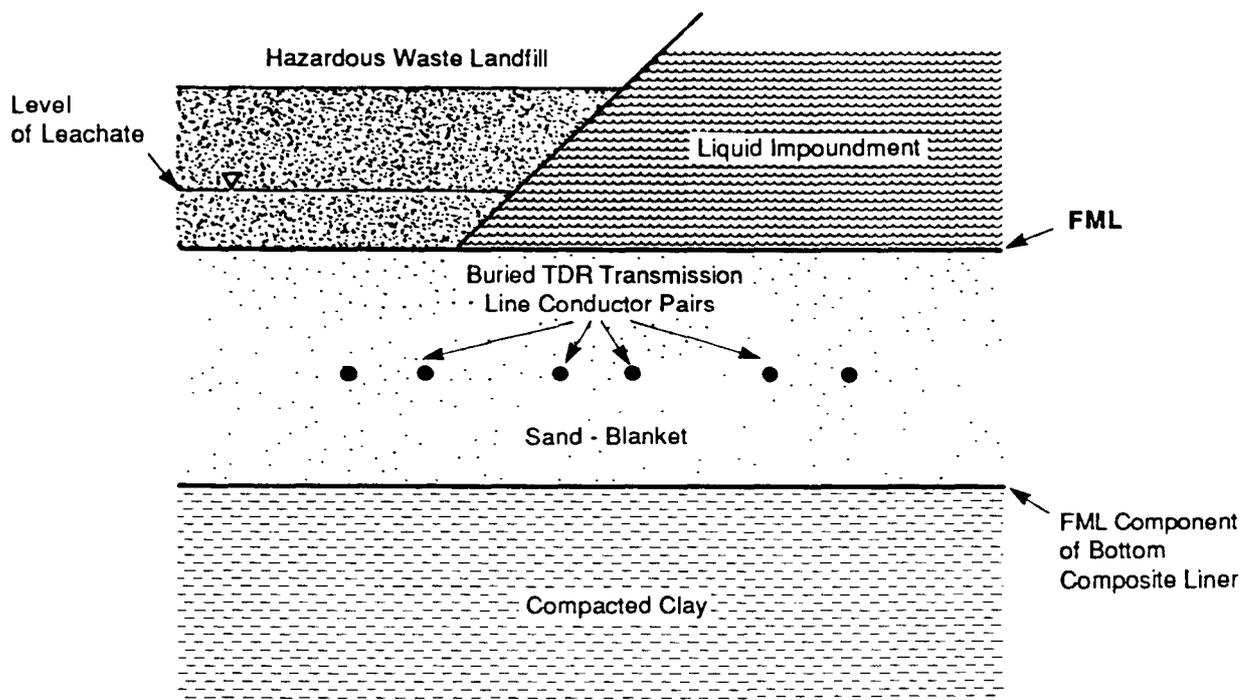


Figure 11-8. Schematic of a TDR system installed at a hazardous waste containment unit. (Based on E. C. Jordan, 1984).

ER is a geophysical technique whereby an electrical current is introduced into the ground by a pair of surface electrodes and the resultant potential field is monitored by a second pair of electrodes. For the purpose of leak detection, the current is passed from an electrode within a containment unit to an electrode outside the unit. When no leaks are present, a voltage applied between the material contained in the unit and the earth underneath the liner system produces a relatively uniform electrical potential distribution in the material contained in the unit. Leaks are located by mapping any anomaly in the potential distribution caused by current flowing through a leak (Shultz et al, 1984). The electrical leak location method was successful in finding leaks in a full-scale impoundment that had been fully tested using the vacuum box method (Darilek and Parra, 1988a and 1988b). A schematic of the electrical leak location method is shown in Figure 11-9.

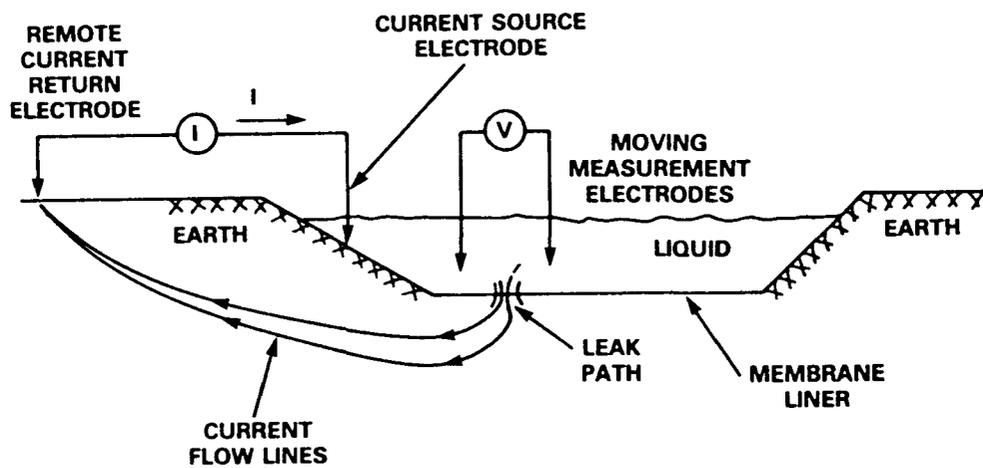


Figure 11-9. Schematic of the electrical resistivity testing technique for detecting and locating leaks in an FML system. (Source: Darilek and Parra, 1988a).

Even though the ER technique has had only limited field use to date, it has shown promise particularly for locating leaks in surface impoundments known to leak, for CQA during large-scale hydrostatic testing (which is discussed in Section 10.4.5.4), and for CQA verification of certain portions of an installed liner, such as the sump area. Methods of using the technique to locate leaks in final cover systems for landfills or impoundments are being developed.

EPRI (1985) and E. C. Jordan (1984) discuss these techniques in more detail.

11.6 MONITORING THE COMPONENTS OF A LINING SYSTEM FOR A WASTE CONTAINMENT UNIT AND RELATED MAINTENANCE ACTIVITIES

The lining system for a waste containment is made up of a number of different components, each of which needs to function properly so that the lining system as a whole can meet its performance requirements. In addition to monitoring the overall performance of the lining system to determine whether or not leaks have developed, the owner/operator needs to monitor the condition of the different components of the system, insofar as such monitoring is possible. By monitoring these components, potential problems in the lining system can be detected and corrected before constituents of the contained materials are allowed to escape in an uncontrolled manner. Techniques of monitoring the different components are discussed in the following subsections.

11.6.1 Monitoring an In-Service Liner

Observing the in-service condition of a liner, particularly of an FML, is desirable in order to determine whether exposure to the service environment has resulted in changes in properties that can significantly affect the ability of the lining system to act as a barrier controlling the escape of constituents from the containment unit. Of particular interest are the combined effects of mechanical and chemical stresses.

The simplest method of monitoring an in-service FML is to visually inspect the liner on a regular basis. Penetrations in the lining systems (e.g. inflow/outflow pipes, etc.) and their connection with an FML in particular should be inspected regularly since these areas are exposed to complex mechanical stresses. Accessibility of the FML to observation is, of course, a major difficulty in many situations, especially in the case of the bottom liner of double-liner systems. In the case of a double-lined surface impoundment without a soil cover on top of the top FML, the upper surface of the top liner can be observed on the slopes during service and on the bottom if the surface impoundment is drained. In the case of landfills and waste piles, there is almost no accessibility to the lining system because of the waste covering the FML.

To determine the actual effects of exposure on an FML-lined system, a sample removed from the in-place liner should be tested for physical and analytical properties. Analysis and fingerprinting of FMLs are discussed in Section 4.2.2.6. Testing a sample removed from an in-place liner requires cutting into the liner itself. In the case of an FML exposed to chemical environments (e.g. a waste liquid), the resultant hole would be essentially impossible to repair adequately by known techniques, i.e. the repair would not meet the performance requirement of being equivalent to a newly installed liner (Haxo, 1987).

A possible means of observing some of the effects of the waste liquid on the FML and other components of the lining system during service is to submerge coupons of the materials in the sump or in other locations in the unit. Examples of coupon placement are shown in Figures 11-10 through 11-12.

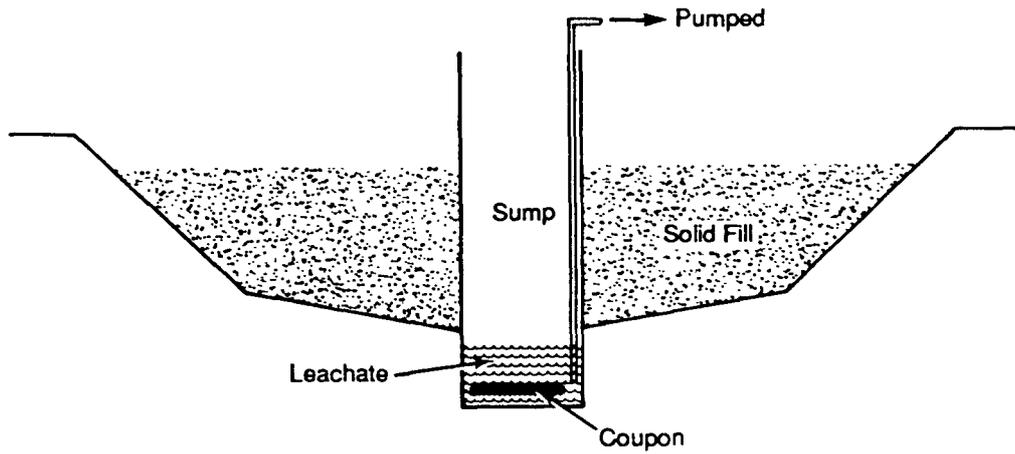


Figure 11-10. Schematic for a coupon in a landfill. (Based on Tratnyek et al, 1985).

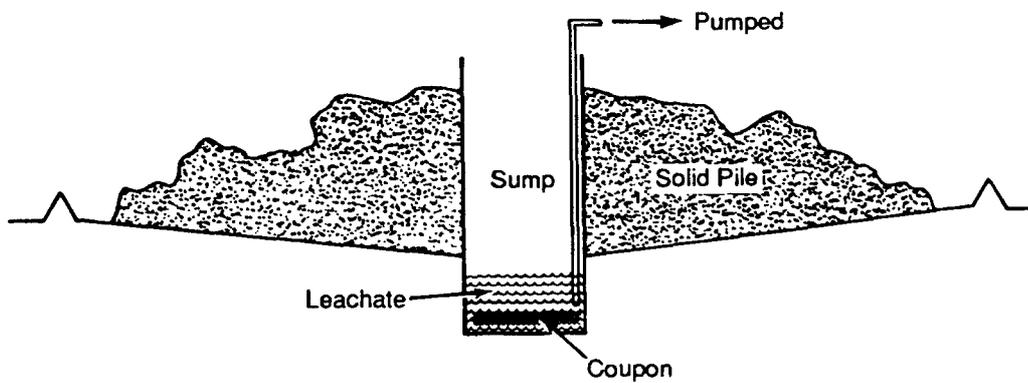


Figure 11-11. Schematic for a coupon in a waste pile. (Based on Tratnyek et al, 1985).

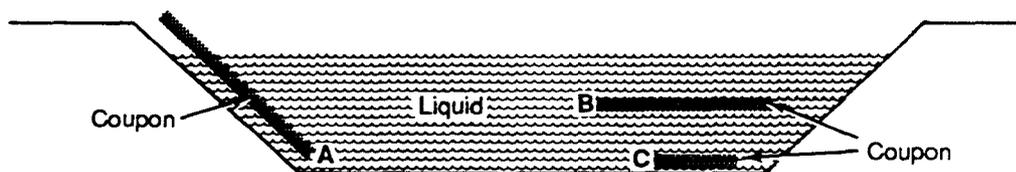


Figure 11-12. Schematic for coupon options in a surface impoundment. (Based on Tratnyek et al, 1985).

The use of coupons is briefly described in Chapter 5 for determining the compatibility of an FML with the waste to be contained. Tratnyek et al (1985) described a methodology for using removable coupons to monitor the effect of exposure in a landfill by exposing samples of the FML and ancillary materials of a lining system in a sump, or, in the case of a surface impoundment, on the slopes or floor of the unit. The samples can be withdrawn periodically for visual inspection or physical and analytical testing. This type of exposure, however, can only assess the chemical compatibility of the materials with the leachate or waste liquid; it will not reflect the combined chemical and mechanical stresses that are placed on the FML and the ancillary materials during the actual exposure. Nevertheless, this type of test yields results that can indicate which constituents in a waste stream are being absorbed by the materials and potentially could affect performance of the liner system. Combining such data with changes in mechanical properties will be useful in assessing the rates of deterioration and in estimating the long-term service life of an FML and the ancillary materials.

Coupons are being used by the Bureau of Reclamation to monitor (over a 5-year period) the performance of a fabric-reinforced FML that is lining the Mt. Elbert Forebay Reservoir. Large coupons (20 x 100 ft) which incorporated seams were placed on a 2-in. cushion of sand to separate them from the main lining on the bottom of the reservoir. A soil cover was placed over the coupons and was removed for retrieving and testing the coupons for changes in physical properties and seam strengths (Frobel and Gray, 1984).

The difficulties involved in a coupon testing program are caused by practical limitations, particularly if coupons are to be placed in a landfill or waste pile sump. The institution of a coupon testing program needs to be coordinated with the sump design during the design phase so that the coupons do not interfere with pump operation, maintenance, and inspection. Retrofitted designs in which coupon samples are exposed to leachate after it has been pumped from the sump can also be considered.

Surface impoundments holding wastewater may require cleaning to remove sludges. Care must be taken during cleaning so as not to damage the liner. Cleaning crews should be supervised by someone familiar with the liner to ensure that punctures or tears are prevented, or patched if they occur. However, in order to achieve a reliable bond between the patch and the liner, the patching requires thorough cleaning and drying of the area to be patched. If sludge is to be removed from the bottom of a wastewater impoundment, some type of nonmechanical means should be used, e.g. a suction hose or dredging head. This should minimize the potential for liner damage. Following cleaning, the FML should be thoroughly inspected for possible distress before liquid is introduced into the unit.

Any damage that is observed in an area of a surface impoundment liner that is exposed to the weather should be repaired as quickly as possible in order to avoid growth of the break. An opening on the slope could allow rain water or liquid from the impoundment to get under the liner and could result in a massive failure of the embankment on which the liner was placed. Openings in the liner above the water line have resulted in major damage to

the earthwork below. In these locations on the uncovered slopes, reliable repairs can be made and maintained.

11.6.2 Monitoring, Maintenance, and Repair of Leachate Collection and Removal Systems

LCRSs are required in landfills above the top liner and, in the case of hazardous waste landfills, between the top and the bottom liners of a double-liner system. The LCRS above the top liner is required to maintain a head of leachate above the liner no greater than 1 foot. The LCRS between the top and bottom liners functions as a potential leak-detection system which requires rapid flow through the system to a sump area. In managing such a landfill, the LCRSs must function over extended periods of time without clogging, i.e. through the post-closure care period, which is at least 30 years. LCRS in waste piles and surface impoundments function similarly.

A variety of conditions can develop in an LCRS which would reduce the flow. These conditions include mineralization, biological clogging, and in the case of synthetic drainage systems, collapse of the polymeric components due to the combined effects of softening (resulting from absorption of organics from the leachate) and overburden pressure. Constant vigilance is required as to the level of the leachate above the top liner in a landfill and the appearance of leachate in the sumps. The pipes that are associated with the LCRSs should be sufficiently large, e.g. 6-in. diameter, to allow monitoring, maintenance, and potential repair.

At present, there is little direct experience with the maintenance of LCRSs in waste containment units. (Bass, 1986) describes a variety of mechanical, hydraulic, and chemical techniques borrowed from sewer technology for maintaining and repairing of drainage pipes. These techniques were devised for cleaning and removing debris from underground sewer pipes and agricultural drainage systems. However, there are major constraints in using these techniques in waste containment units including:

- Limited access to the pipes, i.e. risers are generally used instead of manholes, and the manholes that are used are surrounded by waste.
- Potential damage to the pipes by mechanical cleaning. Because of their chemical resistance, plastic pipes are used in collection systems; these pipes are generally not as durable as metal or concrete pipes with respect to mechanical cleaning operations.

In addition, there is the general problem of operator safety due to the potentially hazardous nature of the leachate.

There are no demonstrated techniques for the maintenance and repair of either synthetic or granular layers, although some chemical procedures for cleaning have been suggested by Bass (1986).

11.6.3 Monitoring the Gas-Venting System

The air gas vents installed near the crest or on the berm of a containment unit for releasing gas generated in or below a unit and for preventing airlift should be inspected regularly and cleaned out, if necessary, to avoid plugging. The same equipment used for inspecting and cleaning LCRS pipes could be used for inspecting and cleaning the venting pipes. Equipment that may find use in cleaning LCRS pipes is discussed by Bass (1986).

11.6.4 Monitoring the Earthworks

The integrity of the embankments is essential to the proper performance of surface impoundments and landfills. In the case of surface impoundments, regular inspections should be made of the embankments and berms. Attention should be given to possible ground movements, cracks, and erosions of the earth. Since an erosion control problem usually exists when earth is exposed on an embankment slope, preventive measures should be taken in the design. However, the inspection is still needed because failure of the earthwork can result in failure of the liner.

The condition of the soil in the dikes can be monitored through the use of piezometers and observation wells installed on the outside of the embankments to measure seepage of water or leachate into the embankments. This procedure is being followed at the Mt. Elbert Forebay Reservoir to measure the groundwater level within the embankment at the end of the reservoir (Frobel and Gray, 1984). Prior to the installment of the FML liner which replaced a clay liner, the piezometers had indicated a higher than anticipated groundwater level in the dam of the reservoir, which was lined at that time with a clay. After lining the reservoir with an FML, the water level rose in the observation wells in response to the initial filling; the water level levelled off and later dropped, indicating reduced seepage from the reservoir. In addition, tests were run with inclinometers along the face of the reservoir, and observations were made on the inside of the reservoir.

11.6.5 Vegetation Control

Growth of vegetation inside and around a containment unit must be controlled to prevent damage to the liner from the anchor trench down the side slope. Damage can result if weed growth begins under an FML or, if a soil cover is present, on top of the liner. In the latter case, roots of plants might penetrate the FML creating a hole which, once opened, can increase in size. However, no such type of failure by roots has been reported, as roots tend to grow laterally on an FML surface. Ideally, the berm area around the impoundment should be treated with weed killer initially, and maintained in a weed-free condition.

11.6.6 Rodent Control

Rodents, such as gophers, squirrels, rats, muskrats, and mice, have been reported to have caused severe damage to the soil embankments of lined waste containment units. These animals can honeycomb an embankment and may possibly damage a liner if the liner blocks the path to food or water. Rodents, particularly certain ground squirrels, have also been known to eat some PVC material. The presence of these animals at the construction site should be assessed during the design phase. Provisions to control their impact can then be made and incorporated into both the design and the maintenance procedures for the facility. Any holes in the earthworks dug by burrowing animals should be filled in as soon as possible even if the animal leaves the site.

11.6.7 Monitoring of Diversion Drainage System

If a diversion drainage system is set up around the unit to prevent water from entering the unit, it should be inspected periodically to ensure that the system is still capable of managing the design capacity, e.g. the water volume resulting from a 24-hour, 25-year storm.

11.6.8 Monitoring to Prevent Vandalism and Unauthorized Dumping

The site must be carefully monitored to prevent vandalism and unauthorized dumping of wastes. These may be curtailed by limiting vehicular access to the disposal site, locating the site out of general view, and by fencing in ponds and similar impoundments.

11.7 MAINTENANCE OF THE FINAL COVER

At the end of the operational period for a landfill, a final cover is constructed over the fill. The purpose of the cover is to minimize leachate formation within the landfill by preventing surface water from infiltrating the fill throughout and beyond the post-closure care period. The final cover system also controls the venting of gases that may be generated within the fill and isolates the wastes from the surface environment. The final cover system is designed and constructed so that it functions with *minimum* maintenance, promotes drainage, minimizes erosion, accommodates settlement and subsidence, and has a permeability less or equal to that of the bottom liner system. Lutton (1986) and McAneny et al (1986) discuss the design, construction, and maintenance of cover systems in more detail. See also Chapter 7 (Section 7.5.8) and EPA 1987b for additional information on final covers.

As set forth in RCRA guidance, the final cover is a multi-layer structure consisting of soil layers of different types and probably an FML constructed on a mass of waste that can settle unevenly. As such, the final cover is potentially subject to a variety of problems which are listed in Table 11-1.

TABLE 11-1. POTENTIAL PROBLEMS WITH FINAL COVER SYSTEMS

Chronic erosion	Chronic vegetation failure
Erosion event	Vegetation failure event
Inadequate drainage system	Frost disturbance
Slope creeping	Wind erosion
Slope sliding	Cracking
Subsidence	Plugging of porous soil
Differential settlement	Deterioration of synthetics
Flooding	Loss of locations and monuments
Burrowing animals	Root penetration

Based on Lutton, 1986, p 133.

A program of maintenance and repair suggested by Lutton (1986), consists of the following measures:

- Periodic grooming of the vegetative cover, such as the one described by Conover (1977), to maintain the vegetation and recondition the soil.
- A program of repairs to deal with the development of gullies, subsidence of the cover, slope instability, defective drainage systems, and leakage spots through which there can be an upward flow of gas or capillary water which could be toxic to plant growth.
- Reconstruction of major damage.

Lutton (1986) also suggests that the maintenance program concentrate its effort in the early years to ensure that long-range problems can be recognized and corrective actions taken.

The principal objective in managing the cover system is to maintain the effectiveness of the final cover. Management of the final cover begins essentially with the completion of cover construction and the planting of the vegetative cover and extends a minimum of an additional 30 years. Management entails regular inspections of all of the components, with particular attention to the drainage system which must be able to control the run-on and run-off equivalent to a 24-hour, 25-year storm. The surface drainage system must be maintained to prevent any intrusion of surface water into the landfill. Maintenance of the vegetative cover and the gas-venting systems is also of critical importance. The vegetative cover is important in preventing erosion, and the gas-venting system is necessary to prevent a gas buildup from forming inside the closed landfill. Continuous observation must be made to detect any settlement and subsidence of the cover, which must be corrected to prevent depressions in the cover through which surface water may pool and enter the landfill.

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CHAPTER 12

COSTS ASSOCIATED WITH MATERIALS AND CONSTRUCTION OF WASTE STORAGE AND DISPOSAL UNITS

12.1 INTRODUCTION

If, after chemical compatibility and performance requirements have been considered, it appears that a number of different FMLs and ancillary materials can be used in the construction of a particular storage or disposal unit, then cost may become an important factor in the ultimate design of the liner system and in the selection of materials. Although the costs of these materials are only part of the overall construction cost of such a unit, they can significantly affect the overall cost. Consequently, costs will be considered by designers and engineers in selecting specific materials for use in construction.

This chapter discusses factors influencing the cost of constructing a waste containment unit and discusses the cost of various liner materials as well as other construction materials such as pipes, geogrids, geonets, drainage materials, etc. Some costs for earthworks construction and factors that can affect liner installation costs are presented. The cost of different storage or disposal alternatives are compared, and lastly, costs for quality assurance inspection of the materials and the construction are discussed.

12.2 FACTORS AFFECTING COSTS OF WASTE CONTAINMENT UNITS

A wide range of factors are involved in the total cost of the design and construction of waste containment units:

- The types of materials required by the design. Costs of the FML and the other polymeric components of the liner system are largely determined by the prices of the resins necessary to their manufacture. A choice between some materials, e.g. drainage materials, may be made on a cost-benefit basis.
- The location of the facility and the transportation costs involved in bringing the lining material or fill to the site. Liner projects in remote areas with rugged terrain will have higher costs than those at sites with more favorable topography and geology or those located nearer to the source of liner materials.

- As with most construction activities, the time of the year and its effect on labor availability and productivity. In addition, inclement weather can disrupt liner installation. In the case of FMLs, successful field seaming requires a fairly narrow range of environmental conditions; they cannot be placed in excessive heat or cold, snow or rain, or on nonstable or wet ground. Delays in construction and liner placement can thus result. Adverse weather conditions can affect the placement of other construction materials as well.
- The size of the disposal facility unit. Size can significantly affect the cost per unit area of liner. As with most projects and construction materials, the larger the project, the lower the unit cost of work productivity and materials. Large liner projects usually have significant economies of scale.
- Type of soil on site. In the construction of hazardous waste disposal units, soil materials are needed for construction of the soil component of a composite liner, the embankments, and, if called for in the design, the soil protective cover above the top liner. In addition, granular materials may be used in the leachate collection systems. The availability or lack of availability of soil materials on the site that are adequate for use in constructing the unit will significantly affect cost.
- Type of FML selected. Differences in FML properties can have a small effect on the cost of site preparation and installation, particularly if the selected FML requires a relatively small particle size bedding. In addition, the type of FML selected may make it necessary to apply a herbicide to the bedding surface to alleviate concern about plant growth that might lead to puncture of an overlying installed FML.
- Differences in FML installation costs. Some materials will require more work effort and quality control than others, particularly in the field seaming of the sheeting or panels into the final liner. However, final installed costs quoted for the FMLs will take these differences into account.
- The quality control and quality assurance that is needed at all stages of construction and liner installation. The risk of a containment failure with its potentially high liability makes it essential that all specifications are met.

The basic design assumptions, both economic and technical, must be established before a detailed cost estimate can be prepared for any system. Potential cost elements of a waste containment unit are listed in Table 12-1. All technical design assumptions should be stated in making the cost estimate for constructing the unit. These assumptions include:

- The anticipated operating life of the disposal facility.
- The annual waste storage or disposal requirement.

TABLE 12-1. POTENTIAL COST ELEMENTS
OF A WASTE CONTAINMENT UNIT^a

Geotechnical investigation of site
Clearing and grubbing
Excavation volume
Grading and compaction
Berm embankment construction
Compatibility testing of the component materials
Soil component of bottom liner
FML component of composite bottom liner
Components of a secondary leachate collection system:
Drainage layer (synthetic or granular)
Filter layer
Protective soil layer
Geotextile support layer
Leachate collection pipes
FML top liner
Components of a primary leachate collection system (if unit is a landfill or a waste pile)
Soil cover above top liner
Auxiliary cleanouts
Pump
Sump
Diversion ditch
Riprap
Quality control and quality assurance

^aMany of these cost elements can be divided into material costs and installation/construction costs.

Based on Sai and Zabcik, 1985.

- Type of constructed unit, i.e., whether the unit is constructed above or below grade or a combination of the two.
- Design of liner system including top liner, bottom liner (if double-lined), leachate collection system, and leak-detection system.
- Site-specific requirements based on size of the unit. For example, if the unit to be constructed is a surface impoundment, these requirements will include depth, freeboard zone, berm width, and height of embankments.

Once the basic design assumptions for a particular unit are finalized, it is possible to estimate the cost of materials and construction.

12.3 LINER SYSTEM COMPONENT COSTS

12.3.1 Factors Influencing Component Costs

Except for the soil and sand/gravel components of the lining system for a hazardous waste storage or disposal unit, the components of the system are made from polymeric materials as is described in Chapter 4. These components can include FMLs, geotextiles, synthetic drainage materials, geogrids, and pipe. As the costs involved in manufacturing these polymeric components are relatively moderate, their price is largely determined by the prices of the raw materials necessary to their manufacture.

As the industry that produces the polymeric components of a lining system is a minor segment of the polymer industry, raw material costs are set by producers of polymers and other ingredients of the component compound. Because the polymers themselves are made from chemicals from petroleum sources, costs ultimately depend on the cost of natural gas or crude oil feedstocks. Increases in the price of these commodities throughout the 1970s resulted in a corresponding rise in polymer costs.

In the 1980s, the costs of natural gas and crude oil feedstocks have stabilized considerably, and this has contributed to the stabilization of monomer prices and, consequently, polymer prices.

12.3.2 Flexible Membrane Liners

Prices for flexible membrane liners (FMLs) are quoted in a variety of ways:

- As "rolled goods" or sheeting as produced by liner manufacturers.
- As "fabricated liners," e.g. the price of membranes produced by the factory seaming of sheeting into large panels which are then sold to installers.
- As "final installed costs" which include the cost of installing the FML at the site.

Due to the structure of the industry, the prices of some liners are quoted in all three ways. When the liner manufacture, fabrication, and installation are performed by a single company, only a single price may be quoted, i.e. installed costs.

Table 12-2 provides cost data for selected liner materials based on estimates provided by various manufacturers, fabricators, and installers of the specific materials. Costs are per square foot of liner material, installed in quantities sufficient to line a 100,000 ft² unit with a single liner. Costs presented do not include costs for site and surface preparation, engineering design, or soil cover. Costs will be affected by transport distance, size of project, time of year, local labor, and complexity of the installation. The unit costs shown do not represent the total cost of a liner system, since other components, such as leachate collection and leak-detection systems, may be required. Also, the costs presented do not reflect equal service life or performance of the liners. Since all liners for landfills are covered, the additional cost of the soil cover will not affect the choice of the liner. However, in the case of surface impoundments, some lining materials need to be covered to protect them from ultra-violet light, wind, and sunlight; this additional cost is not reflected in Table 12-2.

12.3.3 Geotextiles

Geotextiles vary considerably in construction and can have a variety of uses in the liner system design of waste containment units. They can be used to reinforce embankment slopes, to protect FMLs against puncture, and as a filter medium in leachate collection systems. The use of geotextiles in waste containment is discussed in Section 4.2.3.

Generally, geotextile manufacturers use many distributors. As in the case of liner materials, economies of scale are realized for large installations versus smaller ones. Table 12-3 lists estimated costs for a variety of geotextile materials based on a 1-sq acre containment unit (44,000 ft²); these costs do not include shipping and installation, which will vary from \$0.04 to \$0.07 per sq ft.

12.3.4 Drainage Materials

Synthetic and granular drainage media can be used in leachate collection systems. Various types of synthetic drainage materials have recently been introduced commercially. However, even though these synthetic media have many potential advantages over granular media, they are still unproven for long-term application. Geonets are grid-like polymeric products used as in-plane drainage systems which must be used in conjunction with geotextiles, FMLs, or other materials on their upper and lower surfaces. The geonets and their use as a drainage medium are described in Section 4.2.5. Also a number of examples of their use in designing of LCRSs are presented in Chapter 7, e.g. Section 7.5.4.2.2. The cost of these materials range from \$0.15 to \$0.45 per ft² depending on the specific product.

TABLE 12-2. INSTALLED 1987 COSTS^a FOR FLEXIBLE MEMBRANE LINERS

Material	Thickness, mil	Type of polyester fabric ^b reinforcement	Cost/sq ft, \$
CPE	30	...	0.45-0.50
	36	10 x 10 - 1,000 d	0.55-0.65
	45	10 x 10 - 1,000 d	0.65-0.70
CSPE	30	8 x 8 - 250 d	0.62-0.65
	36	10 x 10 - 1,000 d	0.65-0.70
	45	8 x 8 - 250 d (2)	0.85-0.90
	45	10 x 10 - 1,000 d	0.72-0.78
	60	10 x 10 - 1,000 d	1.10-1.20
HDPE and LLDPE	40	...	0.40-0.50
	60	...	0.55-0.65
	80	...	0.65-0.75
	100	...	0.75-0.90
PVC	30	...	0.27-0.30
	40	...	0.32-0.35
	50	...	0.40-0.45
	60	...	0.50-0.55
PVC-OR	30	...	0.40-0.45
	40	...	0.47-0.52
Nitrile rubber/PVC alloy	30	8 x 8 - 250 d	0.70-0.75
Ethylene interpolymer alloy	30	6.5 oz/yd ²	0.70-0.75

^aCosts are estimates for an installed FML liner covering for 100,000 ft². Variables that can affect costs are transport fees, labor, time of year, and complexity of site.

^bd = Denier; oz = ounces. Number in parentheses represents the number of plies of reinforcing fabric.

TABLE 12-3. GEOTEXTILE COSTS

Material	Thickness, mil	Cost/sq ft ^a , \$
Nonwoven polypropylene	40	0.05
Nonwoven polypropylene	50	0.06-0.08
Nonwoven polypropylene	90	0.10-0.14
Nonwoven polypropylene	150	0.23-0.26
Woven polypropylene	25	0.06-0.09
Nonwoven polyester	85	0.06-0.09
Nonwoven polyester	100	0.10-0.12
Nonwoven polyester	150	0.20-0.21
Nonwoven polyester	210	0.23-0.32

^aPrices are based on approximately 44,000 sq ft of material and do not include shipping and installation, which will vary from 4 to 7¢ sq ft. Prices for individual geotextiles will also vary from distributor to distributor.

Source: Sai and Zabcik, 1985.

Geocomposites are a wide range of composite materials which consist of two or more geosynthetics and which are designed to fulfill various functions (see Section 4.2.6). Table 12-4 lists costs of various types of drainage geocomposites by square footage, as well as cost reductions for quantity purchases.

Costs for granular media will be highly site specific and dependent on transport distance, as are all earthen materials. Costs for sand and gravel are presented in Table 12-5.

12.3.5 Geogrids

Geogrids are being used as soil stabilization and reinforcement in the construction of embankments and dikes, as is discussed in Section 4.2.4. They can be used in constructing containment units to steepen earth slopes or to create earth embankments used in subdividing individual units within a disposal facility. As is discussed in Chapters 4 and 7, a large variety of these materials of different structures, compositions, and strengths are

TABLE 12-4. COSTS OF GEOCOMPOSITE DRAINAGE MATS

Configuration					
Core material	Outer geotextile filter	Overall thickness	Shape of core	Maximum stress	1985 unit cost ^a
Nylon	Nonwoven-needled	0.4 in.	Monofilament web	27 psi	\$0.56/ft ² \$0.53/ft ² (quantity)
Nylon	Nonwoven-needled	0.8 in.	Monofilament web	27 psi	\$1.12/ft ² \$1.07/ft ² (quantity)
Polystyrene	Nonwoven-heat set or needled	0.75 in.	"Egg-carton"	30 psi	\$1.15/ft ² \$0.76/ft ² (quantity)
Expanded: polystyrene beads bound by bitumen	Nonwoven-needled	Up to 2 ft	Bound beads	Virtually unlimited (compressible)	2-in. thickness \$1.06/ft ² No cost given in quantity
Polystyrene/ polyethylene	Nonwoven-heat set	5/16 in.	Corrugated ribs	...	\$1.00-\$0.75/ft ² \$0.58/ft ² (quantity)
Polyethylene	Nonwoven-needled	1.0 in.	Cylinders	230 psi	\$1.10/ft ² (includes delivery)

^aQuantity costs include delivery.

Source: Sai and Zabcik, 1985, p 30.

available. A compilation and descriptions are available in Koerner 1985 and Geotechnical Fabrics Report 1987. The price for these materials can range from \$1.25 to more than \$6.00 per square yard depending on the material and its strength.

TABLE 12-5. RANGE OF COSTS FOR SAND AND GRAVEL

Media type	Price (delivered \$/yd ³) ^a
Sand (Fine, medium, coarse)	\$3.00 (bank run) \$6.50 (clean)
Gravel (Well-graded)	\$3.00 (bank run) \$6.50 (clean)
Gravel (Coarse, uniform)	\$7.00 to \$8.00 ...

^aHaul distance can increase costs substantially.

Source: E. C. Jordan, 1984, p 22.

12.3.6 Piping

The most common usage of pipe in the lining system is as a component of leachate collection and removal systems as described in Chapter 10. Pipe appropriate for this usage includes polymeric, ferrous, fiberglass, and concrete piping as discussed in Section 4.2.7. Cost data for piping are presented in Table 12-6 as dollars per lineal foot for a 6-in. diameter pipe of each material.

12.4 INSTALLATION COSTS OF LINERS

Certain factors affecting installation costs are specific to a type of liner. Those factors for FMLs can be summarized as follows:

- Sand or soil with a limit on the maximum particle size may be needed as a bedding for the FML. A soil cover may be needed to protect the FML against damage by equipment such as tracked vehicles and compactors that operate above the liners to compact refuse.
- Soil compaction and specific subgrade preparations may be needed for the bedding on which the FML will be placed.
- Herbicides may need to be applied to the bedding surface to prevent plant growth under a newly installed FML in order to prevent puncturing of the FML.

- Some materials are field seamed with different and very specific techniques that may require more work effort and quality control than others. Successful field seaming can require a fairly narrow range of environmental conditions. Most liners cannot be placed in excessive heat or cold, snow or rain, or on unstable or wet ground.
- Quality control and quality assurance.

TABLE 12-6. COSTS FOR PIPE OF DIFFERENT TYPES

Material	Type	Costs, \$/LF	
		Nonperforated	Perforated
Polyvinyl chloride	Flexible	1.20-3.25	1.70-3.75
High-density polyethylene	Smooth, flexible	2.00-8.00	2.50-8.50
Acrylonitrile butadiene styrene	Semirigid	3.00	3.50
Steel	Corrugated, semiflexible	3.00	3.00
Ductile iron	Rigid	5.50	7.50
Fiberglass	Flexible	10.0-20.00 (highly variable)	Labor rate for field perforation
Concrete-porous wall	Rigid	1.30-1.55	Not applicable

^aCost per lineal foot for 6-in. diameter pipe.

Source: E. C. Jordan, 1984, pp 17-18.

12.5 CONSTRUCTION COSTS FOR EARTHWORKS

The cost of using soil as a construction material can vary widely. Details such as groundwater level and local soil availability can affect costs by a factor of two or more. Therefore, budgeting prior to preliminary design work can be very difficult, and a meaningful cost estimate may require a preliminary review of site conditions to form a conceptual design and construction plan. Contingencies of 25% or more are often attached to such estimates. Often the experience of local contractors is invaluable in assessing the cost and practicality of a proposed design.

Most embankment construction for a surface impoundment is similar to that in routine earthwork, as is discussed in Chapter 9.

Table 12-7 lists the costs of major components of an embankment, and the important factors that influence the respective costs.

TABLE 12-7. UNIT COSTS FOR MAJOR EMBANKMENT COMPONENTS
(1986 Level of Costs)

Item	Estimated cost range	Factors influencing cost
Excavation	\$1.50-25.00/cu yd	Size, material disposal, soil conditions, groundwater conditions
Granular embankment	\$2.00-15.00/cu yd	Local availability, distance to source, processing required, compaction requirement
Cohesive embankment	\$2.00-20.00/cu yd	Distance to borrow area, natural moisture content, compaction requirements, soil workability
Drain lines	\$10.00-50.00/ft	Type, trench depth, backfill requirements, diameter
Drain material	\$8.00-25.00/cu yd	Gradation required, size of drain, local availability, compaction requirements
Riprap	\$15.00-30.00/cu yd	Local availability and distance to source
Quality control	0.5-3% of contract price/lump sum	Difficulty of job, regulatory requirements, contractor's conscientiousness

12.6 COSTS FOR LEACHATE COLLECTION AND REMOVAL SYSTEMS

Materials that may be used in the LCRSs include pipe of various types, granular drainage media such as sand and gravel, synthetic drainage media such as geonets and geocomposites, and geotextiles as filters, separators, or protectors. Costs for the individual materials are discussed in Section 12.3. In addition to costs for the materials, there are costs for construction of the LCRS as well as for construction quality assurance.

E. C. Jordan (1984) developed an average cost per unit for LCRSs with either granular media or synthetic drainage layer systems for a 4.8 acre

containment unit. The specifications for the unit on which the cost estimates were based is given in Table 12-8. The design of the system on which the cost estimate of the granular drainage system was based is presented in Figure 12-1. All itemized costs for major system components are presented in Table 12-9. Costs include materials, installation, overhead, and profit. This estimate shows considerable savings for synthetic drainage systems over granular systems due to the greater ease in which the synthetic materials are placed, and the use of minimum thickness materials. Use of the more costly, high transmissivity geocomposites presented in Table 12-4 would bring costs of the two systems into close proximity.

In actuality, the experience with leachate collection systems is limited. A database on leachate collection systems, compiled for the EPA (1983), indicated that the range of costs for single landfill systems ranged from a minimum of \$15,000 to maximum of \$1,470,000, the median costs for for which were \$200,000. The largest site pumped quantities of around 5,550,000 gal/year of leachate; the median capacity was 22,500 gal/year of leachate.

12.7 COSTS FOR A ONE-ACRE DOUBLE-LINED SURFACE IMPOUNDMENT

The basic design assumptions, both economic and technical, must be established before a detailed cost estimate can be prepared for any system involving construction with earthworks and large purchases of materials. A cost model of a one-acre double-lined surface impoundment incorporating the standards specified in the RCRA amendments of 1984 (Hazardous and Solid Wastes Act) was developed by Sai and Zabcik (1985). The model uses a LOTUS 1,2,3 spreadsheet to calculate the design variables and the engineering and construction costs.

Components of a double-lined waste containment unit are presented in Table 12-1, and a cost summary based on a specific scenario is shown in Table 12-10. The scenario surface impoundment consists of an FML/composite double liner, a sand drainage layer with pipe drains and collection sumps. The surface impoundment is designed to contain 5 ft of liquid and have a surface area of one acre. A slope of 3:1 was assumed as a typical value that should provide adequate berm stability for the surface impoundment cost model. Figure 5-4 presents a schematic cross section of the scenario surface impoundment.

The cost of clearing and grubbing is dependent on the vegetation at the construction site. For the cost calculations in Table 12-10, it was assumed that the area was flat and had no trees. The cost model calculates a set of surface impoundment optimum design dimensions for freeboard and minimizing earthwork. These optimum impoundment dimensions are determined by using the concept of fill efficiency ratio, which assumes that the most cost effective dimensions for a given surface impoundment volume are those with the highest ratio of storage volume to fill volume.

TABLE 12-8. SPECIFICATIONS FOR UNIT USED TO ESTIMATE COST OF LEACHATE COLLECTION AND REMOVAL SYSTEMS

Item	Criteria value
Disposal unit:	
Site	Landfill
Area	4.8 acres
Dimensions	350 x 600 ft
Waste layer depth	...
Side slopes ^a	3:1
Liner material	HDPE
Drainage layer:	
Slope	≥2%
Depth:	
Pipe in drainage media	2 ft
Synthetic drainage layer	1/4 in.
Drainage layer:	
Pipe in drainage media	b
Synthetic drainage layer	Geonet
Collection system:	
Laterals	6-in. dia. PVC - perforated
Headers	8-in. dia. PVC - perforated
Discharge line	8-in. dia. PVC - solid wall
Geotextile wrap	Polypropylene
Slope	0.005 ^c
Lateral spacing	50 ft
Structures:	
Manholes	Precast concrete - 4-ft dia.
Auxiliary cleanouts:	
Pipe in drainage media	6-in. dia. PVC - solid wall
Pipe in synthetic media	None

^aSide slopes at landfill and surface impoundments have been designed at 3:1. Using this angle should avoid sloughing of any of the drainage media evaluated (Bass et al, 1984).

^bSee Figure 12-1.

^cEPA guidance calls for a minimum slope of 2% in the collection system.

Source: E. C. Jordan, 1984.

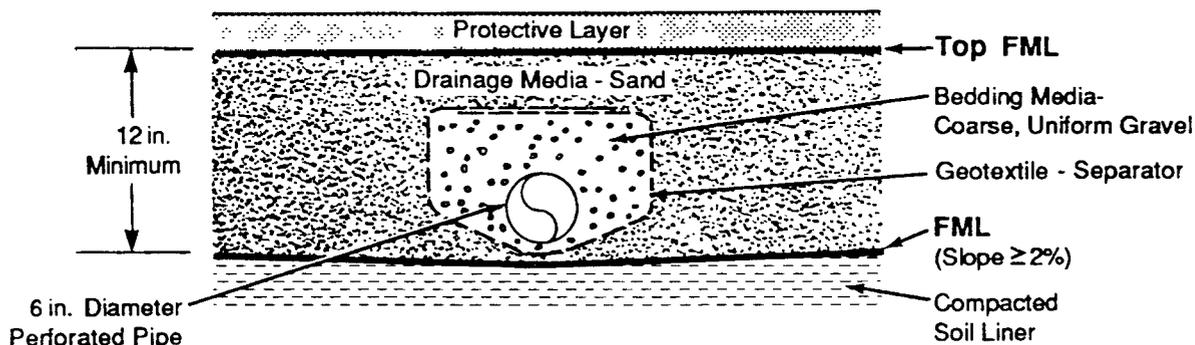


Figure 12-1. Configuration of a granular drainage system for a secondary leachate collection system. (Source: E. C. Jordan, 1984, p 29).

TABLE 12-9. COST COMPARISON BETWEEN GRANULAR AND SYNTHETIC DRAINAGE SYSTEMS^a

Granular drainage system		Synthetic drainage system	
Pipe	\$ 11,500	Net	\$24,700 ^b
Drainage layer	106,300	Pipe	3,000
Filter fabric	3,600	Structures	5,100
Structures	<u>7,000</u>	Fittings	<u>2,200</u>
Total	<u>\$133,000</u>	Total	<u>\$35,000</u>

^aSee Table 12-8 for specifics of cell used to estimate cost. See Figure 12-1 for schematic cross section of granular drainage system design.

^bUse of any of the geocomposite drainage mats listed in Table 12-4 would place costs for synthetic drainage systems much closer to those for granular systems.

Source: E. C. Jordan, 1984, p 54.

The unit costs included in the model reflect average 1984 dollars and do not include cost and profit margins. The unit costs were obtained from Means (Godfrey, 1984) cost data and are for an average site condition which may not reflect cost variations due to specific location, construction, or practice. Design, engineering, and supervisory services are not included in the total cost of construction. These costs usually comprise between 8 and 20% of the total direct project costs. Other costs not estimated by the model include land costs, leachate analysis and waste compatibility testing costs, and other management costs. Construction costs used in these

TABLE 12-10. CONSTRUCTION COSTS FOR A SURFACE IMPOUNDMENT DESIGNED TO CONTAIN FIVE FEET OF LIQUID^a

Component	Unit	Unit cost (1984) ^b		Number of units	Cost
		Material	Installation/ construction		
Geotechnical investigation of site	site	...	\$12,441.00	1.0	\$ 12,441
Clearing and grubbing	acre	...	1,406.30	1.5	2,109
Excavation	cu yd	...	2.14	15,613	33,412
Grading and compaction	sq yd	...	0.57	8,113	4,624
Berm construction (fill and spread)	cu yd	...	2.19	1,979	4,334
Berm compaction	cu yd	...	1.37	1,979	2,711
Clay liner	cu yd	4.90	2.73	8,023	61,216
Compaction of clay liner	cu yd	...	1.15	8,023	9,226
Drainage layer (sand)	cu yd	6.50	2.73	2,172	20,048
Compaction of drainage layer	cu yd	...	1.24	2,172	2,693
Protective soil	cu yd	8.50	2.73	2,192	24,616
Geotextile protection layer	sq ft	0.09	0.07	49,958	7,993
Top FML	sq ft	0.28	0.18	49,958	22,980
Geotextile support	sq ft	0.09	0.07	49,958	7,993
FML in bottom composite liner	sq ft	0.28	0.18	56,983	26,212
Leachate drain pipe (main)	ft	1.41	2.16	218	778
Leachate drain pipe (lateral)	ft	1.52	1.11	840	2,209
Pump	ea	1,450.00	265.00	1.0	1,715
Sump	ea	1,990.00	385.00	1.0	2,375
Diversion ditch	ft	...	2.41	1,295	3,121
Riprap	cu yd	8.75	11.25	324	6,480
Subtotal (materials)					\$118,857
Subtotal (installation/construction)					\$140,429
Total					\$259,286

12-15

^aCosts are for a surface impoundment lined with an FML/composite double liner and constructed with a secondary leachate collection system that uses a sand drainage layer.

^bGodfrey, 1984.

Source: Sai and Zabcik, 1985.

calculations were based on standard equipment and construction practices and average climatic conditions.

12.8 COSTS FOR ADMIX AND SPRAYED-ON LINERS

Cost estimates for admix and sprayed-on asphalt membrane liners are presented in Table 12-11. As with the cost estimates for the FMLs, the costs shown include neither the costs for site and surface preparation, nor the costs of a soil cover. Specific cost data for these liner types are difficult to obtain and are heavily influenced by geographic location, especially transportation costs.

TABLE 12-11. COST ESTIMATES FOR SOIL CEMENT, ASPHALT CONCRETE, AND ASPHALT MEMBRANE LINERS

Liner type	Installed cost, \$/sq yd 1987 ^a
Soil cement 6-in. thick + sealer (2 coats - each 0.25 gal/sq yd)	9.00 ^b
Asphalt concrete, dense-graded paving without sealer coat (hot mix, 4-in. thick)	3.40-5.60
Asphalt concrete, hydraulic (hot mix, 4-in. thick)	5.62-7.88
Bituminous seal (catalytically blown asphalt) 1 gal/sq yd	3.15
Asphalt emulsion on mat (polypro- pylene mat sprayed with asphalt emulsion)	1.00-2.00

^aEstimated installed costs on West Coast.

^bOn large projects price can range from \$4.50-6.75/sq yd. The lower price applies to an installation of about 40 acres.

The costs for asphalt-concrete liners are closely related to those for asphalt paving concrete. Existing equipment and technology are available which can be used as is or with modification to install liners. Thus, admix lining materials may be cost-effective for lining some waste disposal impoundments, provided they meet the technical requirements.

12.9 COMPARISON OF COSTS OF ALTERNATE LAND WASTE DISPOSAL TECHNOLOGIES

Hallowell et al (1984) compared the cumulative costs of four alternatives for the management of hazardous wastes, including:

- An excavated conventional hazardous waste landfill.
- A mound-type landfill.
- Above-ground storage.
- Crystalline bedrock disposal.

The conventional landfill considered is a state-of-the-art (as of 1984) secure chemical landfill, 30- to 40-ft below existing ground level and containing liners, leachate collection system, cap, and soil cover. The facility is developed on a cell basis.

The mound landfill involves the development of a base layer at existing ground level that includes the installation of liners and leachate collection systems, followed by the build-up of waste and cap or cover at a height of about 40 feet above the original ground level. The facility is developed in steps in separate cells, creating a series of mound structures.

Above-ground storage involves the storage of wastes in drums in enclosed buildings and liquids in large tanks, either until ultimate disposal at closure or until technologies or needs are developed to recycle or reuse valuable constituents of the waste. The closure of such a site is characterized by quick removal of all accumulated wastes, decontamination, and site cleanup which would result in minimum or no post-closure monitoring.

Crystalline bedrock disposal involves permanent disposal in underground vaults from a few hundred to 1,000 ft under the surface of the earth.

Three different annual capacities of facilities were considered for the economic comparison:

- Low: 5,000 tons per year.
- Medium: 30,000 tons per year.
- High: 80,000 tons per year.

Data showing the comparison of cumulative costs are given in Table 12-12 and represented graphically in Figure 12-2.

12.10 COSTS OF QUALITY ASSURANCE

The cost of quality assurance is described in detail by Giroud and Fluet (1986). They concluded that the major portion of the cost of quality

assurance relating to a lining system for a waste storage or disposal unit is in construction quality assurance. Table 12-13 shows the magnitude of funds which should be budgeted for quality assurance of lining systems. The cost percentages shown are for complete (100%) quality assurance documentation. The actual cost percentage for a particular site will depend on the degree of quality assurance desired (partial or full), the size of the project, the quality of the design and the construction work, site-specific conditions, and problems encountered.

TABLE 12-12. COMPARISON OF CUMULATIVE COSTS OVER 20 YEARS OF FOUR ALTERNATIVE TECHNOLOGIES FOR MANAGEMENT OF HAZARDOUS WASTES

Type of disposal facility	Waste capacity, ton/year		
	5,000	30,000	80,000
	Total cumulative costs, millions of dollars		
Conventional landfill	19.0	39.3	71.1
Mound landfill	19.4	40.2	68.8
Above-ground storage:			
Without recycle	116.3	604.0	1,503.0
With recycle	57.0	294.4	729.3
Crystalline bedrock disposal	52.0	172.0	380.0
	Per-ton costs, dollars/ton		
Conventional landfill	190	67	44
Mound landfill	194	67	43
Above-ground storage:			
Without recycle	1,163	1,007	940
With recycle	570	490	456
Crystalline bedrock disposal	520	290	240

Source: Hallowell et al, 1984.

An example was developed by Giroud and Fluet (1986) for typical costs for third party quality assurance and are presented in Table 12-14. The example is described as a moderately sized landfill (500,000 ft²) with a lining system comprised of an FML top liner, a composite bottom liner (FML over clay), geonets for primary and secondary leachate collection systems,

and a geotextile for the primary leachate collection system filter. Such a lining system will, therefore, contain 1,000,000 ft² of FML. The installation might require from 10 to 20 weeks for completion. The costs shown in Table 12-14 assume 12 weeks for completion of construction and that a comprehensive quality assurance plan is already in effect for the project. If such a plan does not exist, then it should be prepared, and the cost must be added to those shown in Table 12-14. The cost of the FML lining system used in the example is estimated at \$1,000,000 exclusive of the cost of quality assurance. The cost of the quality assurance up through acceptance of the unit by the owner/operator would, therefore, be approximately 26% of the installed geosynthetic lining system cost.

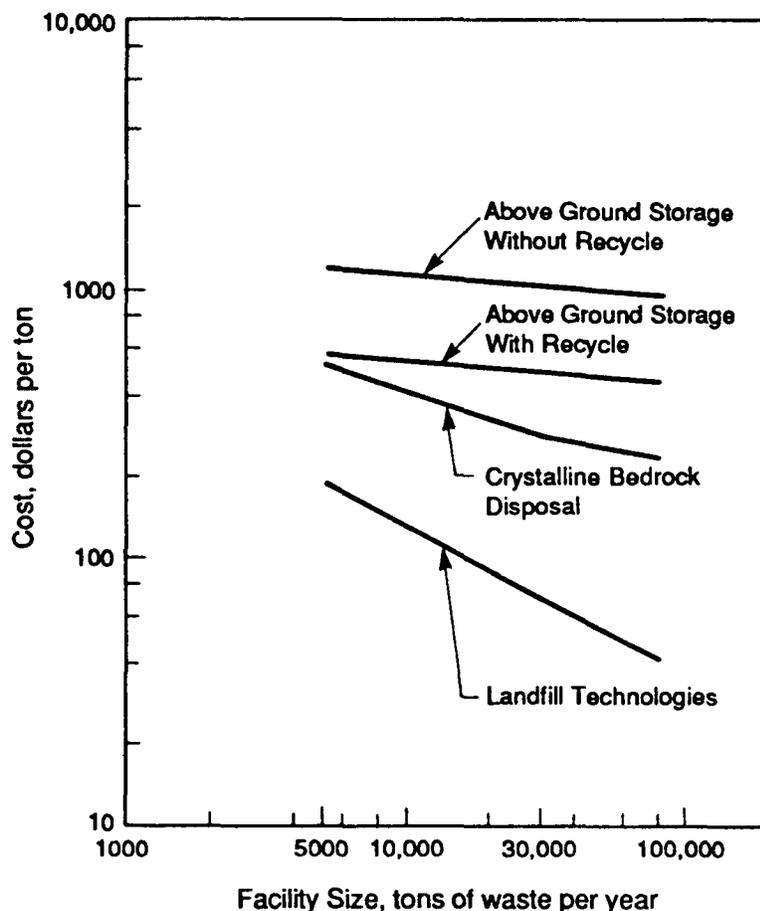


Figure 12-2. Comparison of the costs of four disposal technologies. (Source: Hallowell et al, 1984).

TABLE 12-13. COST OF QUALITY ASSURANCE

Phase	Percent of cost of installed lining system
Design	1 to 3
Manufacturing	1 to 2
Fabrication	1 to 3
Lining system construction	20 to 30
Final report review	1 to 2
Operations	<1 per year
Closure system construction (final cover)	5 to 10
Post closure care period	<1 per year

Source: Fluet, 1987.

TABLE 12-14. COST OF THIRD PARTY QUALITY ASSURANCE FOR DOUBLE-LINED 500,000 FT² WASTE LANDFILL UNIT

Phase	Personnel	Number	Time ^a	Typical cost ^b
Design	Managing engineer	1	2 to 8 days	\$ 4,000
Manufacturing	Manager	1	2 to 5 days	3,500
Fabrication	Managing engineer	1	0 to 1 day	500
	Manager	1	0 to 1 day	300
	Monitor	1	1 to 2 weeks	4,000
Installation	Managing engineer	1	15 to 25 days	17,000
	Manager	1	11 to 12 weeks	45,000
	Monitor(s)	1 to 10	4 to 10 weeks	170,000
Total personnel cost				\$244,300
Laboratory costs				15,000
Total cost				\$259,300

^aAssume a total completion time of 12 days.

^bIncludes travel and daily allowance.

Source: Giroud and Fluet, 1986.

12.11 REFERENCES

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APPENDIX A
SIGNIFICANT WASTE SOURCES AND TYPES OF WASTES

This appendix presents examples of significant waste sources and the types of wastes generated by these sources. Selected representative wastes of the following types are discussed:

- Municipal solid waste.
- Hazardous wastes from eleven industries:
 - Electroplating and metals finishing.
 - Inorganic chemicals.
 - Metal smelting and refining.
 - Organic chemicals.
 - Paint and coatings formulating.
 - Pesticide.
 - Petroleum refining.
 - Pharmaceutical.
 - Pulp and paper.
 - Rubber and plastics.
 - Soap and detergent.
- Uranium tailings.
- Other nonradioactive wastes.
- Substances stored in underground storage tanks.

This appendix is intended only to be illustrative. The objective is to give examples of wastes from the different sources that may be encountered and which may or should be impounded in lined facilities. Interactions between wastes and specific liner materials are discussed in Chapter 5.

MUNICIPAL SOLID WASTE

Description of the Waste

Municipal solid waste (MSW), the refuse from residential and commercial sources, is typically composed of paper, glass, plastics, rubber, wood, metal, food and garden wastes, ceramics, rocks, textiles, leather, etc. Major components and rough wet weight percents are presented in Table A-1 from Ham et al (1979). See Wigh (1979) for additional data. It is, however, the leachate produced by the waste, whether primary or secondary, that is of principal concern with respect to pollution and liner durability.

Characteristics of Leachate From Municipal Solid Waste

The leachate produced from municipal refuse is a highly complex liquid mixture of soluble, organic, inorganic, ionic, nonionic, and bacteriological constituents and suspended colloidal solids in a principally aqueous medium. It contains products of the degradation of organic materials and soluble ions which may present a pollution problem to surface and ground waters (Phillips and Wells, 1974). The quality of the leachate depends on the composition of the waste and the combined physical, chemical, and biological activities.

The precise composition of leachate is waste and site specific, depending on such variables as type of waste, amount of infiltrating water, age of landfill, and pH. Table A-2 lists parameters of leachate which are used as analytical indicators of landfill leachate in the groundwater near a landfill (EPA, 1977). Tables A-3 and A-4 present data to show the complexity in composition of actual leachate from MSW, its site specific character, and its variation with time.

Griffin and Shimp (1978) compared the analyses of municipal landfill leachate with drinking water standards. Chemical oxygen demand (COD) and biochemical oxygen demand (BOD) of landfill leachates were generally high and the pH ranged from 4 to 9. Alkalinity, hardness, phosphate, nitrogen, heavy metals, and concentrations of other elements were also determined. The levels of these components varied over very wide ranges as shown in Tables A-3 and A-4.

Leachates generated in the disposal of hazardous wastes may include high concentrations of such metals as mercury, cadmium, and lead; toxic substances, such as barium and arsenic; organic compounds, including chlorinated solvents, aromatic hydrocarbons, and organic esters; and various corrosive, ignitable, or infectious materials.

Potential Pollution by MSW Leachate

Municipal landfill leachates degrade groundwater quality by introducing the constituents shown in Tables A-3 and A-4, as well as biological contamination (Phillips and Wells, 1974).

TABLE A-1. COMPOSITION AND ANALYSIS OF AN AVERAGE MUNICIPAL REFUSE FROM STUDIES BY PURDUE UNIVERSITY

Component	Percent of all refuse, by weight	Moisture percent, by weight ^b	Analysis, percent dry weight ^a						Non combustibles
			Volatile matter	Carbon	Hydrogen	Oxygen	Nitrogen	Sulfur	
Rubbish, 64%:									
Paper	42.0	10.2	84.6	43.4	5.8	44.3	0.3	0.20	6.0
Wood	2.4	20.0	84.9	50.5	6.0	42.4	0.2	0.05	1.0
Grass	4.0	65.0	...	43.3	6.0	41.7	2.2	0.05	6.8
Brush	1.5	40.0	...	42.5	5.9	41.2	2.0	0.05	8.3
Greens	1.5	62.0	70.3	40.3	5.6	39.0	2.0	0.05	13.0
Leaves	5.0	50.0	...	40.5	6.0	45.1	0.2	0.05	8.2
Leather	0.3	10.0	76.2	60.0	8.0	11.5	10.0	0.40	10.1
Rubber	0.6	1.2	85.0	77.7	10.4	...	...	2.0	10.0
Plastic	0.7	2.0	...	60.0	7.2	22.6	...	...	10.2
Oils, paints	0.8	0.0	...	66.9	9.7	5.2	2.0	...	16.3
Linoleum	0.1	2.1	65.8	48.1	5.3	18.7	0.1	0.40	27.4
Rags	0.6	10.0	93.6	55.0	6.6	31.2	4.6	0.13	2.5
Street sweepings	3.0	20.0	67.4	34.7	4.8	35.2	0.1	0.20	25.0
Dirt	1.0	3.2	21.2	20.6	2.6	4.0	0.5	0.01	72.3
Unclassified	0.5	4.0	...	16.6	2.5	18.4	0.05	0.05	62.5
Food Wastes, 12%:									
Garbage	10.0	72.0	53.3	45.0	6.4	28.2	3.3	0.52	16.0
Fats	2.0	0.0	...	76.7	12.1	11.2	0.0	0.00	0.0
Noncombustibles, 24%:									
Metals	8.0	3.0	0.5	0.8	0.04	0.2	...	...	99.0
Glass & ceramics	6.0	2.0	0.4	0.6	0.03	0.1	...	...	99.3
Ashes	10.0	10.0	3.0	28.0	0.5	0.8	...	0.5	70.2
Composite refuse, as received:									
All refuse	100	20.7	...	28.0	3.5	22.4	0.33	0.16	24.9

Source: Ham et al, 1979.

^aAnalysis of the respective components.

^bMoisture content of the respective components in the waste.

TABLE A-2. PARAMETERS FOR CHARACTERIZING MSW LEACHATE

Physical	Chemical		Biological
	Organic	Inorganic	
Appearance	Phenols	Total bicarbonate	Biochemical oxygen demand (BOD)
pH	Chemical oxygen demand (COD)	Solids (TSS, TDS)	Coliform bacteria (total, fecal; fecal streptococcus)
Oxidation-reduction potential	Total organic carbon (TOC)	Volatile solids	Standard plate count
Conductivity	Volatile acids	Chloride	
Color	Organic nitrogen	Phosphate	
Turbidity	Tannins, lignins	Alkalinity and acidity	
Temperature	Ether soluble (oil and grease)	Nitrate-N	
Odor	MBAS	Nitrite-N	
	Organic functional groups as required	Ammonia-N	
	Chlorinated hydrocarbons	Sodium	
		Potassium	
		Calcium	
		Magnesium	
		Hardness	
		Heavy metals (Pb, Cu, Ni, Cr, Zn, Cd, Fe, Mn, Hg, As, Se, Ba, Ag)	
		Cyanide	
		Fluoride	

Source: EPA (1977).

TABLE A-3. COMPOSITION OF THREE MSW LANDFILL LEACHATES
 Concentration of Constituents (mg/L), Except pH and Electrical Conductivity

Constituent	Source of data		
	Wigh (1979)	Breland (1972)	Griffin and Shimp (1978)
BOD ₅	...	13,400	...
COD	42,000	18,100	1,340
TOC	...	5,000	...
Total solids	36,250	12,500	...
Volatile suspended solids	...	76	...
Total suspended solids	...	85	...
Total volatile acids as acetic acid	...	9,300	333
Acetic acid	...	5,160	...
Propionic acid	...	2,840	...
Butyric acid	...	1,830	...
Valeric acid	...	1,000	...
Organic nitrogen as N	...	107	...
Ammonia nitrogen as N	950	117	862
Kjeldahl nitrogen as N	1,240	...	...
pH	6.2	5.1	6.9
Electrical conductivity (μ mho/cm)	16,000	...	...
Total alkalinity as CaCO ₃	8,965	2,480	...
Total acidity as CaCO ₃	5,060	3,460	...
Total hardness as CaCO ₃	6,700	5,555	...
Chemicals and metals:			
Arsenic	...	...	0.11
Boron	...	...	29.9
Cadmium	...	...	1.95
Calcium	2,300	1,250	354.1
Chloride	2,260	180	1.95
Chromium (total)	...	...	<0.1
Copper	...	...	<0.1
Iron (total)	1,185	185	4.2
Lead	...	...	4.46
Magnesium	410	260	233
Manganese	58	18	0.04
Mercury	...	...	0.008
Nickel	...	...	0.3
Phosphate	82	1.3	...
Potassium	1,890	500	...
Silica	...	...	14.9
Sodium	1,375	160	748
Sulfate	1,280	...	<0.01
Zinc	67	...	18.8

TABLE A-4. CHARACTERISTICS OF MSW LEACHATES^a

Constituent	Reference ^b	Reference ^c	Reference ^d	Reference ^e	Reference ^f	
	(mg/L)	(mg/L)	(mg/L)	(mg/L)	Fresh	Old
BOD ₅	9-54,610	...	7,500-10,000	...	14,950	...
COD	0-89,520	100-51,000	16,000-22,000	500-1,000	22,650	81
Total dissolved solids	0-42,276	...	10,000-14,000	...	12,620	1,144
Total suspended solids	6-2,685	...	100-700	...	327	266
Total nitrogen	0-1,416	20-500	...	...	989	7.51
pH	3.7-8.5	4.0-8.5	5.2-6.4	6.3-7.0	5.2	7.3
Electrical conductivity (µmho/cm)	...	...	6,000-9,000	1,200-3,700	9,200	1,400
Total alkalinity as CaCO ₃	0-20,850	...	800-4,000	630-1,730	...	...
Total hardness as CaCO ₃	0-20,800	200-5,250	3,500-5,000	390-800	...	...
Chemicals and Metals:						
Cadmium (Cd)	...	...	0.4	...	...	...
Calcium (Ca)	5-4,080	...	900-1,700	111-245	2,136	254
Chloride (Cl)	34-2,800	100-2,400	600-800	100-400	742	197
Copper (Cu)	0-9.9	...	0.5	<0.04-0.11	0.5	0.1
Iron (Fe)- total	0.2-5,500	200-1,700	210-325	20-60	500	1.5
Lead (Pb)	0-5.0	...	1.6	...	...	...
Magnesium (Mg)	16.5-15,600	...	160-250	22-62	277	81
Manganese (Mn)	0.6-1,400	...	75-125	1.02-1.25	49	...
Phosphate (P)	0-154	5-130	...	21-46	7.35	4.96
Potassium (K)	2.8-3,770	...	295-310	107-242	...	...
Sodium (Na)	0-7,700	100-3,800	450-500	106-357	...	...
Sulfate (SO ₄)	1-1,826	25-500	400-650	13-84	...	...
Zinc (Zn)	0-1,000	1-135	10-30	<0.04-0.47	45	0.16

^aEPA (1975a). ^bEPA (1973). ^cSteiner et al (1971). ^dGenetelli and Cirello (1976). ^eHam (1975). ^fBrunner and Carnes (1974).

The quantity of leachate produced is a function of the moisture content of the waste itself and the volume of water added through infiltration and percolation from surface and ground sources. Leachate is being recycled in some installations to enhance biodegradation in the landfill by providing nutrients and water. The quantity of leachate that leaves the landfill and the pollution potential are thus reduced.

One of the reasons for the development of the proposed TCLP (EPA, 1986) is the concern of possible codisposal of volatile solvents and other organics in MSW. The proposed procedure will allow for the determination of the volatile organics that are in the proposed list for toxicity characteristic.

Potential Effects of MSW Leachate Upon Liners

MSW leachate is not inert toward lining materials; constituents of the leachate can affect liners in different ways, depending on their concentrations in the leachate and on the specific liner materials. Furthermore, the effects of the constituents can be synergistic and can vary with time as the concentrations change with the aging of the waste. Dissolved salts and ions may be damaging to some lining materials, particularly soils and clays. Acidity or alkalinity may dissolve components of soils or soil cements. Organic molecules (indicated by volatile acid content, volatile solid, and total organic carbon (TOC) can be damaging to rubber and plastic liners causing them to swell, to become more permeable and softer and lose in properties, such as tensile strength and tear resistance, and thus to be more easily torn and damaged. Water also can cause some liners to swell. These effects are discussed in detail in Chapter 5. Also discussed in Chapter 5 is the need for compatibility testing when the waste liquid or leachate is known to contain constituents that are aggressive to some types of liner materials.

Gas Production in MSW

Gases are also produced in the decomposition of organic matter in MSW landfills. These gases, primarily methane and carbon dioxide, may present problems if their migration is not controlled or if they are not collected. Methane is flammable, can be explosive, is damaging to plants and trees, and, in high enough concentration, may result in asphyxiation of animals and people; it is of commercial value as a heating fuel and some generated in MSW landfills is being used in this manner. Carbon dioxide is absorbed in leachate and tends to lower pH and thus to solubilize calcium, magnesium, and other metals.

HAZARDOUS WASTES BY INDUSTRY

Industrial wastes are a major source of hazardous wastes, the components of the latter are usually metals, strong acids or bases, and a large array of organic and inorganic chemicals. As shown in Table A-5, taken from the EPA Report to Congress on the disposal of hazardous wastes (EPA, 1974a), each industry produces wastes with different characteristics and components. Also, wastes generated by the same industry vary from source to source. The

TABLE A-5. REPRESENTATIVE HAZARDOUS SUBSTANCES WITHIN INDUSTRIAL WASTE STREAMS

Industry	Hazardous substances										
	As	Cd	Chlorinated hydrocarbons ^a	Cr	Cu	Cyanides	Pb	Hg	Misc. organics ^b	Se	Zn
Battery	...	X	...	X	X	...	...	...	...	...	X
Chemical manufacturing	...	...	X	X	X	...	...	X	X	...	...
Electrical and electronic	...	...	X	...	X	X	X	X	...	X	...
Electroplating and metal finishing	...	X	...	X	X	X	...	...	...	...	X
Explosives	X	...	...	...	X	...	X	X	X	...	...
Leather	...	...	...	X	...	...	...	...	X	...	...
Mining and metallurgy	X	X	...	X	X	X	X	X	...	X	X
Paint and dye	...	X	...	X	X	X	X	X	X	X	...
Pesticide	X	...	X	...	...	X	X	X	X	...	X
Petroleum and coal	X	...	X	...	...	...	X	...	...	...	...
Pharmaceutical	X	...	...	...	...	...	...	X	X	...	...
Printing and duplicating	X	...	...	X	X	...	X	...	X	X	...
Pulp and paper	...	...	...	...	...	...	...	X	X	...	...
Textile	...	...	...	X	X	...	...	...	X	...	...

^aIncluding polychlorinated biphenyls.

^bFor example: acrolein, chloropicrin, dimethyl sulfate, dinitrobenzene, dinitrophenol, nitroaniline, and pentachlorophenol.

Source: EPA (1974a).

chemical nature and reactivity, as well as concentration of the waste components, must be considered when designing a lining system for a specific waste storage or disposal facility. The characteristics of the wastes from several selected industries are discussed below, and are illustrative of specific wastes which are generated and must be disposed of in environmentally sound methods. Special attention is given those constituents in the waste liquids that are aggressive to lining materials.

Solid wastes that have been identified as hazardous wastes by the EPA are listed in 40 CFR 261, Subpart D. These wastes include:

- Generic hazardous wastes from nonspecific sources, such as spent halogenated solvents used in degreasing, and sludges from the solvents used in degreasing operations. Identified wastes have been assigned an industry and EPA hazardous waste number preceded by the letter "F". The bases for identifying these wastes as hazardous are presented in Appendix 7 of 40 CFR 261; specific hazardous constituents that are presented in the individual wastes are shown.
- Hazardous wastes from specific sources, such as bottom sediment sludge from the treatment of wastewater from wood preserving processes that use creosote and pentachlorophenol. Identified wastes have been assigned an industry and EPA hazardous number preceded by the letter "K". The bases for identifying these wastes as hazardous are presented in Appendix 7 of 40 CFR 261; specific hazardous constituents that are presented in the individual wastes are shown.
- Wastes which are discarded commercial chemical products, off-specification products, container residues, and spill residues and which have been generically identified as either "acute hazardous wastes" or "toxic wastes." These terms are defined in 40 CFR 261, Subpart B. The generic commercial chemical products, the manufacturing chemical intermediates, and off-specification commercial chemical products and manufacturing chemical intermediates that have been identified as acute hazardous wastes have been assigned a hazardous waste number preceded by a "P"; those that have been identified as toxic wastes have been assigned a hazardous waste number preceded by a "U".

Electroplating and Metals Finishing Industry

The electroplating industry can be classified into three principal segments: plating, metal finishing, and the manufacture of printed circuit boards. The plating segment can be further subdivided into common metal electroplating, precious metal electroplating and electroless plating. Subsegments of the metal finishing category include: anodizing, chemical conversion coating, chemical milling, etching, and immersion plating. Because of the heavy metal content of most wastes from the electroplating and metal finishing operations, many wastes from this industry may be hazardous; appropriate tests should be run to determine whether the waste liquids are hazardous.

In common metal electroplating, a ferrous or nonferrous basis material is electroplated with copper, nickel, chromium, zinc, tin, lead, cadmium, iron, aluminum, or combinations of these elements. Precious metal electroplating also uses either a ferrous or nonferrous basis material, but the metal plated onto the basis material is either gold, silver, palladium, platinum, rhodium, or combinations of these metals. Electroless plating is used on both metals and plastics.

Anodizing, coatings (e.g. chromating or phosphating), coloring, and immersion plating processes apply a surface coating to a workpiece for specific functional or decorative purposes. Chemical milling and etching processes are used to produce specific design configurations and tolerances on metal parts by controlled dissolution with chemical reagents or etchants.

Wastewaters from plating and metal finishing operations are discharged from all three phases of the electroplating process: workpiece pretreatment; the plating, coating, or basis material removal process; post treatment. Wastewaters are generated by rinse water disposal, plating or finishing bath dumping, ion-exchange unit regenerant bleed streams, vent scrubber discharges, and maintenance discharges (EPA, 1979).

Treatment may involve degreasing with soaps, alkaline cleaning (sometimes with the aid of wetting agents), acid dipping, or, in the case of aluminum alloys, desmutting to remove finely divided particles of base material. The compositions of treatment cleaners (and thus, waste streams) vary with the type of base metal being cleaned and the kind of material being removed.

Wastewater constituents generated from the electroplating depend on the metals being plated and the plating solution used. Table A-6 lists some of the various types of plating solutions used for electroplating. Plating solutions for the metals in the platinum group are proprietary. The most common plating solutions for electroless plating are copper and nickel, although iron, cobalt, gold, palladium, and arsenic are also used. Of particular concern among the constituents of electroless plating baths are the chelating agents, which are used to hold the metal in solution (so the metal will not plate out indiscriminately). There are three main types of chelating agents: amino carboxylic acids, amines, and hydroxy acids. One of the drawbacks in the use of chelating agents is the difficulty in precipitating chelated metals out of wastewater during treatment.

Wastes from metal finishing operations come from cleaning, pickling, anodizing, coating, etching, and related operations. The constituents in these wastes include the basic material being finished, as well as the components in the processing solutions. Baths used for anodizing, coating, and etching usually contain metal salts, acids, bases, dissolved basis metals, complexing agents, and other deposition control agents. Bath constituents for chemical removal of basis metals include mineral acids, acid chlorides, alkaline ammonium solutions, nitro-organic compounds, and such compounds as ammonium peroxysulfate.

TABLE A-6. TYPICAL ELECTROPLATING SOLUTIONS

Plating compound	Constituents	Concentration (g/L)
Cadmium cyanide	Cadmium oxide	22.5
	Cadmium	19.5
	Sodium cyanide	77.9
	Sodium hydroxide	14.2
Cadmium fluoborate	Cadmium fluoborate	251.2
	Cadmium (as metal)	94.4
	Ammonium fluoborate	59.9
	Boric acid	27.0
	Licorice	1.1
Chromium electroplate	Chromic acid	172.3
	Sulfate	1.3
	Fluoride	0.7
Copper cyanide	Copper cyanide	26.2
	Free sodium cyanide	5.6
	Sodium carbonate	37.4
	Rochelle salt	44.9
Electroless copper	Copper nitrate	15
	Sodium bicarbonate	10
	Rochelle salt	30
	Sodium hydroxide	20
	Formaldehyde (37%)	100 mL/L
Gold cyanide	Gold (as potassium gold cyanide)	8
	Potassium cyanide	30
	Potassium carbonate	30
	Dipotassium phosphate	30
Acid nickel	Nickel sulfate	330
	Nickel chloride	45
	Boric acid	37
Silver cyanide	Silver cyanide	35.9
	Potassium cyanide	59.9
	Potassium carbonate (minimum)	15.0
	Metallic silver	23.8
	Free cyanide	41.2
Zinc sulfate	Zinc sulfate	374.5
	Sodium sulfate	71.5
	Magnesium sulfate	59.9

Source: Metal Finishing Guidebook and Directory (1979).

Post treatment processes in the plating segment encompass chemical conversion coatings (chromating, phosphating, and coloring), which are process steps for the metal finishing segment. Post treatment processes for metal finishing include: sealing and coloring of anodic coatings, bleaching or dyeing of chromate coatings, and chemical rinsing after phosphating.

Table A-7 is a compilation of the various pollutants found in each subsegment of the electroplating industry. The concentrations presented are the range of values for each constituent, based on a statistical analysis of 50 metal finishing plants and 67 plating establishments (EPA, 1979).

Hallowell et al (1976) identified four waste streams as being destined for land disposal, i.e. water pollution control sludges, process wastes, degreasing sludges, and the salt precipitates from electroless nickel bath regeneration. Hallowell et al have estimated the quantities of these which could be generated in 1975, 1977, and 1983. These data are presented in Table A-8.

Inorganic Chemicals Industry

The waste streams of a few of the specific industries in this category are briefly described in this subsection.

The chlor-alkali industry, whose main product is chlorine, also produces soda ash (NaOH) and potash (KOH) as co-products. Brine-purification sludges resulting from this industry contain mainly calcium carbonate, magnesium hydroxide, barium sulfate, and water. These slightly hazardous or non-hazardous wastes do not necessarily require strict landfilling precautions or procedures. Lead carbonate and asbestos waste products must be handled more carefully. Lead must be completely isolated from the environment before land disposal. Asbestos is insoluble, but the dust and small fibers present a serious potential health hazard. The surface of a disposal site for asbestos should be protected from wind and erosion. Chlorinated hydrocarbons and mercury are also by-products of certain processes.

The hazardous waste products from inorganic pigment manufacture include chrome and small amounts of mercury or lead. Most of the mercury, lead, zinc, and antimony is reclaimed. Minimally toxic wastes such as chlorides and nontoxic metal oxides from ore residues are usually disposed of in municipal sanitary landfills.

Other inorganic chemicals produce wastes such as ore residues, silicates or easily neutralized liquids. Most hazardous components are reclaimed or become part of a saleable by-product. Those hazardous components not reclaimed are usually disposed of in lined impoundment facilities (Hallowell et al, 1976).

TABLE A-7. CHARACTERIZATION OF WASTE STREAM FROM ELECTROPLATING INDUSTRY

Pollutant parameter	Segment of industry - concentrations (mg/L)					
	Common metals plating	Precious metals plating	Electroless plating	Anodizing	Coatings	Chemical milling and etching
Copper	0.032-272.5		0.002-47.90			0.206-272.5
Nickel	0.019-2,954		0.028-46.80			
Chromium, total	0.088-525.9			0.268-79.20	0.190-79.20	0.088-525.9
Chromium, hexavalent	0.0005-534.5			0.005-5.000	0.005-5.000	0.005-334.5
Zinc	0.112-252.0				0.138-200.0	0.112-200.0
Cyanide, total	0.005-150.0	0.005-9.970	0.005-12.00	0.005-78.00	0.005-126.0	0.005-126.0
Cyanide, amenable	0.003-130.0	0.003-8.420	0.005-1.00	0.004-67.56	0.004-67.56	0.005-101.3
Fluoride	0.022-141.7		0.110-18.00			0.022-141.7
Cadmium	0.007-21.60					
Lead	0.663-25.39					
Iron	0.410-1,482				0.410-168.0	0.075-263.0
Tin	0.060-103.4				0.102-6.569	0.068-103.4
Phosphorus	0.020-144.0	0.020-144.0	0.030-109.0	0.176-33.0	0.060-53.30	0.060-144.0
Total suspended solids	0-10,000	0-10,000	0-40	36-924.0	20-5,300	0-4,300
Silver		0.050-176.4				
Gold		0.013-24.89				
Palladium		0.038-2.207				
Platinum		0.112-6.457				
Rhodium ^a		0.034				

^aOnly one plant had a measurable level of this pollutant.

Source: EPA (1979).

TABLE A-8. HAZARDOUS WASTES DESTINED FOR LAND DISPOSAL FROM THE ELECTROPLATING AND METALS FINISHING INDUSTRY (JOB SHOPS) - DATA IN METRIC TONS ON A DRY BASIS

Type of waste	1975	1977	1983
Water pollution control sludges	19,740	56,399	73,882
Process wastes	42,141	42,141	55,206
Degreaser sludges	5,434	5,434	7,118
Electroless nickel wastes	<u>11,422</u>	<u>11,422</u>	<u>15,063</u>
Total	<u>78,737</u>	<u>115,396</u>	<u>151,269</u>

Source: Hallowell et al (1976).

Metal Smelting and Refining Industry

Smelting and refining of metal includes the following major operations and industry segments:

- Coking produces the residue (coke) by the destructive distillation of coal, which serves as a fuel and a reducing agent in the production of iron and steel.
- Steel production methods include open hearth, basic oxygen furnace, blast furnace, and electric furnace.
- Steel finishing involves a number of processes that impart desirable surface or mechanical characteristics to steel.
- Ferro alloy production produces the iron-bearing products which contain considerable amounts of one or more alloying elements such as chromium, silicon, or manganese.
- Iron foundries mold or cast hot iron into desired shapes.
- Nonferrous metal smelting and refining involves the purification of nonferrous metal concentrates drawn from ores or scrap into refined metals and metal products.

A general list of the sources of potentially hazardous waste streams generated by metal smelting and refining and the constituents of these waste streams that are considered potentially hazardous or aggressive to lining materials are given in Table A-9.

TABLE A-9. POTENTIALLY HAZARDOUS WASTE STREAMS GENERATED BY THE METAL SMELTING AND REFINING INDUSTRY

Product or activity	Waste stream	Constituents that are hazardous or aggressive to liners
Coking	Ammonia still lime sludge.	Oil and grease, cyanide, naphthalene, phenolic compounds, arsenic, heavy metals.
	Decanter tank tar sludge.	Oil and grease, phenol, naphthalene, pyrites, polyaromatics, nitrogen, heterocycles, heavy metals.
Electric furnace production of steel	Emission control dusts or sludges.	Metals, e.g. chromium, lead, cadmium.
Steel finishing	Spent pickle liquor.	Metals, e.g. chromium, lead, high pH.
	Sludge from lime treatment of spent pickle liquor.	Metals, e.g. chromium, lead.
Ferro-chromium-silicon production	Emission control dust or sludge.	Metals, e.g. chromium.
Ferro-chrome production	Emission control dust or sludge.	Metals, e.g. chromium, lead.
Ferro-manganese production	Emission control dust or sludge.	Metals, e.g. chromium, lead, manganese.
Gray and ductile iron foundry (Cupola furnace)	Emission control dust or sludge.	Metals, e.g. cadmium, lead.
Primary copper smelting	Acid blowdown slurry.	Metals, e.g. antimony, arsenic, lead, cadmium, copper, selenium, zinc.
Primary lead smelter	Surface impoundment solids.	Metals, e.g. arsenic, cadmium, lead, mercury.
Primary zinc smelter	Wastewater treatment sludge or acid plant blowdown.	Metals, e.g. arsenic, cadmium, selenium, zinc.
	Electrolytic anode slimes or sludges.	Metals, e.g. lead, cadmium, zinc.
	Cadmium plant leach.	Metals, e.g. lead, cadmium, zinc.
Primary aluminum smelting	Spent potliner (cathodes).	Metals, e.g. copper, lead, cyanides, fluorides.
Secondary lead smelting	Emission control dust or sludge.	Metals, e.g. chromium, lead, cadmium, zinc.

Source: Brown, K. W., and Associates (1980; pp 368-376).

Organic Chemicals Industry

The petrochemical and organic chemicals industry is second only to petroleum refining in the volume of hazardous wastes it generates. Industrial petrochemical complexes and specialized organic chemical plants generate a wide variety of organic products and, as a result, each can generate an array of organic-rich hazardous wastes. The basic feedstocks for organic chemical producers are supplied principally by petrochemical plants and consist of gaseous and liquid fractions of crude oil produced in oil refineries. The feedstocks are used to manufacture "end use" organic products such as plastics, rubber, pharmaceuticals, paints, pesticides, organic pigments, inks, adhesives, explosives, soaps, synthetic fibers, and cosmetics. Many of the large petrochemical plants themselves also produce "end use" organic products such as pesticides, solvents, or heat transfer fluids.

Several of the segments of the organic chemicals industry, such as pesticides, pharmaceuticals, rubber, and plastics, are discussed individually in separate subsections.

The compositions of the waste streams are not well documented and many are considered to be proprietary. In addition, the waste streams can be a complex mixture of streams coming from different processes within a given plant; nevertheless, most of these waste streams will contain organic constituents as well as inorganic (EPA, 1975b).

Paint and Coatings Formulating Industries

The paint and allied products industries utilize many organic and inorganic raw materials, some of which are present in the wastes. There is no waste stream in the sense of wastes as by-products of production. The wastes come mainly from the packaging of raw materials, air and water pollution control equipment, off-grade products and spills, most of which is reclaimed and reused except for paint absorbed onto the final clean-up material. Coatings containing significant amounts of toxic metals are reworked and wastes contain little or no metallic residues. Most spoiled batches are incorporated in later batches whenever possible and spills are salvaged.

In the formulation of paint and coatings, a number of metal compounds are used as pigments; oils and polymer resins are used as bases and solvents are used as thinners. These ingredients become part of the waste as spoiled batches or spills. Such waste constitutes about 0.2% of production. Toxic chemical usage is strictly limited so a proportionally small amount of toxic substances (mainly mercury and lead) reach the waste stream from this source.

Waste wash solvents generally have higher boiling points and similar solvency to those used in the paint. Waste wash solvent is often retained and reused in later batches or is reclaimed by distillation or sedimentation on site. It may be sent to an outside contractor for processing and the recycled solvent is returned to the plant for reuse. Waste wash solvents are also incinerated and some are placed in drums that are landfilled.

Equipment used for water-thinned paints is cleaned with water and sometimes with detergent. The wash water is settled, used as a thinner for later batches of the same type of paint or, where acceptable, released to the municipal sewer system. Wash water from very dark colors, experimental, or spoiled batches is usually placed in drums that are landfilled.

The potentially hazardous materials in paints include: inorganic metals such as arsenic, beryllium, cadmium, chromium, copper, cobalt, lead, mercury, selenium, asbestos, cyanides, and organic compounds, such as halogenated hydrocarbons and pesticides (WAPORA, 1975).

Of the total estimated waste stream of 389,000 metric tons generated by the paint and coatings industry, 24.6% is potentially hazardous, 3.6% is hazardous solvents, and 0.2% is toxic chemical compounds. A detailed list of waste components and quantities is available in the reference by WAPORA, Inc. (1975). The organic constituent of the solvent can be particularly aggressive to liners based on asphalt, polymers, and, in some cases, clay soils.

Pesticide Industry

The diverse nature of the pesticide industry and the wide distribution of the products make it difficult to analyze and assess the pollutional impact of specific active ingredients and their finished formulations. For example, there were some 24,000 different formulations available from 139 manufacturers and 5,660 formulators as of February 1976. Over 50,000 different products are said to have been registered by the EPA. Each company that markets a given formulation of finished pesticide must have a registered label for it. Over 3,500 companies hold federal registrations for one or more products. In addition, many pesticides are registered for intrastate sale only; an estimated 2,000 pesticidal products are registered in California alone (Wilkinson et al, 1978).

Many pesticide wastes are aqueous solutions or suspensions of organic and halogenated organic compounds. Some biocide wastes are generated in the production of: Dieldrin, Methylparathion, Dioxin, Aldrin, Chlordane, DDD, DDT, 2,4-D, Endrin, Guthion, Heptachlor, and Lindane. Inorganic based wastes result from the production of arsenic, arsenate, and mercurial compounds. Thallium and thallium sulfate are found in rodenticide wastes (EPA, 1974a).

Pesticide wastes result largely from the periodic cleaning of formulation lines, filling equipment, spills, area washdown, drum washing, air pollution control devices, and area runoff. Wash waters and steam condensates from cleaning operations are the sources of liquid waste from the formulation lines and filling equipment. Steam cleaning condensates and rinse waters from other processing units such as the mix tanks, drum washers, and air pollution control equipment are also sources of pesticide wastes. The scrubber waters themselves are a waste stream with area washdown, leaks, and spills making up the remaining principal sources.

The principal constituents of wastewaters from the pesticide industry are dissolved organics, suspended solids, dissolved inorganic solids, and variable pH. As stated above, the great variety of manufactured end products effectively precludes the presentation of a "general" waste composition chart or table. Again, it is the water and the dissolved constituents that may be aggressive toward liner materials.

Because of the great range of sizes of pesticide manufacturing plants, it is plausible to expect the following developments to occur with respect to the disposal of generated wastes. For the small generator, the produced waste, due to small total volume and small relative volume, might be accepted into a municipal wastewater management system. In such an instance, the pollution impact, if discernible, would be minor. For the large generator, the facility would probably have its own wastewater pretreatment or treatment system; in this case, the waste would most likely be partially treated, then concentrated. The concentrated waste would be disposed of in a landfill, or stabilized or containerized and then placed in a landfill.

Petroleum Refining Industry

Different waste streams generated by the petroleum refining industry vary with the refining process. Highly caustic sludges result from operations including washing, sweetening, and neutralizing. Spent caustic solutions are discharged from alkylation, and isomerization units, and low pressure gas (LPG) treating processes. The waste stream is roughly 3-3.5% NaOH by weight. Oily refinery sludges contain sand, silt, heavy metals, and an array of organic compounds in addition to oil and water. The oil content of such wastes ranges from 1-82% by weight. Table A-10 presents concentrations and quantities of several wastes resulting from refining processes.

The oils, organics, high pH, and high ion concentrations may all be harmful to landfill or disposal site liners. Compatibility studies should be made before installing liners for this class of waste (Landreth, 1978).

Pharmaceutical Industry

Wastes generated by the pharmaceutical industry include chemically and biologically derived components. Many biological wastes may be treated by standard wastewater treatment methods, others are incinerated or landfilled.

Wastes containing heavy metals, Cr, Zn, Hg, etc. are produced in limited quantities. The metals are recovered from these wastes and the residues are landfilled under carefully controlled conditions. Solvents are recycled or incinerated. Nonhazardous solid wastes which include biological sludge from wastewater treatment, aluminum hydroxide, magnesium, and sodium salts (McMahan et al, 1975) are usually landfilled.

The major waste producing processes are extraction and concentration (product by product), and equipment washings. See Table A-11 for raw waste sources and constituents. Biological wastes result from the production of vaccines, serums, and other products derived or extracted from plant and

TABLE A-10. RANGES OF CONCENTRATIONS AND TOTAL QUANTITIES FOR REFINERY SOLID WASTE SOURCES

(All Values in Milligram Per Kilogram Except Where Noted)

Parameters	Sludge from clarified once through cooling water	Exchange bundle clearing sludge	Slop oil emulsion solids	Cooling tower sludge	API/Primary clarifier-separator bottom	Dissolved air flotation float	Kerosene filter clays	Lube oil filter clays	Waste biosludge
Phenols	0.0-2.1	8-18.5	5.7-68	0.6-7.0	3.8-156.7	3.0-210	2.0-25.2	0.05-6.4	1.7-10.2
Cyanide	0.01-0.74	0.0004-3.3	0-4.6	0-14	0-43.8	0.01-1.1	Trace	0.01-0.22	0-19.5
Selenium (Se)	0.1-1.7	2.4-52	0.1-6.7	0-2.4	0-7.6	0.1-4.2	0.01-26.1	0.1-2.1	0.01-5.4
Arsenic (As)	0.1-18	10.2-11	2.5-23.5	0.7-21	0.1-32	0.1-10.5	0.09-14	0.05-1.4	1.0-0.6
Mercury (Hg)	0.42-1.34	0.14-3.6	0-12.2	0-0.1	0.04-7.2	0.07-0.89	0-0.05	0.04-0.33	0-1.28
Beryllium (Be)	0.013-0.63	0.05-0.34	0-0.5	Trace	0-0.43	0-0.25	0.025-0.35	0.025-0.5	Trace
Vanadium (V)	15-57	0.7-50	0.17-75	0.12-42	0.5-48.5	0.05-0.1	13.2-42	0.5-65	0.12-5
Chromium (Cr)	16.6-103	310-311	0.1-1325	181-1750	0.1-6790	2.8-260	0.9-25.8	1.3-45	0.05-475
Cobalt (Co)	5.5-11.2	0.2-30	0.1-82.5	0.38-7	0.1-26.2	0.13-85.2	0.4-2.3	1.3-5	0.05-1.4
Nickel (Ni)	20.5-39	61-170	2.5-288	0.25-50	0.25-150.4	0.025-15	0.025-15	0.25-22	0.013-11.3
Copper (Cu)	56-180	67-75	8.5-111.5	49-363	2.5-550	0.05-21.3	0.4-12,328	0.5-8.0	1.5-11.5
Zinc (Zn)	93-233	91-297	60-656	118-1,100	25-6,596	10-1,825	6.6-35	0.5-115	3.3-225
Silver (Ag)	0.84-1.3	Trace	0-20.1	0.01-1.6	0.05-3	0-2.8	0.02-0.7	0.013-1.0	0.1-0.5
Cadmium (Cd)	0-1.0	1.0-1.5	0.025-0.19	0.06-0.6	0.024-2.0	0-0.5	0.19-0.4	0.025-1.5	0.16-0.54
Lead (Pb)	17.2-138	0.5-155	0.25-380	1.2-89	0.25-83	2.3-1,320	4.25-12	0.25-2.3	1.2-17
Molybdenum (Mo)	0.5-33	1.0-12	0.25-30	0.25-2.5	0.25-60	0.025-2.5	0.012-8.8	0.025-0.05	0.25-2.5
Ammonium Salts (as NH ₄ ⁺)	0.01-13	5-11	0-44	0.07-14	0.05-24	8.7-52	ca 0.01	2-4	28-30
Benz-a-pyrene Oil (wt., %)	0-1.8 0.24-17.0	0.7-3.6 8-13	0-0.01 23-62	0-0.8 0.07-4.0	0-3.7 3.0-51.3	0-1.75 2.4-16.9	1.7-1.8 0.7-5.6	0.02-0.2 ca.3.9	Trace 0.01-0.53
Total weight Metric tons/year	9.7-18.0	0.4-1.0	1.4-29.2	0.1-0.13	0.3-45	13.6-31.0	0.79-127	102-682	1.8-38.5

Continued . . .

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TABLE A-10. (CONTINUED)

Parameters	Coke fines	Silt from Storm water runoff	Leaded tank bottoms	Non-leaded product tank bottoms	Neutralized HF alkylation sludge (CaF ₂)	Crude tank bottoms	Spent line from boiler feedwater treatment	Fluid catalytic cracker catalyst fines
Phenols	0.4-2.7	6.3-13.3	2.1-250	1.7-1.8	3.2-15.4	6.1-37.8	0.05-3.6	0.3-10.5
Cyanide	Trace	0.48-0.95	Trace	0-14.7	0.21-4.6	0.01-0.04	0-1.28	0.01-1.44
Selenium (Se)	0.01-1.6	1.1-2.2	0.1-3.1	1.5-22.4	0.1-1.7	5.8-53	0.01-9.2	0.01-1.4
Arsenic (As)	0.2-10.8	1.0-10	63-455	Trace	0.05-4.5	5.8-53	0.01-2.3	0.05-4.0
Mercury (Hg)	0-0.2	0.23-0.36	0.11-0.94	0.41-0.04	0.05-0.09	0.07-1.53	0-0.5	0-0.16
Beryllium (Be)	0-0.2	Trace	Trace	0.025-0.49	0.012-0.13	Trace	Trace	0.025-1.4
Vanadium (V)	400-3,500	25-112	1.0-9.8	9.1-34.6	0.25-5	0.5-62	0-31.6	74.4-1,724
Chromium (Cr)	0.02-7.5	32.5-644	9.0-13.7	12.7-13.1	0.75-5	1.9-75	0.025-27.9	12.3-19
Cobalt (Co)	0.2-9.2	11.0-11.3	26.5-71	5.9-8.2	0.3-0.7	3.8-37	0-1.3	0.25-37
Nickel (Ni)	350-2,200	30-129	235-392	12.4-41	7.4-103	12.8-125	0.13-26.2	47.5-950
Copper (Cu)	3.5-5.0	14.8-41.8	110-172	6.2-164	2.5-26	18.5-194	0.22-63.2	4.1-336
Zinc (Zn)	0.2-20	60-396	1190-17,000	29.7-541	7.5-8.6	22.8-425	2.0-70	19-170
Silver (Ag)	0.01-3.0	0.4-0.6	0.05-1.7	0.5-0.7	0.12-0.25	0.03-1.3	0.05-0.7	0.5-8.0
Cadmium (Cd)	0.015-2	0.1-0.4	4.5-8.1	0.25-0.4	0.012-0.12	0.025-0.42	0-1.3	0-0.5
Lead (Pb)	0.5-29	20.5-86	158-1,100	12.1-37.3	4.5-9.6	10.9-258	0.01-7.3	10-274
Molybdenum (Mo)	0.1-2.5	6.3-7.5	0.5-118	0.25-18.2	Trace	0.025-95	0-0.05	0.5-21
Ammonium Salts (as NH ₄ ⁺)	No value	1.0	No value	0.2	Trace	2.0	Trace	No value
Benz-a-pyrene	Trace	0.03-2.5	0.02-0.4	0.3-0.9	No value	0-0.6	Trace	0-1.0
Oil (wt., %)	0-1.3	2.2-5.5	18.9-21	45.1-83.2	6.7-7.1	21-83.6	0.04-0.5	0.01-0.8
Total Weight Metric tons/year	0.06-4.2	2.7	0.2-1.3	34.7-77	28-67	0.14-0.26	28.5-214.7	0.65-23.6

Source: Stewart (1978).

TABLE A-11. RAW WASTE CONSTITUENTS FROM THE PHARMACEUTICAL INDUSTRY
(g/kg Production)

Area or Process	TDS	NO ₃ -N	Total P	Oil and grease	Cl	SO ₄	Sulfide	Total hardness	Ca	Mg	Cu	Phenol
Fermentation	5.990	4.68	22.0	413	1.260	274	...	294	123	30	0.005	0.15
Biological products and natural extractive manufacturing	895	0.02	7.3	3.62	211	277	...	...	36.4	...	0.12	0.073
Chemical synthesis	1.060	0.20	7.83	21.6	104	203	...	61.6	15.2	5.68	0.002	0.16
Formulation	11.3	0.053	0.15	0.78	2.51	0.52	0.007	5.82	1.01	...	0.001	...
Research	1.33	Trace	0.23	...	0.94	1.27	...	...	...	...	...	...

Source: Riley (1974).

animal sources. Fermentation and chemical synthesis wastes resulting from this industry frequently are a mixture of aqueous, organic, and inorganic constituents.

Thus, waste-liner compatibility studies are essential before lining a disposal site for this complex type of waste.

Pulp and Paper Industry

The companies that make up the pulp and paper industry are large, diverse corporations that produce pulp, paper, and paperboard. The activities of this industry that produce wastes include chemical wood pulping, wastepaper pulping, paper production, de-inking of recycled paper, paperboard production, electricity production, and wastepaper reclamation. The waste streams that are associated with these activities are wastewater-treatment sludge, bark and hog fuel wastes, coal and bark ash, and wastepaper reclamation wastes. Table A-12 presents analyses of various sludges that are generated by the pulp and paper industry.

TABLE A-12. CHEMICAL ANALYSIS OF PRIMARY AND SECONDARY TREATMENT SLUDGES FROM THE PULP AND PAPER INDUSTRY

Constituent ^a	Primary and secondary sludge from semi-chemical pulping	De-inking sludge #1 (recycled paper)	De-inking sludge #2	Pretreatment sludge from paper coating	Board mill sludge	Combined primary and secondary sludge
Water (%)	90-96	77.06	...	86	...	40
Solids (%)	4-10	22.4	...	14	...	60
Ash (%)	1-2.5	...	...	...	...	40
COD	60,000-120,000	...	...	400,000	...	...
Phenol	5	...	...	...	...	...
PCB	<13	...	...	...	...	...
Oil and grease	1	...	...	...	...	...
Total nitrogen	1,400	...	...	...	...	4
Aluminum	...	21,300	...	100,000	...	...
Cadmium	1.5	32	...	...	...	4.6
Calcium	4,000-15,000	4,390	...	...	...	...
Chloride	...	332	...	...	...	...
Chromium	...	20	180	...	79	16
Copper	ND ^b	...	330	...	62	...
Iron	...	538	1,500	200,000	2,400	...
Lead	120	32	1,300	...	380	47
Magnesium	...	1,170	...	...	...	...
Manganese	250	16	...	...	...	1,146
Nickel	25	2.3	8	3,000	11	52
Phosphorous	...	310	...	...	...	2
Potassium	1,600	114	...	...	...	...
Sodium	1,400	146	...	...	...	...
Sulfate	120	0.03	...	...	...	...
Zinc	260	151	300	4,000	350	397

^aIn ppm unless otherwise noted.

^bND = none detected.

Source: Energy Resources Company (1979) and EPA (1979).

The pulping processes can be classified into chemical and mechanical processes. However, it is the chemical pulping operations that generate the hazardous waste streams through the use of chemicals to separate the fibers from the lignin in the wood. The kraft or sulfate pulping process generates sludges high in chromium, lead, and sodium, as shown in Table A-12. Fortunately, a large proportion of the plants using this process recycle many of their wastes, including the burning of the lignin as fuel.

Wastewater treatment sludges arise from primary treatment such as settling, filtration and flotation, and secondary treatment in activated sludge and aerated lagoons. The concentration of specific pollutants may vary widely, depending upon the fibers and processes used.

Most of the pulping plants produce their own electricity from coal, oil, and bark. The bark ashes that are generated contain a low content of toxic metals. The coal ashes are similar to those discussed under the electric power industry.

Rubber and Plastics Industry

The rubber and plastics industry includes the production and manufacture of several types of natural and synthetic polymers. The properties and constituents of environmental concern in the process waste streams are:

Alkalinity	Aluminum
Color	Antimony
Cyanides	Cadmium
Dissolved solids (principally inorganic chemicals)	Chromium
Fluorides	Cobalt
Nitrogenous compounds (organics, amines, and nitrates)	Copper
Numerous organics chemicals	Iron
Oils and greases	Lead
pH	Magnesium
Phenolic compounds	Manganese
Phosphates	Mercury
Sulfides	Molybdenum
Temperature	Nickel
Turbidity	Vanadium
	Zinc

The major pollutants in the wastewater from the rubber products industry are oil, grease, suspended solids, and extreme pH. The synthetic rubber industry has a wastewater of high COD and BOD contents; heavy metals, cyanides, and phenols are usually present in less than 0.1 mg/L concentrations (Riley, 1974). The oils, organics, and metal ions are all potentially damaging to various lining materials (Landreth, 1978). Concentrations of individual wastewater contaminants are frequently not reported, but the waste stream in general is characterized by COD, BOD₅, TSS, TDS, and TOC (Becker, 1974 and 1975).

Soap and Detergent Industry

Soap manufacturing produces wastes high in fatty acids, zinc, alkali earth salts, and caustic soda. Glycerine is formed as a by-product of soap production but much of this is recovered and recycled. Sulfuric acid and sulfonic acid are used in the preparation of some soaps; the pH of the wastes generated in these processes is very low. Soap production wastes also include alcohols and alkylbenzenes. The waste stream is generally high in

COD, BOD₅, TDS, acidity, oil, and grease, as indicated in the EPA publication on soap and detergent manufacturing (Gregg, 1974), which is a good source of additional information on the manufacturing processes, waste constituents, and waste disposal techniques for this industry.

Soap and detergent industry waste is emphasized here due to the potential synergistic effects it may have upon a liner by creating a broader dispersion of pollutants from mixing.

URANIUM TAILINGS

The chemical compositions of several acidic uranium tailings leachates are presented in Table A-13 (Mitchell and Spanner, 1984). There are also alkaline leachates (Williams, 1982).

Organic constituents in the leachate are not reported in the literature, though trace amounts may be present. Typically, organics such as kerosene, alkyl amine, and alcohol are used to remove uranium from the pregnant leachate, but their fate in the milling process is uncertain (US NRC, 1980). Of the organics, kerosene is probably the only organic component that could threaten a polymeric FML at a tailings pond.

OTHER NONRADIOACTIVE WASTES

Large amounts of nonradioactive wastes are generated by two major industries, the coal-fired electric power industry and the mining industry. These industries generate large quantities of wastes, some of which are potentially hazardous and may have to be impounded in lined storage or disposal facilities. The wastes from both industries are characterized by their inorganic nature and trace metal content. Neither waste contains significant organic material. In view of the magnitude and variety of the wastes and the anticipated growth of the industries, some of the specific wastes are described and briefly discussed in the following subsections.

Coal-Fired Electric Power Industry

The wastes produced by this industry fall into two major groups. The first group consists of the following high-volume wastes: fly ash, bottom ash, flue-gas desulfurization sludges and slurries, and combinations of these. The second group consists of a variety of low-volume wastes, some of which may be hazardous. The latter group includes:

- Air-preheater waste water.
- Coal pile drainage.
- Cooling water, once through.
- Cooling water, recirculating.
- Metal cleaning waste water: boiler, fireside; boiler, waterside.

TABLE A-13. URANIUM MILL LEACHATE COMPOSITIONS^a

Major species	Highland Mill ^b	NRC Model Mill ^c	EPA TRU values ^c	Sweetwater Mill ^d
Al	600	2000	700-1600	151-180
As	1.8	3.5	0.2	0.4
Ca	537	500	1.4-2.1	61-127
Cd	<0.1	0.2	0.08-5	NDE ^e
Cl	97.1	300		40-100
Cr	2.7		0.02-2.9	2.0
Cu	2.3	50	0.7-8.6	1.0
F		5		0.5-1.6
Fe	2215	1000	300-3000	495-1350
Hg		0.07		0.004
K				1-610
Mg	688		400-700	124
Mn	63.5	500	100-210	23
Mo	<5	100	0.3-16	0.1
Na	343	200		100-109
NH ₃		500		
Ni	3		0.13-1.4	1.3
P	30			0.05-0.09
Pb	<1	7	0.8-2	<1
Se		20		0.03
Si	233.5			186-281
SO ₄	12850	30000		9312-9529
V		0.1	0.1-120	2.8-3.2
Zn	8.4	80	...	1.6-31
pH (units)	1.8	2.0	...	0.9-1.99
<u>Radionuclides, pCi/L^f</u>				
Pb-210	250	...	...	1541
Po-210	250	...	...	361
U	3300	...	...	5.4 (ppm)
Ra-226	250	...	...	47.99
Th-230	90,000	...	...	3035
Bi-210	250	...	...	...

^aValues in parts per million (ppm).

^bGee et al (1980).

^cUS NRC (1980).

^dFrom site visit.

^eND = none detected.

^fPico Curie per Liter.

Source: Mitchell and Spanner (1984).

- Water-treatment wastes, especially brines.
- Miscellaneous wastes, such as equipment washdown, floor drainage, and sanitary wastes.

High-Volume Wastes

High volume wastes generated by electric utilities consist of the various types of ash produced during fuel combustion and the waste produced from flue-gas desulfurization systems. Generally, the components of the high volume wastes are: fly ash, which is collected from the flue gas; bottom ash and boiler slag, which accumulate inside the boiler; and flue gas desulfurization (FGD) sludge, which is produced in the process of removing sulfur dioxide gas from the flue gas. Fly ash is usually an extremely fine powder, bottom ash consists of granular particles, while slag consists of fused ash deposits.

The amounts of ash produced from a given system are primarily dependent on coal characteristics and on ash collection efficiency. For example, most coal in the United States has coal ash content ranging between 6 and 20 percent depending on the coal source, thus actual amounts of ash produced at a particular site could vary by a factor of 3 to 4 for the same amount of coal burned. The proportion of fly ash to bottom ash is dependent on coal characteristics, coal preparation prior to combustion, and the type of boiler furnace used. The volume of FGD sludge also varies widely, since volumes are influenced by fuel sulfur content, the FGD process used, as well as additives to the sludge, such as lime, limestone, or fly ash.

Large quantities of ash (fly ash and bottom ash) are produced by coal-fired power plants with disposal by ponding (sluiced or wet ash) or by landfilling (dry ash collection and transport). For the most part, ashes are fine particles that do not interact with most liner materials. Table A-14 presents data on ash pond liquids. Several documents (Engineering Science, 1979; EPRI, 1979 and 1980) present excellent background information.

Flue-gas cleaning wastes include the previously mentioned fly ashes and desulfurization sludges. As much as possible, the water in desulfurization sludges is recovered and recycled within the process system. Flue-gas desulfurization (FGD) sludges vary widely in composition and characteristics. Because of the large quantities and the thixotropic nature of most unstabilized FGD sludge, it could pose a significant potential for pollution. Stabilized FGD sludge, in its many forms, is desirable because of improved structural stability, reduced moisture content, reduced total volume, reduced permeability, and improved handling (EPRI, 1980). The data presented in Table A-15 show the range in values of several constituents and parameters for three different FGD systems. Additional data and information is available (EPRI, 1979 and 1980; Leo and Rossoff, 1978).

TABLE A-14. ELEMENTAL MAXIMUM CONCENTRATIONS AND OTHER PARAMETERS IN VARIOUS WASTE STREAMS FROM COAL COMBUSTION^a

Element	Fly ash pond	Bottom ash/slag pond	Fly ash overflow	Ash pond leachate
Al	8.80	8.00	5.30	...
Sb	0.012	0.012	0.03	0.03
As	0.023	0.015	0.02	0.084
Ba	0.40	0.3-3.0	0.30	40.0
Be	0.02	0.01	0.003	0.003
B	24.60	24.60	1.03	16.90
Cd	0.052	0.025	0.04	0.01
Ca	180.0	563.0	...	1.00
Cl	14.0	189.0	2,415	...
Cr	0.17	0.023	0.139	...
Co	...	0.70	...	...
Cu	0.45	0.14	0.09	0.092
F	1.00	14.85	10.40	17.30
Ge	...	...	0.10	<0.10
Fe	6.60	11.0	2.90	...
Pb	0.20	0.08	...	0.024
Li	0.40	0.08	...	...
Mg	20.0	102.0	156.0	...
Mn	0.63	0.49	0.02	<0.002
Hg	0.0006	0.006	0.0002	0.015
Mo	...	0.49	0.10	0.69
Ni	0.13	0.20	0.015	0.046
P	0.06	0.23	0.41	...
K	6.60	7.00	...	...
Se	0.004	0.05	0.015	0.47
Si	15.0	51.0	...	...
Ag	0.01	0.02	...	...
Na	...	294.0	982.0	...
Sr	...	0.80	...	...
Ta	...	0.02	...	...
Ti	...	0.02	...	...
V	...	0.02	0.20	<0.20
Zn	2.70	0.16	2.50	0.19
Zr	...	0.07	...	...
TDS	820.0	404.0	3,328	...
TSS	256.0	657.0	100.0	...
Bi	...	0.20	...	...
SO ₄	...	2,300	527	...

^aData are in mg/L.

Source: EPRI (1978, pp 94 and 95).

TABLE A-15. RANGE OF CONCENTRATIONS OF CHEMICAL CONSTITUENTS IN FGD SLUDGES FROM LIME, LIMESTONE, AND DOUBLE-ALKALI SYSTEMS

Scrubber constituent	Liquor concentration, mg/L (except pH)	Solids, mg/kg
Aluminum	0.03 - 2.0	...
Arsenic	0.004 - 1.8	0.6 - 52
Beryllium	0.002 - 0.18	0.05 - 6
Cadmium	0.004 - 0.11	0.08 - 4
Calcium	180 - 2,600	105,000 - 268,000
Chromium	0.015 - 0.5	10 - 250
Copper	0.002 - 0.56	8 - 76
Lead	0.01 - 0.52	0.23 - 21
Magnesium	4.0 - 2,750	...
Mercury	0.0004 - 0.07	0.001 - 5
Potassium	5.9 - 100	...
Selenium	0.0006 - 2.7	2 - 17
Sodium	10.0 - 29,000	48,000
Zinc	0.01 - 0.59	45 - 430
Chloride	420 - 33,000	9,000
Fluoride	0.6 - 58	...
Sulfate	600 - 35,000	35,000 - 473,000
Sulfite	0.9 - 3,500	1,600 - 302,000
Chemical oxygen demand	1 - 390	...
Total dissolved solids	2,800 - 92,500	...
pH	4.3 - 12.7	...

Source: Leo and Rossoff (1978).

Low-Volume Wastes

Boiler-cleaning wastes are produced intermittently, but this waste stream contains several components that are toxic and potentially aggressive to liners (Engineering-Science, 1979; EPA, 1974b, p 143; EPA 1980, p 200). These components consist of both the chemicals used in the cleaning solution and the material removed from the heat-transfer surfaces, some of which are shown in Table A-16. There are two main types of cleaning operations: waterside and fireside. Waterside cleaning consists of cleaning the inside of tubes and other boiler water passages, usually by chemical means. Fireside cleaning is more mechanical, consisting of high pressure nozzles directed against the surfaces to be cleaned (EPA, 1974b, p 147). The cleaning solution often contains alkalis to dissolve oil and grease, and detergents to keep the removed material in colloidal suspension (Table A-17).

Water-treatment wastes can be classified into two categories: sludges from clarification, softening and filter backwashing operations; and waste brine from the several types of deionization processes. The composition of the first category depends on the raw water quality and method of treatment. Such sludges can usually be dewatered and the solid residue landfilled. The supernatant water can be recycled for other in-plant uses.

Wastes from deionization processes are characterized by a high dissolved solids concentration as shown in Table A-18. Waste brines from the regeneration of ion-exchange resins can also be highly acidic or alkaline depending upon the exchange resin being used. Such water is often neutralized and treated for suspended solids removal for subsequent use in other in-plant operations which can tolerate low quality water (EPA, 1974b, p 132; EPA 1980, p 177).

Recirculating cooling wastewater or cooling tower blowdown is the bleed stream from the recirculation water cooling system. The cooling tower blowdown contains various chemical additives to prevent scale formation, corrosion and biological fouling of surfaces. The blowdown is relatively high in total dissolved solids, usually several times the concentration of the feedwater. The potential for pollutants in blowdown is high, thus most blowdown waters are ponded. In some cases, the blowdown water is used as feedwater or make up water for sluicing ashes from boilers or for sulfur dioxide scrubbing solution (EPA, 1974b, p 115; EPA 1980, p 44).

Wastes such as once-through cooling water and coal pile runoff, which do not generally discharge to lined ponds are not discussed in this document. Once-through cooling water is usually discharged to a receiving water body, coal pile runoff occurs only occasionally and its character is dependent on the type of coal, and miscellaneous wastes are generally discharged to a municipal wastewater treatment plant.

Mining and Refining Industries

The selection of specific process and waste streams for discussion reflects, in part, the available information and the relative importance of

TABLE A-16. COMPOSITION OF BOILER BLOWDOWN

Parameter	Concentration, mg/L
<u>Conventional measures of pollution</u>	
pH	8.3 - 12.0 ^a
Total solids	125 - 1,407
Total suspended solids	2.7 - 31
Total dissolved solids	1.08 - 11.7
BOD ₅	10 - 1,405
COD	2.0 - 157
Hydroxide alkalinity	10 - 100
Oil and grease	1 - 14.8
<u>Major chemical constituents</u>	
Phosphate, total	1.5 - 50
Ammonia	0.0 - 2.0
Cyanide, total	0.005 - 0.014
<u>Trace metals</u>	
Chromium, total	ca 0.02
Chromium ⁺⁶	0.005 - 0.009
Copper	0.02 - 0.19
Iron	0.03 - 1.40
Nickel	ca 0.030
Zinc	0.01 - 0.05

^apH unit.

Source: EPRI (1978, p 58).

TABLE A-17. FIRESIDE WASTEWATER CHARACTERISTICS

Constituent	Concentration, mg/L	
	Maximum	Average
Total chromium	15	1.5
Hexavalent chromium	<1.0	0.02
Zinc	40	4.0
Nickel	900	70
Copper	250	6.0
Aluminum	21	2.0
Iron	14,000	2,500
Manganese	40	3.5
Sulfate	10,000	1,000
TDS	50,000	5,000
TSS	25,000	250
Oil and grease	Virtually absent	

Source: EPA (1980, p 213).

TABLE A-18. ION-EXCHANGE REGENERATION WASTES

Parameter	Mean value	Minimum value	Maximum value
pH, units (122 entries)	6.15	1.7	10.6
Suspended solids, mg/L (88 entries)	44	3.0	305
Dissolved solids, mg/L (39 entries)	6,057	1,894	9,645
Oil and grease, mg/L (29 entries)	6.0	0.13	22

Source: EPA (1980, p 187).

the specific streams with respect to future liner usage. There are other factors such as total pollution potential, which were also considered. Tables A-19 and A-20 present estimates of solid waste production in mining industry segments, metals, and nonmetals (except coal), respectively. The columns on tailings indicate the portion of solid waste that is most likely to need lined impoundments. It is important to note that the data presented does not include the liquid component of tailings generation.

Mining process and waste liquids are generally highly complex materials usually containing water and a wide range of inorganic and organic dissolved constituents. Residues of the reagents used in froth flotation of ores to recover the valuable minerals and found in the aqueous portion of the tailing is shown in Table A-21. Most of the organics, such as hydrocarbons, alcohols, and ethers that remain in the tailings water evaporate, decompose, or biodegrade. The inorganics generally are in low concentrations (Baker and Bhappu, 1974, p 77).

Individually, most of the constituents of mining process and waste liquids are well characterized as to their toxicity and pollution potential. The difficulty with these liquids is that they are complex blends of components that can act synergistically and be toxic and affect lining materials in a variety of ways different from individual constituents. Some liquids can also be highly concentrated and relatively simple. Analytical capabilities have developed greatly in recent years; therefore, an accurate compositional analysis can generally be made of any given liquid. The fluid must be characterized to determine its major constituents.

TABLE A-19. ANNUAL SOLID WASTE PRODUCTION STATISTICS AT SURFACE AND UNDERGROUND MINES^a - METALS

(In Thousand Short Tons)

Industry segment	Mine waste ^b	Tailings ^c	Total	Percent of total for all non-coal minerals
Bauxite	11,500	1,400	13,000	<1
Copper	378,000	260,000	638,000	29
Gold	11,800	5,400	17,200	1
Iron	277,000	175,000	452,000	20
Lead	2,270	8,900	11,200	<1
Molybdenum	13,100	30,400	43,500	2
Silver	2,010	1,900	3,910	<1
Tungsten	210	1,750	1,960	<1
Uranium	306,000	16,200	322,000	14
Zinc	1,270	6,700	7,970	<1
Other ^d	<u>17,000</u>	<u>e</u>	<u>17,000</u>	<u>1</u>
Total	1,020,000	508,000	1,510,000	68

^aBased on data obtained from 1978-79 Minerals Yearbook, U.S. Bureau of Mines.

^bIncludes overburden from surface mining operations and waste discarded on the surface from underground mining operations.

^cEstimated by PEDCO from data in the 1978-79 Minerals Yearbook.

^dAntimony, beryllium, manganiferrous ore, mercury, nickel, rare earth metals, tin, and vanadium.

^eQuantitative information on these wastes are not compiled since relatively insignificant amounts are generated.

Source: PEDCO (1981).

TABLE A-20. ANNUAL SOLID WASTE PRODUCTION STATISTICS AT SURFACE AND UNDERGROUND MINES^a - NONMETALS

(In Thousand Short Tons)

Industry segment	Mine waste ^b	Tailings ^c	Total	Percent of total for all non-coal minerals
Asbestos	4,150	2,180	6,330	<1
Clays	43,000	0	43,000	2
Diatomite	d	d	d	d
Feldspar	192	920	1,110	<1
Gypsum	2,700	700	3,400	<1
Mica (scrap)	467	1,310	1,780	<1
Perlite	107	294	401	<1
Phosphate rock	420,000	136,000	556,000	25
Potassium salts	163	17,200	17,400	<1
Pumice	108	210	318	<1
Salt	d	1,100	1,100	<1
Sand and gravel	d	6,000	6,000	<1
Sodium carbonate (natural)	322	5,080	5,410	<1
Stone:				
Crushed or broken	82,400	0	82,400	4
Dimension	1,620	2,830	4,450	<1
Talc, soapstone, pyrophyllite	<u>1,460</u>	<u>420</u>	<u>1,880</u>	<u><1</u>
Total	572,000	174,000	724,000	32

^aBased on data obtained from 1978-79 Minerals Yearbook, U.S. Bureau of Mines.

^bIncludes overburden from surface mining operations and waste discarded on the surface from underground mining operations.

^cEstimated by PEDCO from data in the 1978-79 Minerals Yearbook.

^dQuantitative information on these wastes are not compiled since relatively insignificant amounts are generated.

Source: PEDCO (1981).

TABLE A-21. COMMON FLOTATION REAGENTS USED IN THE RECOVERY OF MINERALS FROM ORES

Reagent type and name	Chemical composition	Amount added	Reagents distribution		Toxic species
			Solids	Solution	
Collectors					
Xanthate	ROCSSH	<0.1	Mostly complexed	Minor	CS ₂
Thiophosphates	(RO) ₂ PSSH	<0.1	Mostly complexed	Minor	H ₂ PO ₄ ⁻ , HS ⁻ , H ₂ S
Fatty acids	RCOOH	0.5 to 2.0	Complexed with minerals and ions	Minor	Biodegradable
Sulfonates and sulfates	RSO ₃ H RSO ₄	0.5 to 2.0	Complexed with minerals and ions	Minor	Biodegradable (except cyclic)
Amines	RNH ₂ Acetate	0.2 to 2.0	Absorbed on silicates	Minor	Free amine ^a
Fuel oils	Saturated	0.1	Selectively absorbed	Minor	Volatile hydrocarbons
Frothers					
Pine oil	Aromatic alcohols	<0.1	Carried over in froth	Appreciable	Volatile, carcinogenic
Dow froth	Higher alcohols	<0.1	Carried over in froth	Appreciable	Volatile, biodegradable
MIBC	Methyl isobutyl-carbinol	<0.1	Carried over in froth	Appreciable	Volatile, biodegradable
Conditioners					
Sodium sulfides	Na ₂ S, NaHS	1 to 15	Selectively complexed	Major	HS ⁻ , H ₂ S, SO ₄ ⁻
Phosphorous pentasulfide	P ₂ S ₅	1 to 4	Selectively complexed	Major	HS ⁻ , H ₂ S
Sodium cyanide	NaCN	0.005 to 0.1	Mostly complexed	Minor	CN ⁻
Sodium silicate	Na ₂ SiO ₃	0.2 to 1.0	Mostly complexed	Appreciable	H ₄ SiO ₄
Milk of lime	Ca(OH) ₂	1 to 4	Mostly complexed	Appreciable	OH ⁻
Separan	Polyacrylamide	<0.01	Mostly absorbed	Minor	Biodegradable

^aUnknown toxicity.

Source: Baker and Bhappu (1974, p 77).

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APPENDIX B

REPRESENTATIVE LIST OF ORGANIZATIONS IN THE LINER INDUSTRY

As of June 1988

A. POLYMERIC FLEXIBLE MEMBRANE LINERS

1. Polymer producers
2. Manufacturers of polymeric membrane sheetings
3. Fabricators of liners
4. Installing contractors

B. OTHER LINER MATERIALS

APPENDIX B (Continued)

A. POLYMERIC FLEXIBLE MEMBRANE LINERS

1. Polymer Producers

ALLIED CHEMICAL CORPORATION
P.O. Box 53006
Baton Rouge, LA 70805

Contact: Patrick Snell
Phone: (504) 775-4330

CHEVRON CHEMICAL COMPANY
FM1006
Orange, TX 77630

Contact: George L. Baker
(409) 882-2167

B.F. GOODRICH CHEMICAL COMPANY
6100 Oak Tree Blvd.
Cleveland, OH 44131

Phone: (216) 447-6000

DOW CHEMICAL CO.
2040 Dow Center
P.O. Box 1847
Midland, MI 48640

Contact: David M. Cheek
Marketing Manager
Polyethylene Group
Plastics Department
Phone: (517) 636-1000, Ext. 0151

E.I. du PONT de NEMOURS & CO., INC.
Polymer Products Department
Wilmington, DE 19898

Contact: Inquiry Handling Center
Phone: (800) 441-7111

Contact: Austin Snow
Sr. Marketing Rep. - Hytrel
Barley Mill Plaza,
Garrett Mill Building
Wilmington, DE 19898
Phone: (302) 992-3296

EXXON CHEMICAL CO.
Elastomer Technology Division
P.O. Box 45
Linden, NJ 07036

Contact: S. Alexander Banks
Phone: (201) 474-0100

MONSANTO INDUSTRIAL CHEMICALS CO.
260 Springside Drive
Akron, OH 44313

Contact: Michael A. Fath
Product Development Manager
Phone: (216) 666-4111

OCCIDENTAL CHEMICAL COMPANY
300 Berwyn Park, Suite 300
P.O. Box 1772
Berwyn, PA 19312

Contact: Rich Webb
Phone: (215) 251-1070

PHILLIPS CHEMICAL CO.
Bartlesville, OK 74004
Phone: (918) 661-6600

POLYSAR, LTD.
Elastomers Research and Development
Division
Vidal Street
Sarnia, Ontario
CANADA N7T 7M2

Contact: Charles McGinley
Application Development Specialist
Industrial Products Group
Phone: (519) 337-8251

SHELL CHEMICAL COMPANY
605 N. Main Street
Altamont, IL 62411

Contact: Larry Watkins
Phone: (618) 483-6517

APPENDIX B (Continued)

A. POLYMERIC FLEXIBLE MEMBRANE LINERS

1. Polymer Producers

SOLTEX POLYMERS CORPORATION
P.O. Box 27328
Houston, TX 77227

Contact: Richard Koob
Marketing Manager for
Extrusion Polyethylene
Phone: (713) 522-1781

UNION CARBIDE CORPORATION
Polyolefins Division
39 Old Ridgebury Road
Danbury, CT 06817

Contact: Christer Rundlof
Phone: (203) 794-2050

UNIROYAL CHEMICAL CO.
Spencer Street
Naugatuck, CT 06488

Contact: Thomas L. Jablonowski
Phone: (203) 723-3205

APPENDIX B (Continued)

A. POLYMERIC FLEXIBLE MEMBRANE LINERS

2. Manufacturers of Polymeric Membrane Sheetings

B. F. GOODRICH CO.
Engineered Rubber Products Division
500 S. Main Street
Akron, OH 44318

Contact: Larry Cifoni
Phone: (216) 374-3115

BURKE RUBBER CO.
2250 South Tenth Street
San Jose, CA 95112

Contact: Larry Schader, Sales Manager
Flexible Membranes
Phone: (408) 297-3500

COOLEY, INC.
50 Esten Avenue
Pawtucket, RI 02862

Contact: Paul Eagleston
Vice President
Phone: (401) 724-9000

DUNLOP CONSTRUCTION PRODUCTS, INC.
2055 Flavelle Blvd.
Mississauga, Ontario
CANADA L5K 1Z8

Contact: Robert Rayfield
Phone: (416) 823-8200

DYNAMIT NOBEL, INC.
10 Link Drive
Rockleigh, NJ 07647

Contact: Bernard Strauss
Customer Service Rep.
Phone: (201) 767-1660

GUNDLE LINING SYSTEMS, INC.
1340 East Richey Road
Houston, TX 77073

Contact: Hal Pastner, Vice President
Phone: (713) 443-8564 (Texas)
(800) 435-2008 (National)

LORD CORPORATION
Film Products Division
2000 W. Grandview Blvd.
P.O. Box 10038
Erie, PA 16514-0038

Contact: G. J. Bartko
Phone: (814) 868-3611, Ext. 3278

NATIONAL SEAL CO.
1255 Monmouth Blvd.
Galesburg, IL 61402-1448

Contact: John Hardison
Vice President
Hans Poetsch
Phone: (800) 323-3820
(312) 359-7810

OCCIDENTAL CHEMICAL CORPORATION
P.O. Box 456
Burlington, NJ 08016

Contact: Tim Kronbach
Phone: (609) 499-2300, Ext. 2207

POLY-AMERICA, INC.
2000 W. Marshall Drive
Grand Prairie, TX 75051

Contact: William C. Neal
Vice President, Marketing
Phone: (800) 527-3322
(214) 647-4374

APPENDIX B (Continued)

A. POLYMERIC MEMBRANE LINERS

2. Manufacturers of Polymeric Membrane Sheetings

SARNAFIL (U.S.), INC.
Canton Commerce Center
Canton, MA 02021

Contact: Marc Caputo
Phone: (617) 828-5400

SLT NORTH AMERICAN, INC.
P.O. Box 7730
The Woodlands, TX 77380

Contact: Lawrence J. Cirina
President
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SHELTER-RITE, INC.
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STEVENS ELASTOMERICS
J. P. Stevens & Co., Inc.
P.O. Box 658
Northhampton, MA 01061

Contact: Arnold G. Peterson
Phone: (413) 586-8750

APPENDIX B (Continued)

A. POLYMERIC MEMBRANE LINERS

3. Fabricators of Liners

ALASKA TENT & TARP, INC.
529 Front Street
Fairbanks, AK 99701

Contact: David Applebee
Phone: (907) 456-6328

COLUMBIA RESERVOIR SYSTEMS, LTD.
6814 - 6th S.E., Bay K
Calgary, Alberta
CANADA T2H2K4

Contact: Neil McLeod
Phone: (403) 252-9772

in USA
COLUMBIA GEO-SYSTEMS

Contact: Kevin Wynkoop
Phone: (303) 394-3766

ENGINEERED TEXTILE PRODUCTS
P.O. Box 7474
Mobile, AL 36607

Contact: John Robinson, President
Phone: (205) 479-6581

ENVIRONMENTAL LINERS, INC.
2009 N. Industrial Road
Cortez, CO 81321

Contact: Stuart Stroud
Phone: 1-800-821-0531
(303) 565-9540

ENVIRONMENTAL PROTECTION, INC.
111 West Park Drive
Kalkaska, MI 49646

Contact: Fred Rohe, President
Phone: (800) 345-4637
(616) 587-9208

ENVIRONETICS, INC.
9824 Industrial Drive
Bridgeview, IL 60455

Contact: Ray Winters, President
Phone: (312) 585-6000

LAYFIELD PLASTICS
14604 115A Avenue
Edmonton, Alberta
CANADA T5M3C5

Contact: Imre Bogovics
Phone: (403) 453-6731

MIDESSA LINING COMPANY
5203 West 42nd, Route 4
Odessa, TX 79764

Contact: Rubin Velasquez
Phone: (915) 381-2077

MPC CONTAINMENT SYSTEMS, LTD.
4834 South Oakley
Chicago, IL 60609

Contact: Jack Moreland
Vice President, Engineering
Phone: (800) 621-0146

PALCO LININGS, INC. (WEST)
7571 Santa Rita Circle
P.O. Box 919
Stanton, CA 90680

Contact: Richard Cain, President
Phone: (714) 898-0867

PALCO LININGS, INC. (EAST)
2500-B Hamilton Road
South Plainfield, NJ 07080

Contact: John Kursten
Phone: (201) 753-6262

APPENDIX B (Continued)

A. POLYMERIC MEMBRANE LINERS

3. Fabricators of Liners

PROTECTIVE COATINGS, INC.
1602 Birchwood Avenue
Ft. Wayne, IN 46803

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Phone: (219) 424-2900

REVERE PLASTICS
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Contact: Ed Smith
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SERROTT CORPORATION
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Huntington Beach, CA 92647

Contact: G. M. Torres
President
Phone: (714) 848-0227

STAFF INDUSTRIES
240 Chene Street
Detroit, MI 48207

Contact: Ed Staff Sr., President
Ed Staff Jr., Vice President
Phone: (313) 259-1820
(800) 526-1368

STAFLEX CORPORATION
1501 Lana Way
Hollister, CA 95023

Contact: Paul Weber
Phone: (408) 637-6622

UNIT LINER COMPANY
P.O. Box 789
Shawnee, OK 74884

Contact: Russell Fregia
Phone: (405) 275-4600

WATERSAVER COMPANY, INC.
5890 East 56th Avenue
Commerce City, CO 80022

P.O. Box 16465
Denver, CO 80216

Contact: Jim Bryan
Vice President
Phone: (303) 289-1818

MANUFACTURER WHO ALSO FABRICATES

National Seal Company

APPENDIX B (Continued)

A. POLYMERIC MEMBRANE LINERS

4. Installing Contractors

AQUILINE SYSTEMS
P.O. Box 72099
Corpus Christi, TX 78472-2099

Contact: John M. Saenz

CRESTLINE SUPPLY CORPORATION
2987 South 300 West
Salt Lake City, UT 84115

Contact: Guy Woodward, President
Phone: (801) 487-2233

GAGLE COMPANY, INC.
P.O. Box 701193
Tulsa, OK 74170

Contact: Gary Willis, Manager
Sales and Contracts
Phone: (918) 258-7078

GASTON CONTAINMENT SYSTEMS, INC.
1853 North Main Street
P.O. Box 1157
El Dorado, KS 67042

Contact: Larry Gaston
Phone: (316) 321-5140

GEO CON
P.O. Box 17380
Pittsburgh, PA 15235

Contact: Michael W. Bowler
Vice President
Phone: (412) 244-8200

GULF SEAL CORPORATION
601 Jefferson Street, Suite 535
Houston, TX 77002

Contact: William J. Way
Vice President &
General Manager
Phone: (713) 759-0861

MCKITTRICK MUD CO.
P.O. Box 3343
Bakersfield, CA 93305

Contact: Gary Leary
Phone: (805) 325-5013

MWM CONTRACTING CORPORATION
2359 Avon Industrial Division
Rochester Hills, MI 48057

Contact: Jim Green
Phone: (313) 852-8910

MWM CONTRACTING CORPORATION
100 Sun Eagle Drive
Mount Dora, FL 32757

Contact: Raymond Wild
Phone: (904) 383-7148

NILEX, USA, INC.
10 Arapahoe Corporation Park
12503 E. Euclid Drive
Englewood, CO 80111

Contact: Morris Jett, Vice President
Phone: (303) 790-7222

NORTHWEST LININGS, INC.
20222 87th Avenue South
Kent, WA 98032

Contact: Rod Newton
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PLASTI-STEEL, INC.
1999 Amidon, Suite 208
Wichita, KS 67203

Contact: M. C. Green, President
Phone: (316) 832-0624

APPENDIX B (Continued)
A. POLYMERIC MEMBRANE LINERS
4. Installing Contractors

FABRICATORS WHO ALSO INSTALL

Alaska Tent & Tarp, Inc.
Columbia Reservoir Systems, Ltd.
Environmental Liners, Inc.
Environmental Protection, Inc.
Layfield Plastics
McKittrick Mud Company
Midessa Lining Company
National Seal Company
Palco Linings, Inc.
Serrot Corporation
Staff Industries
Staflex Corporation
Unit Liner Company
Watersaver Company

MANUFACTURERS WHO ALSO INSTALL

Gundle Lining Systems, Inc.
Schlegel Lining Technology, Inc.

APPENDIX B (Continued)
B. OTHER LINER MATERIALS

THE ASPHALT INSTITUTE
Asphalt Institute Building
College Park, MD 20740

Contact: E. R. Harrigan
Phone: (301) 277-2458

GACO WESTERN, INC.
P.O. Box 88698
Seattle, WA 98188

Contact: Rodney E. Bechtel
Sales Manager
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MICHELLE CORPORATION
Division of Weychem Canada Limited
P.O. Box 4794
Charleston Heights, SC 29405

Contact: F. Weyrich, President
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NATIONAL LIME ASSOCIATION
3601 N. Fairfax Drive
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PHILLIPS PETROLEUM COMPANY
Commercial Development Division
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Contact: Floyd H. Holland
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PORTLAND CEMENT ASSOCIATION
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RELIANCE UNIVERSAL, INC.
P.O. Box 1113
Houston, TX 77251

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(206) 293-3433

APPENDIX C

POLYMERS FORMERLY USED IN MANUFACTURE OF FMLS

This appendix presents information on polymers that are at present no longer being used in the manufacture of FMLs. The polymers discussed in this appendix include:

- Butyl rubber.
- Elasticized polyolefin.
- Epichlorohydrin rubbers.
- Ethylene-propylene rubber.
- Neoprene.
- Nitrile rubber.
- Thermoplastic elastomers.

Manufacture of FMLs based on these polymers was discontinued for a variety of reasons, including both technical and economic. In general, the manufacture of FMLs based on vulcanized polymers was discontinued because of difficulties in developing an adequate system for seamig vulcanized FMLs in the field.

C.1 Butyl Rubber

The first synthetic FMLs were based on butyl rubber [isobutylene-isoprene rubber (IIR)], and were used for irrigation and water impoundment; some of these have been in this type of service for about 30 years (Smith, 1980). Butyl rubber is a copolymer of isobutylene (97%), with small amounts of isoprene in the polymer chain to furnish chemically active sites for vulcanization or crosslinking. Relevant properties of butyl rubber vulcanizates that have been used as liner materials for water and waste storage, and waste disposal include:

- Low gas and water vapor permeability.
- Thermal stability.

- Moderate resistance to ozone and weathering.
- Moderate chemical and moisture resistance.
- Resistance to animal and vegetable oils and fats.

Butyl rubber is usually compounded with fillers and some oil, and vulcanized with sulfur. Vulcanizates of butyl rubber swell substantially when exposed to hydrocarbon solvents and petroleum oils, but are only slightly affected by oxygenated solvents and other polar liquids. These materials have good resistance to mineral acids, high tolerance for extremes in temperature, retention of flexibility throughout service life, good tensile strength, and desirable elongation qualities.

Butyl rubber FMLs were manufactured in both fabric-reinforced and unreinforced versions. They were difficult to seam and repair in the field because they required special vulcanizing adhesives that could crosslink at ambient temperatures. Because these adhesives crosslinked only slightly, they were generally less resistant to the service conditions than the FML itself was.

C.2 Elasticized Polyolefin

Elasticized polyolefin (ELPO) was a blend of rubbery and crystalline polyolefins. FMLs based on ELPO were introduced in 1975 as black, unvulcanized, thermoplastic sheetings, which could be heat sealed with a specially designed welder either in the field or at the factory. ELPO had a low density (0.92) and was relatively resistant to weathering, alkalies, and acids (Haxo et al, 1985). ELPO FMLs were manufactured by blow extrusion and were supplied without fabric reinforcement in sheets, 20-ft wide and up to 200-ft long.

C.3 Epichlorohydrin Rubbers

Epichlorohydrin-based elastomers (CO and ECO) are saturated, high molecular weight, aliphatic polyethers with chloromethyl side chains. The two types available are a homopolymer and a copolymer of epichlorohydrin with ethylene oxide. These polymers are crosslinked with a variety of reagents that react difunctionally with the chloromethyl group, including diamines, urea, thioureas, 2-mercaptoimidazoline, and ammonium salts.

Epichlorohydrin elastomer vulcanizates exhibit the following characteristics that were relevant to FML performance:

- Moderate resistance to hydrocarbon solvents, fuels, and oils.
- Resistance to ozone and weathering.
- Low permeability to gases and hydrocarbon vapors.
- Thermal stability.

- Good tensile and tear strengths.

Epichlorohydrin rubber has a high tolerance for extreme temperatures and retains its flexibility at low temperatures. The homopolymer has a performance range of 0° to 325°F. The copolymer shows improved low temperature flexibility and is recommended for service from -40° to 300°F. Epichlorohydrin elastomers are seamed at room temperature with vulcanizing adhesives. FMLs based on these rubbers were developed for service with nonaqueous waste streams.

C.4 Ethylene-Propylene Rubber

Ethylene-propylene rubbers (EPDM) form a family of terpolymers of ethylene, propylene, and a minor amount of nonconjugated diene hydrocarbon. The diene supplies double bonds to the saturated polymer chain so that there are chemically active sites for vulcanization. EPDM is usually vulcanized with sulfur. EPDM FMLs were generally based on vulcanized compounds; however, thermoplastic EPDM FMLs were also available. The latter generally featured EPDM of high molecular weight, high ethylene content, and high oil extension. Both thermoplastic and crosslinked versions were manufactured with and without fabric reinforcement.

FMLs based on vulcanized EPDM compounds had good resistance to weather and ultraviolet exposure and, when compounded properly, resisted abrasion and tear. They also tolerated a broad temperature range and maintained their flexibility at relatively low temperatures. They had good resistance to dilute acids, alkalis, silicates, phosphates, and brine, but were not recommended for contact with either petroleum solvents (hydrocarbons) or aromatic or halogenated solvents.

In fabricating field seams, vulcanized EPDM FMLs required special adhesives that crosslinked at ambient temperature. Careful application was necessary to assure satisfactory field seaming. These adhesives were less resistant to service conditions than the FML itself. Thermoplastic EPDM liners were generally seamed by thermal methods.

Because of its excellent ozone resistance, minor amounts of EPDM were sometimes added to butyl rubber compounds to improve weather resistance.

C.5 Neoprene

Neoprene (CR) is the generic name of the synthetic rubbers that are derived from chloroprene. These rubbers are vulcanizable, usually with metal oxides, but also with sulfur. They closely parallel natural rubber in such mechanical properties as flexibility and strength. Neoprene vulcanizates are superior to natural rubber vulcanizates in their resistance to oils, weathering, ozone, and ultraviolet radiation, and are generally resistant to puncture, abrasion, and mechanical damage. Neoprene FMLs were used primarily to impound liquids containing traces of hydrocarbons. They also reportedly performed satisfactorily in the containment of certain combinations of oils and acids which other materials, available at that time, could not contain

adequately over long periods of time. Neoprene sheeting used as FMLs was vulcanized; seaming was relatively difficult because cements and adhesives that cure at ambient temperatures had to be used.

C.6 Nitrile Rubber

Nitrile rubbers (NBR) make up a family of copolymers of butadiene and 18 to 50% acrylonitrile. The principal feature of these copolymers is their oil resistance, which increases with increasing acrylonitrile content. In most applications, nitrile rubber is compounded with plasticizers and vulcanized; however, it is also blended with other polymers such as polystyrene, phenolics, and PVC to produce thermoplastic compositions that range in flexibility from rubbery compositions to hard, impact-resistant plastics.

Nitrile rubber used in the manufacture of FMLs was generally used in blends of polymers to produce thermoplastic sheetings that were oil resistant. Nitrile rubber has been mixed with PVC in amounts less than 50% to form thermoplastic compounds in which it functions as a nonmigrating and nonextractable plasticizer.

C.7 Thermoplastic Elastomers

Thermoplastic elastomers are a broad class of rubbery materials that are thermoplastic, unvulcanized, and can contain some crystallinity (Walker, 1979). They include a wide variety of polymeric compositions from highly polar materials to the nonpolar materials, such as ethylene-propylene block polymers. It should be noted that polyester elastomers, which are thermoplastic elastomers, are presently being used in the manufacture of FMLs. These are discussed in Section 4.2.2.1.3. These polymers are plastic at the high temperatures at which they are processed and shaped. At normal ambient temperatures, they behave much like vulcanized rubbers. Products made of these polymers have a limited upper-temperature service range, which is substantially above the temperatures encountered at waste disposal sites. FMLs based on thermoplastic elastomers were heat sealed to make seams.

REFERENCES

- Haxo, H. E., R. S. Haxo, N. A. Nelson, P. D. Haxo, R. M. White, and S. Dakessian. 1985. Liner Materials Exposed to Hazardous and Toxic Wastes. EPA-600/2-84-169. U.S. Environmental Protection Agency, Cincinnati, OH. 256 pp.
- Smith, W. S. 1980. Butyl - The Original Watersaver Elastomer. In: The Role of Rubber in Water Conservation and Pollution Control. Proc. Henry C. Remsberg Memorial Education Symposium, 117th meeting, Rubber Division, American Chemical Society, May 22, 1980, Las Vegas, NV. The John H. Gifford Memorial Library and Information Center, University of Akron, Akron, OH. pp III-1 - III-19.
- Walker, B. M. 1979. Handbook of Thermoplastic Elastomers. Van Nostrand Reinhold, New York. 345 pp.

APPENDIX D

POUCH TEST FOR PERMEABILITY OF POLYMERIC FMLS

SCOPE

This test measures the permeability of polymeric FMLs to water and to various constituents of a waste liquid. Because of the need for narrow-width seams in the pouches, only those FMLs that can be heat-seamed successfully using laboratory equipment can be tested in accordance with this procedure. (Note: Even though pouches fabricated with solvents and bodied solvents have also been tested successfully, it is far more difficult to obtain reliable narrow-width seams and to control the interior dimensions of a fabricated pouch using these methods.) Whenever possible, testing an unreinforced FML is preferred over testing a fabric-reinforced FML to avoid any potential pinholes and leaks that could be associated with the threads of the fabric reinforcement.

SUMMARY OF METHOD

Waste liquid is sealed in a small pouch fabricated of the FML to be tested. This pouch is placed in a larger plastic bag containing deionized water to create a concentration gradient across the FML which results in the movement by osmosis of water, ions and other dissolved constituents through the pouch walls. Weight and conductivity measurements are taken periodically to determine, respectively, the extent of movement of water into the FML and the extent to which constituents in the waste liquid permeate through the FML. At the end of the exposure, the pouch is dismantled and the pouch wall material tested for physical and analytical properties.

APPLICABLE DOCUMENTS

- ASTM D297, "Methods for Rubber Products - Chemical Analysis."
- ASTM D412, "Test Methods for Rubber Properties in Tension."
- ASTM D624, "Test Method for Rubber Property - Tear Resistance."
- ASTM D638, "Test Method for Tensile Properties of Plastics."
- ASTM D882, "Test Methods for Tensile Properties of Thin Plastic Sheeting."

- ASTM D1004, "Test Method for Initial Tear Resistance of Plastic Film and Sheeting."
- ASTM D2240, "Test Method for Rubber Property - Durometer Hardness."
- ASTM D3421, "Recommended Practice for Extraction and Analysis of Plasticizer Mixtures from Vinyl Chloride Plastics."
- FTMS 101C, Method 2065, "Puncture Resistance and Elongation Test (1/8-inch Radius Probe Method)."
- Matrecon Test Method 1, "Procedure for Determination of the Volatiles of Exposed and Unexposed Membrane Liner Materials" (See Appendix G).
- Matrecon Test Method 2, "Procedure for Determination of the Extractables Content of Exposed and Unexposed Membrane Lining Materials" (see Appendix E).

EQUIPMENT AND SUPPLIES

Equipment

- Heat sealer, e.g. P.A.C. Bag Sealer Model 12 PI with long interval timers.
- Clamp made of two 0.5-in. square steel bars 4-in. long with 0.25-in. bolts and thumb screws located 0.5-in. from the ends.
- Wooden racks with compartments 1 x 8 x 6.5 in. deep.
- pH meter.
- Conductivity meter, e.g. Industrial Instruments Conductivity Bridge Model RC 16B2.
- Balance, 1000 g capacity, accurate to ± 0.1 g.
- Stress-strain machine suitable for measuring tensile strength, tear resistance, and puncture resistance in accordance with the appropriate test methods.
- Jig for measuring puncture resistance in accordance with FTMS 101C, Method 2065.
- Apparatus for running extractables, e.g. Soxhlet extractor (ASTM D3421) or ASTM D297 rubber extraction apparatus (see Matrecon Test Method 2, presented in Appendix E). All glass apparatus is preferred for chlorinated solvents or for liner materials which contain chlorine, because materials containing chlorine sometimes corrode the tin condensers of the D297 apparatus.

- Analytical balance.
- Two-inch interior diameter circular die.
- Dies for cutting tensile and tear test specimens as required.
- Individual dessicators containing calcium chloride (CaCl₂).
- Air oven.

Supplies

- Deionized or distilled water.
- Polybutylene bags with a wall thickness of 6 to 10 mils, and with dimensions of 8.5 x 10 inches.
- Cotton swabs.
- Medium size binder clips.

TEST SAMPLE

Each pouch requires two 7 x 7-in. squares of FML. In addition to the material required to fabricate the pouches, sufficient material from the same roll should be on hand to perform physical and analytical testing of the unexposed FML. At the same time that a pouch is fabricated, a seam sample should be fabricated using the same procedure (i.e. the same heat and dwell time) to be used in measuring the strength of the unexposed seam. Pouch tests of a given liner/waste liquid combination should be run in duplicate.

PROCEDURE

- Obtain a representative sample of the waste liquid. Note if waste classifies or separates and determine the pH, electrical conductivity, and total solids of each phase of the waste sample as necessary. A more extensive waste analysis may also be required.
- Perform the following tests on an unexposed sample of the polymeric FML from the same roll as the material used in fabricating the pouch.
 - Volatiles, Matrecon Test Method 1 (Appendix G).
 - Extractables with suitable solvent, Matrecon Test Method 2 (Appendix E).
 - Tear resistance, machine and transverse directions, five specimens each direction. See Table D-1 for appropriate test method and recommended speed of test.

- Puncture resistance, five specimens, FTMS 101C, Method 2065.
 - Tensile properties, machine and transverse directions, five specimens each direction. See Table D-1 for appropriate test method, recommended test specimen, speed of test, and values to be reported. The recommended test specimen for thermoplastic and semicrystalline thermoplastic FMLs is presented in Figure D-1.
 - Hardness, Duro A (Duro D if Duro A reading is greater than 80), ASTM D2240.
 - Seam strength in peel mode, 5 specimens, ASTM D413, in 90° peel with 1-in. wide strips at a jaw separation rate of 2 ipm. ASTM D638 Type I specimens may be substituted for the 1-in. wide strips if necessary to concentrate stress on the seam area. Report the locus of break of the tested specimens. Seam testing should be performed on a sample fabricated at the same time as the pouch using the same heat and dwell times of the heat-seaming apparatus.
- Cut two pieces of liner as shown in Figure D-2.
 - Heat seal the two pieces of FML together leaving the neck open. Measure the inside dimensions of the pouch to the nearest millimeter and record the calculated area and dry weight of the pouch.
 - Test the pouch for leaks by filling with deionized water. Close the neck of the pouch with binder clips. Weigh the full pouch again after one week to test for loss by leakage.
 - If there is no leakage, empty the water out of the pouch and pour 100 g of the waste liquid into the pouch through a funnel. Close the pouch by applying the clamp at the base of the neck. Carefully dry the inside of the neck with cotton swabs. Heat seal the neck opening. Remove the clamp, and record the weight of the filled pouch.
 - Place the pouch in a PB bag with 600 mL of DI water. Fold the opening of the polybutylene bag over and secure with binder clips (Figure D-3).
 - Store the assembly in a compartment of the racks so that the sealed pouch is covered by water in the PB bag (Figure D-4).
 - For testing during exposure, remove the pouch from the PB bag, blot dry, and weigh. Measure the pH and conductivity of the water in the outer bag.

TABLE D-1. RECOMMENDATIONS FOR TENSILE AND TEAR TESTING FOR POUCH TEST

Type of Compound and Construction ^a	TP	CX	FR
Tensile properties Method	ASTM D638	ASTM D638	ASTM D751, Method B
Type of specimen	Special dumbbell ^b	Special dumbbell ^b	1-in. wide strip and 2-in. jaw separation
Speed of test	20 ipm	2 ipm	12 ipm
Values to be reported	Tensile strength, psi	Tensile stress at yield, psi	Tensile at fabric break, ppi
	Elongation at break, %	Elongation at yield, %	Elongation at fabric break, %
	Tensile set after break, %	Tensile strength at break, psi	Tensile at ultimate break, ppi
	Stress at 100, 200, and 300% elongation, psi	Elongation at break, %	Elongation at ultimate break, %
	Stress at 100, 200, and 300% elongation, psi	Tensile set after break, %	Tensile set after break, %
Tear resistance Method	ASTM D1004	ASTM D1004	c
Type of specimen	Die C ^d	Die C ^d	---
Speed of test	20 ipm	2 ipm	---

^aTP = thermoplastic; CX = semicrystalline thermoplastic; FR= fabric reinforced.

^bSee Figure D-1.

^cNo tear resistance test is recommended for fabric-reinforced FMLs in the pouch test.

^dDie C from ASTM D624.

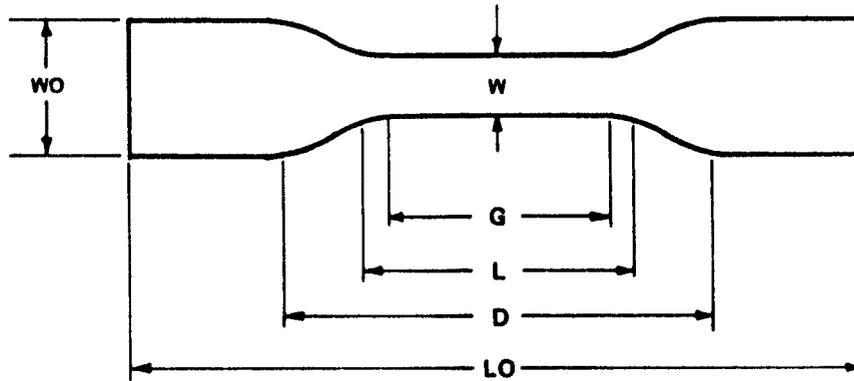


Figure D-1. Die for special dumbbell. Dimensions are as follows:

W - Width of narrow section	0.25 in.
L - Length of narrow section	1.25 in.
WO - Width overall	0.625 in.
LO - Length overall	3.50 in.
G - Gage length	1.00 in.
D - Distance between grips	2.00 in.

The width of the narrow section of this specimen, W, is the same as that of the ASTM D412 Die C dumbbell and the ASTM D638 Type IV dumbbell. It should be noted that these two dumbbells essentially have the same dimensions. The length of the narrow section, L, and the overall length, LO, of the ASTM D412 Die C/ASTM D638 Type IV dumbbell are, respectively, 1.30 in. and 4.50 inches.

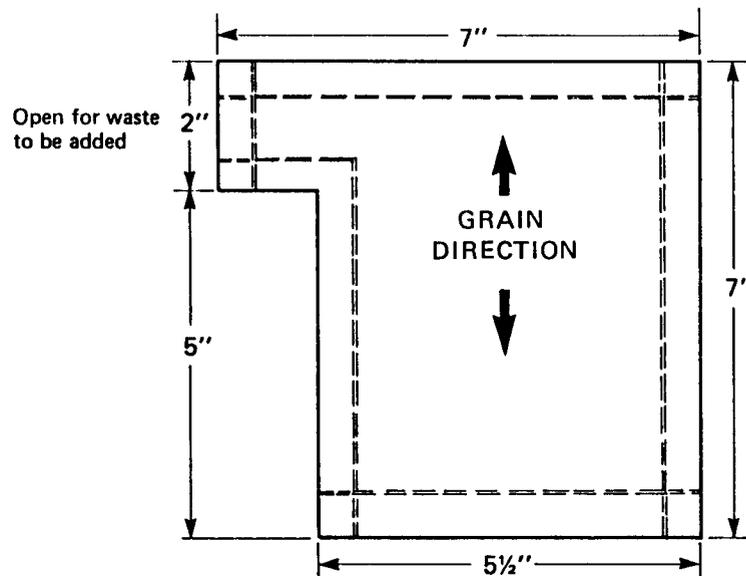


Figure D-2. Pattern for cutting pieces of membrane for making the pouch. Dotted line indicates the heat seal of the pouch. The inside dimension of the pouch is 4.5 x 5.75 inches.

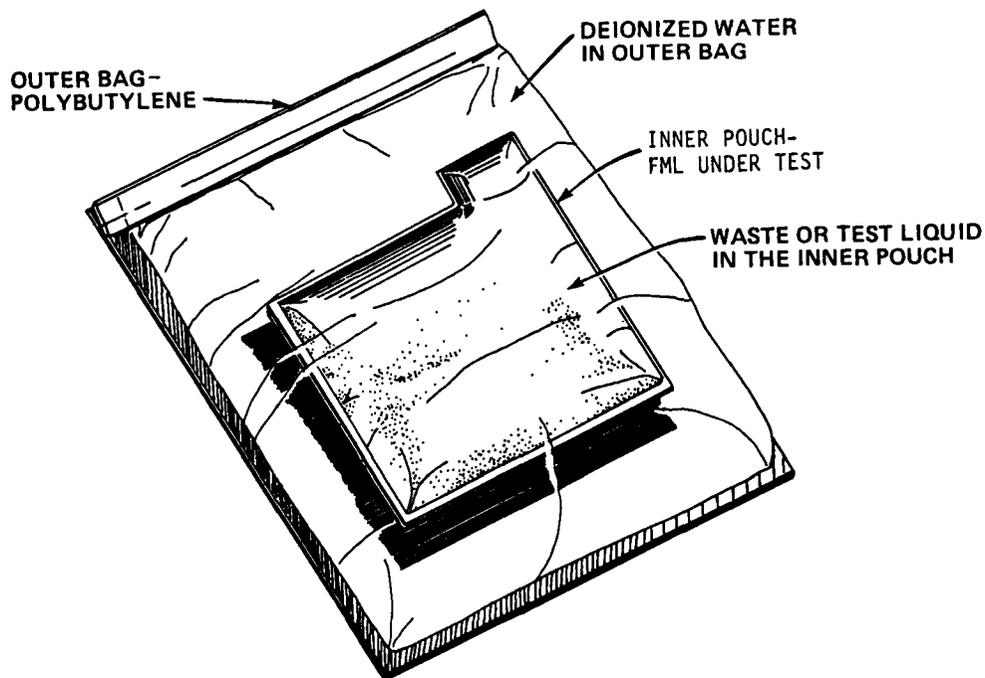


Figure D-3. Schematic of pouch assembly. The pouch is filled with waste fluid and sealed at the neck. The outer polybutylene bag, which can be easily opened, is filled with deionized water. The water in the outer bag is monitored for pH and conductivity; the pouch is monitored for weight change.

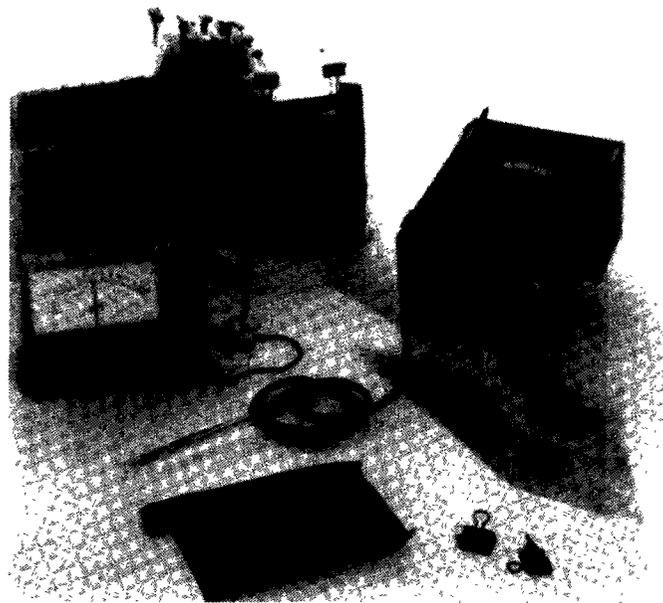


Figure D-4. Pouch and auxiliary equipment for determining permeability of polymeric FMLs to water and constituents of waste liquids.

- These measurements should be made weekly during the first month, twice a month for the next five months, decreasing to once a month, and eventually to once every two months. It is important to watch for leaking bags and pouches.
- The exposure period should end when the increase in weight and conductivity have reached a level of constant change or when the pouch material has changed drastically. The expected exposure period is six months to one year; longer exposures are also recommended.
- When a pouch has failed or at the end of the exposure period, dismantle and test by the following procedure:
 - Weigh the filled pouch before dismantling.
 - Determine pH and conductivity of the water in the outer bag.
 - Measure length and width between seams of pouch.
 - Empty pouch and determine pH, conductivity, and weight of waste.
 - Weigh the emptied pouch.
 - Dismantle pouch at seams, leaving bottom seam together.
 - Prepare specimens for physical tests. A suggested pattern for cutting out specimens out of the exposed pouch is shown in Figure D-5.
 - Perform the following tests:
 - Volatiles, Matrecon Test Method 1 (Appendix G).
 - Extractables with the same solvent used to determine the extractables of the unexposed samples, Matrecon Test Method 2 (Appendix E).
 - Tear resistance, machine and transverse direction, a minimum of two specimens each direction. See Table D-1 for appropriate test method and recommended speed of test.
 - Puncture resistance, a minimum of one specimen, FTMS 101C, Method 2065.
 - Tensile properties, machine and transverse directions, a minimum of two specimens per direction. See Table D-1 for appropriate test method, recommended test specimen, speed of test, and values to be reported. The recommended test specimen for thermoplastic and semicrystalline thermoplastic FMLs is presented in Figure D-1.
 - Hardness, Duro A (Duro D if Duro A reading is greater than 80), ASTM D2240.

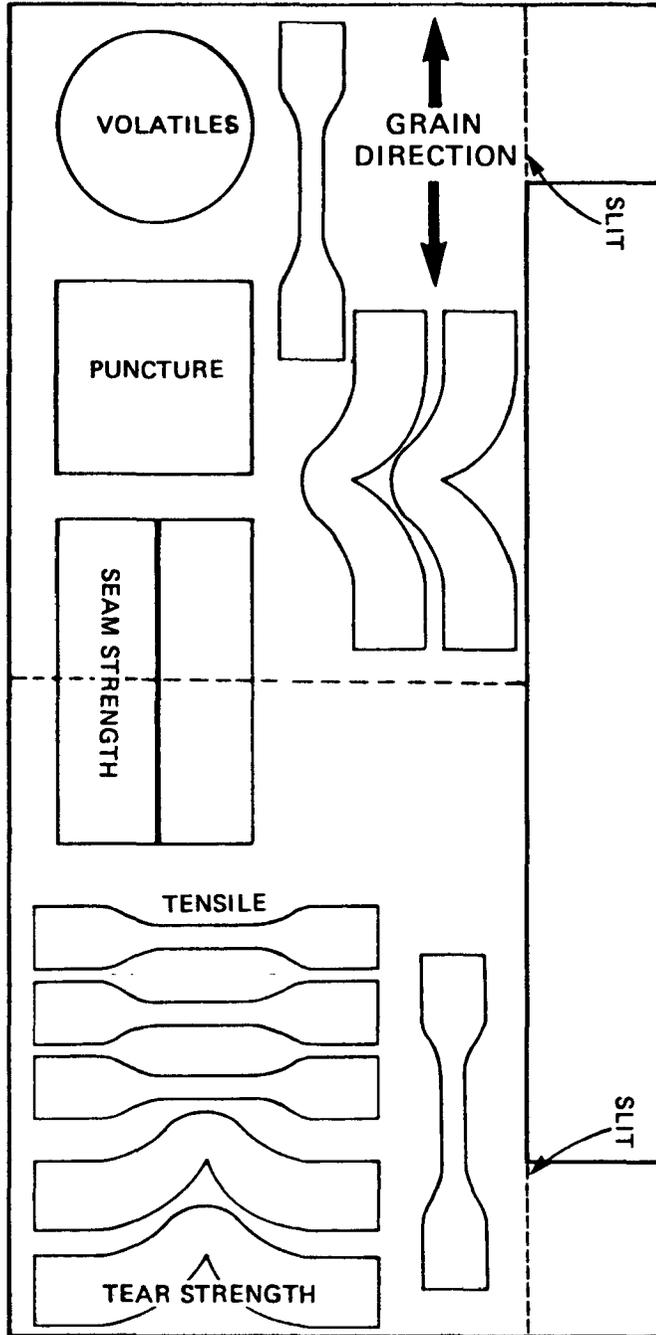


Figure D-5. Suggested pattern for cutting test specimens out of the exposed pouch.

---Seam strength in peel mode, a minimum of two specimens, ASTM D413, in 90° peel at a jaw separation rate of 2 ipm with the same type of specimen used to test the unexposed sample.

REPORT

The results of the pouch test should include:

- A description of the waste liquid and the results of the analyses.
- The properties of the unexposed FML.
- The electrical conductivity and pH of the water in the outer pouch as a function of time.
- The change in weight of the filled pouch as a function of time.
- The pH, electrical conductivity, and change in weight of the waste liquid in the pouch at the end of the exposure. Based on the change in weight value, the rate of transmission of water into the pouch should be determined in g per unit area of pouch wall material per unit time.
- The change in weight of the empty pouch at the end of exposure.
- A summary of the properties of the exposed FML. Test values should be reported for the following properties of the exposed FML:
 - Volatiles.
 - Extractables.
 - Puncture resistance.
 - Seam strength in peel mode.
- Percent retention values should be reported for the following properties of the exposed FML:
 - Tensile properties.
 - Tear resistance.
- Hardness values should be reported as a change in durometer points.
- A list of procedures used in the property testing.
- Any observations regarding the exposure of the pouch and the condition of the pouch at the end of the exposure.

APPENDIX E

PROCEDURE FOR DETERMINATION OF THE EXTRACTABLES CONTENT OF EXPOSED AND UNEXPOSED FMLS [MATRECON TEST METHOD 2 (MTM-2) - AUGUST 1982]

Editorially Revised November 1987

SCOPE

This procedure covers the extraction of plasticizers, oils, and other solvent-soluble constituents of polymeric FMLs with a solvent that neither decomposes nor dissolves the polymer. Extractions are performed on specimens from which the volatiles have been removed.

APPLICABLE TEST METHODS

This procedure generally is in accordance with ASTM D3421*, "Recommended Practice for Extraction and Analysis of Plasticizer Mixtures from Vinyl Chloride Plastics." See also ASTM D297, "Methods for Rubber Products--Chemical Analysis," Sections 16-18.

SIGNIFICANCE

The extractables of a polymeric FML can consist of plasticizers, oils, or other solvent-soluble constituents that impart or help maintain specific properties, such as flexibility and processibility. During exposure to a waste, leachate, or test liquid, the extractables content may be extracted resulting in a change of properties. Another possibility is that during an exposure the FML could absorb nonvolatilizable constituents of the liquid it is exposed to. Measuring the extractables content is, therefore, useful for characterizing an unexposed FML and for assessing the effect of an exposure on an FML. The extract and the extracted FML obtained by this procedure can be used for further analytical testing, e.g. gel chromatography, infrared spectroscopy, ash, thermogravimetry, etc.

APPARATUS

- Aluminum weighing dishes.

*The references at the end of this appendix include the ASTM standards cited in this appendix.

- Analytical balance capable of weighing to the nearest 0.0001 gram.
- Air oven.
- Soxhlet extractor or rubber extraction apparatus*.
- Extraction thimbles.
- 500 mL flat-bottomed flask (or 400 mL thin-walled Erlenmeyer flask if rubber extraction apparatus is used).
- Hot plate or steam plate.
- Boiling beads.
- Cotton wool.
- Aluminum foil.

REAGENTS

Table E-1 lists the recommended solvents for extraction of FMLs of each polymer type. Because FMLs can be based on polymeric alloys which are marketed under a trade name or under the name of only one of the polymers, this list can only be taken as a guideline for choosing a suitable solvent for determining the extractables. Once a suitable solvent has been found, it is important that the same solvent is used for determining the extractables across the range of exposure periods if this method is being used to assess the effects of an exposure.

SAMPLE SIZE

If using the Soxhlet extractor, about 5 g of a devolatilized FML are needed per extraction. If using the rubber extraction apparatus, about 2 g are needed. All extractions should be run in duplicate.

PROCEDURE

- Cut the sample into cubes no larger than 0.25 in. on a side.
- Weigh sample into an aluminum weighing dish to the nearest 0.0001 g and dry in moving air at room temperature for more than 16 hours.

*Because HCl splits out during the extraction of PVC and CPE, the rubber extraction apparatus may be substituted for the Soxhlet with all polymers except PVC and CPE. An appropriate reduction in sample size and solvent volume must be made.

TABLE E-1. SUGGESTED SOLVENTS FOR EXTRACTION OF POLYMERIC FMLS

Polymer Type	Extraction Solvent
Butyl rubber	Methyl ethyl ketone
Chlorinated polyethylene	n-Heptane
Chlorosulfonated polyethylene	Acetone
Elasticized polyolefin	Methyl ethyl ketone
Epichlorhydrin rubber	Methyl ethyl ketone or acetone
Ethylene proplene rubber	Methyl ethyl ketone
Neoprene	Acetone
Nitrile rubber (vulcanized)	Acetone
Nitrile-modified polyvinyl chloride	2:1 blend of carbon tetrachloride and methyl alcohol
Polyester elastomer	Methyl ethyl ketone
High-density polyethylene	Methyl ethyl ketone
Polyvinyl chloride	2:1 blend of carbon tetrachloride and methyl alcohol
Thermoplastic olefinic elastomer	Methyl ethyl ketone

- Place in air oven for 20 h at $105 \pm 2^\circ\text{C}$. Weigh the sample to the nearest 0.0001 g. (Note: 2 h are acceptable for unexposed FML samples.)
- Weigh the sample into a tared extraction thimble. Plug small thimbles with a piece of cotton wool to prevent the pieces from floating out of the thimble. (Large thimbles are tall enough to stay above the level of the liquid.)
- Add the necessary amount of extraction solvent to the distillation flask (if using the thin-walled Erlenmeyer flask, the flask is to be pre-weighed). Boiling beads are added to the 500 mL flasks to reduce bumping.
- Place the thimble in the extractor barrel, put the condensor in place, and run the extraction a minimum of 22 hours. Aluminum foil can be wrapped around the extractor and flask to increase the distillation rate.

- When the extraction is complete, rinse all the solvent from the extractor barrel into the distillation flask. Evaporate the solvent on a steam bath with filtered air from the thin-walled flasks. Decant the solvent from large flask into tared 500 mL Erlenmeyer flask and then evaporate. Place the flask in an oven at $70 \pm 2^\circ\text{C}$ and dry 2 hours. Hold the extract for further testing, e.g. gas chromatography and infrared spectroscopy.
- If the extract contains constituents that may volatilize during the evaporation procedure or is to be used for further analysis, heat the flask with extract in solution on a 70°C hot plate or a steam plate to near dryness. Complete evaporation of solvent in vacuum oven at 40°C .
- Remove extracted liner from the thimble* after excess solvent is removed and place in a tared aluminum weighing dish. Heat to constant weight at 70°C^{**} . Hold the extracted liner for further testing.

CALCULATIONS

Calculate the percent volatiles as follows:

$$\text{Volatiles, \%} = [(A-B)/A] \times 100 \quad , \quad (\text{E-1})$$

where

A = grams of specimen, as received, and

B = grams of specimen after heating at 105°C .

[Note: Due to potential loss of volatiles when specimens are cut into cubes, this method of determining volatiles should not be used as replacement for Matrecon Test Method 1 (Appendix G)]

Calculate the percent extractables as follows:

$$\text{Extractables, \%} = (B/A) \times 100 \quad , \quad (\text{E-2})$$

*Note: In cases where the extracted specimen sticks to the extraction thimble, the extraction thimble should be dried to constant weight at 70°C before the extraction and the weight recorded as the true weight of the thimble. After the extraction, the extracted liner can be dried to a constant weight in the thimble.

**Note: Extracted PVC specimens cannot be dried to a constant weight at 70°C when they are extracted with a blend of CCl_4 and CH_3OH . It is recommended that the sample be dried 72 h at 70°C .

where

A = grams of specimen after heating at 105°C, and

B = grams of dried extract.

In cases where the extract may contain some constituents which volatilized while the extraction solvent was evaporated, the percent extractables should also be calculated as follows:

Extractables based on loss from specimen, % = $[(A-B)/A] \times 100$, (E-3)

where

A = grams of specimen after heating at 105°C, and

B = grams of extracted liner.

REPORT

- Identification of the FML.
- In the case of exposed samples, exposure conditions and the length of exposure.
- Extraction solvent.
- Volatiles.
- Extractables.
- Extractables based on loss from specimen, if calculated.

REFERENCES

- ASTM. Annual Book of ASTM Standards. Issued annually in several parts. American Society for Testing and Materials, Philadelphia, PA:
- D297-81. "Methods for Rubber Products--Chemical Analysis," Section 09.01.
- D3421-75. "Recommended Practice for Extraction and Analysis of Plasticizer Mixtures from Vinyl Chloride Plastics," Section 08.03.

APPENDIX F

PROPERTIES OF UNEXPOSED POLYMERIC FMLS AND OTHER COMMERCIAL SHEETINGS

This appendix presents two data sets resulting from testing a wide range of unexposed polymeric FMLs and commercial sheetings for physical and analytical properties. These data sets were developed as part of research projects to evaluate the effects of exposing FMLs to various hazardous wastes (Haxo et al, 1985; Haxo et al, 1986) and to study the equilibrium swelling of FMLs in a range of solvents in order to determine their solubility parameters (Haxo et al, 1988). These data are presented to provide further information on specific FMLs discussed in the text, and to present representative data for different types of FMLs and commercial sheetings.

F-1. Data Set Number 1

These data were developed to establish baseline data for FMLs and other commercial sheetings exposed in long-term compatibility studies with various hazardous wastes (Haxo et al, 1985; Haxo et al, 1986). The results of these studies are presented in Chapter 5. The types of materials tested included FMLs and sheetings based on:

- Butyl rubber.
- Chlorinated polyethylene (CPE).
- Chlorosulfonated polyethylene (CSPE).
- Elasticized polyolefin (ELPO).
- Ethylene propylene rubber (EPDM).
- High-density polyethylene (HDPE).
- Low-density polyethylene (LDPE).
- Neoprene.
- Polybutylene.
- Polyester elastomer (PEL).
- Polypropylene.
- Polyvinyl chloride (PVC).

These FMLs and sheetings were tested in accordance with the methods listed in Table F-1. At the time this testing was performed, it was decided that all

FMLs should be tested in accordance with the same test procedures to minimize experimental biases and ease interpretation of data. Thus, the tensile properties of the FMLs, including the fabric-reinforced FMLs, were determined in accordance with ASTM D412/D638 using a dumbbell-type test specimen and a jaw separation rate of 20 ipm. The dumbbell-type test specimen was a special dumbbell which featured, in comparison with the ASTM D412 Die C/ASTM D638 Type IV dumbbell specimen size, smaller tab ends, a shorter narrowed section and a shorter overall length. The dimensions of this dumbbell are presented in Figure F-1.

TABLE F-1. TEST METHODS USED TO DETERMINE PROPERTIES OF POLYMERIC FMLS

Property	Test method
<u>Analytical properties</u>	
Specific gravity	ASTM D297*, Method A/D792
Ash	ASTM D297
Volatiles	MTM - 1 ^a
Extractables	MTM - 2 ^b
<u>Physical properties</u>	
Tensile properties	ASTM D412/D638 ^c
Modulus of elasticity	ASTM D882 (modified) ^d
Tear resistance	ASTM D624, Die C ^e
Puncture resistance	FTMS 101C, Method 2065 ^f
Hardness	ASTM D2240 ^g

^aMatrecon Test Method 1; see Appendix G.

^bMatrecon Test Method 2; see Appendix E.

^cMeasured at 20 ipm using a special dumbbell that features, in comparison with the ASTM D412 Die C/ASTM D638 Type IV dumbbell specimen size, smaller tab ends, a shorter narrowed section, and a shorter overall length. See Figure F-1 for dimensions of the special dumbbell.

^dMeasured using 0.5 x 6-in. strip specimens with an initial jaw separation of 2.0 in. at the standard initial strain rate of 0.1 in./in. min. Using a specimen size large enough so that specimens are tested with an initial separation of 10.0 in. as specified by ASTM D882 results in somewhat higher values.

^eNot measured on fabric-reinforced FMLs.

^fU.S. GSA, 1980.

^gMeasured on Duro A scale; also measured on Duro D scale if Duro A reading was greater than 80.

*The references at the end of this chapter the ASTM standards cited in this appendix and their titles.

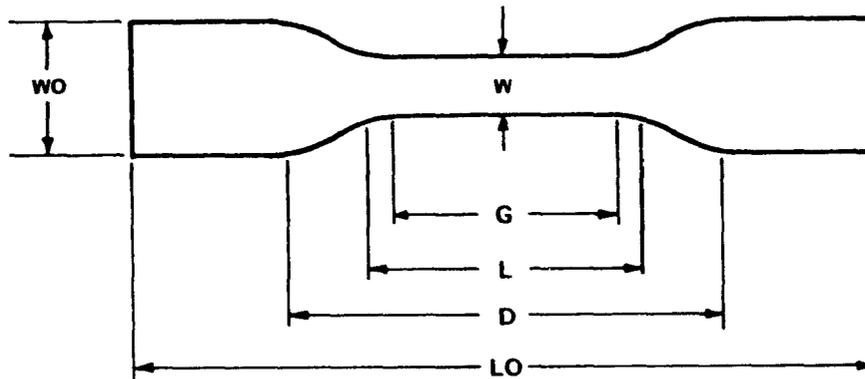


Figure F-1. Die for special dumbbell. Dimensions are as follows:

W - Width of narrow section	0.25 in.
L - Length of narrow section	1.25 in.
WO - Width overall	0.625 in.
LO - Length overall	3.50 in.
G - Gage length	1.00 in.
D - Distance between grips	2.00 in.

The width of the narrow section of this specimen, W, is the same as that of the ASTM D412 Die C dumbbell and the ASTM D638 Type IV dumbbell. It should be noted that these two dumbbells essentially have the same dimensions. The length of the narrow section, L, and the overall length, LO, of the ASTM D412 Die C/ASTM D638 Type IV dumbbell are, respectively, 1.30 in. and 4.50 inches.

This special dumbbell was selected so that exposed and unexposed specimens would be tested in accordance with the same test procedure and so that the number of specimens that could be died out of the limited-size exposure samples would be maximized. The results of this testing are presented in Table F-2. Because the stress-strain characteristics of sheetings containing crystalline domains are sensitive to the speed of test, the tensile and tear properties of the semicrystalline sheetings were also determined at 2 ipm, as is reported in Table F-3. It should be noted that most of these sheetings were not manufactured for use as FMLs; at the time work was initiated on the project for which this testing was performed, HDPE FMLs were not commercially available in the United States.

F-2. Data Set Number 2

These data were developed to establish baseline physical and analytical properties of commercial FMLs used in a study of the equilibrium swelling and solubility parameters of FMLs (Haxo et al, 1988). This study is described in Section 5.4.2.3.1. The results of determining the solubility parameters of the FMLs are presented in Section 4.2.2.4.3. The materials that were tested included FMLs based on the following polymers:

- Chlorinated polyethylene (CPE).

TABLE F-2. PROPERTIES OF UNEXPOSED POLYMERIC FMLS^a

Polymer ^b		Butyl	Butyl	CPE	CPE	CPE	CSPE
Compound type ^d		XL	XL	TP	TP	XL	TP
Fabric, type		...	Nylon	...	...	...	Nylon
Thread count, epi		...	22x11	...	...	...	8x8
Nominal thickness, mil		62.5	34	30	22	36	31
Matrecon FML serial number ^e		44	57R	77	86	100	6R
	Direction of test						
<u>Analytical properties</u>							
Specific gravity		1.176	1.286	1.362	1.377	1.390	1.343
Ash (db) ^f , %		4.28	23.46	12.56	17.37	6.02	3.28
Volatiles, %		0.46	0.29	0.14	0.05	0.66	0.51
Extractables (db) ^f , %		11.79	6.36	9.13	6.02	17.42	3.77
Solvent ^g		MEK	MEK	n-heptane	n-heptane	n-heptane	DMK
<u>Physical properties</u>							
Average thickness, mil		62	34	29	22	36	31
Tensile at fabric break, ppi	Machine	...	73.1	...	...	...	37.7
	Transverse	...	72.3	...	...	...	34.0
Elongation at fabric break, %	Machine	...	25	...	...	...	30
	Transverse	...	25	...	...	...	15
Tensile at ultimate break, psi	Machine	1625	h	2055	1845	1880	1845
	Transverse	1570	h	2340	1510	1935	1610
Tensile at ultimate break, ppi	Machine	104.1	h	59.6	40.6	67.6	59.7
	Transverse	100.2	h	66.7	34.1	69.6	52.5
Elongation at break, %	Machine	415	60	325	355	460	245
	Transverse	470	25	480	595	400	240
Set after break, %	Machine	18	4	140	208	43	97
	Transverse	18	2	160	235	33	93
Stress at 100% elongation, psi	Machine	335	...	1240	870	555	995
	Transverse	280	...	560	275	680	880
Stress at 100% elongation, ppi	Machine	21.4	...	36.0	19.1	20.0	32.2
	Transverse	17.9	...	16.0	6.2	24.4	28.7
Stress at 200% elongation, psi	Machine	750	...	1540	1210	1295	1710
	Transverse	615	...	820	405	1455	1390
Stress at 200% elongation, ppi	Machine	48.0	...	44.7	26.6	46.5	55.4
	Transverse	39.2	...	23.4	9.2	52.3	45.3
Tear strength (Die C), lb	Machine	12.88	...	7.83	4.05	10.58	...
	Transverse	14.05	...	6.93	3.91	10.68	...
Tear strength (Die C), ppi	Machine	201	...	273	187	297	...
	Transverse	221	...	239	178	304	...
Puncture resistance:							
Thickness, mil		62	34	29	22	35	34
Maximum force-average, lb		39.5	26.6	43.9	20.9	40.0	33.7
Deformation at puncture, in.		1.17	0.26	0.94	0.91	0.95	0.59
Hardness, Durometer points		54A	71A	80A	67A	63A	77A

continued . . .

TABLE F-2 (CONTINUED)

Polymer ^b	CSPE	CSPE	CSPE	ELPO	EPDM	EPDM	EPDM
Compound type ^d	TP	TP	TP	CX	XL	XL	TP
Fabric, type	...	...	Polyester	...	...	...	Polyester
Thread count, epi	...	...	8x8	...	...	...	8x8
Nominal thickness, mil	35	33	30	22	62.5	30	40
Matrecon FML serial number ^e	55	85	125R	36	8	26	83R
	<u>Direction of test</u>						
<u>Analytical properties</u>							
Specific gravity	1.371	1.311	1.296	0.938	1.173	1.169	1.199
Ash (db) ^f , %	3.32	4.02	3.99	0.90	6.78	7.67	0.32
Volatiles, %	0.42	0.92	0.12	0.15	0.38	0.50	0.31
Extractables (db) ^f , %	4.08	8.22	8.97	5.50	23.41	22.96	18.16
Solvent ^g	DMK	DMK	DMK	MEK	MEK	MEK	MEK
<u>Physical properties</u>							
Average thickness, mil	35	33	29	23	62	36	39
Tensile at fabric break, ppi	Machine	...	53.4	...	...	...	43.2
	Transverse	...	41.4	...	...	...	29.0
Elongation at fabric break, %	Machine	...	19	...	...	...	20
	Transverse	...	33	...	...	...	...
Tensile at ultimate break, psi	Machine	1860	2345	...	2715	1635	1935
	Transverse	1565	2055	...	2525	1550	1865
Tensile at ultimate break, ppi	Machine	65.0	75.0	53.0	61.0	98.9	74.5
	Transverse	55.1	66.2	46.6	55.6	94.9	70.9
Elongation at break, %	Machine	260	260	220	675	520	440
	Transverse	300	325	245	655	500	460
Set after break, %	Machine	75	167	73	465	14	9
	Transverse	97	192	83	445	11	9
Stress at 100% elongation, psi	Machine	1110	1150	...	940	350	385
	Transverse	650	750	...	905	320	330
Stress at 100% elongation, ppi	Machine	38.9	36.8	41.8	21.1	21.2	14.8
	Transverse	23.1	24.2	29.0	19.9	19.6	12.5
Stress at 200% elongation, psi	Machine	1810	2130	...	1035	800	925
	Transverse	1205	1410	...	1000	740	830
Stress at 200% elongation, ppi	Machine	63.3	68.2	51.8	23.2	48.4	35.6
	Transverse	42.5	66.2	42.5	22.0	45.3	31.5
Tear strength (Die C), lb	Machine	10.31	9.77	...	8.90	12.7	7.33
	Transverse	9.57	8.78	...	8.23	12.8	7.47
Tear strength (Die C), ppi	Machine	294	308	...	388	206	193
	Transverse	271	277	...	369	211	197
<u>Puncture resistance:</u>							
Thickness, mil	35	33	28	22.5	60	37	39
Maximum force-average, lb	45.0	47.8	30.6	26.3	56.9	31.3	33.6
Deformation at puncture, in.	0.83	0.86	0.61	0.97	1.46	1.24	0.61
Hardness, Durometer points	78A	79A	75A	89A	57A	58A	70A
	32D	...	28D	32D	...	...	...

continued . . .

TABLE F-2 (CONTINUED)

Polymer ^b		EPDM	HDPE	HDPE ^c	LDPE ^c	LDPE ^c	Neoprene	Neoprene
Compound type ^d		XL	CX	CX	CX	CX	XL	XL
Fabric, type		...	...	...	...	...	...	...
Thread count, epi		...	...	...	...	...	...	...
Nominal thickness, mil		31	100	31	10	31	31	62.5
Matrecon FML serial number ^e		91	99	105	21	108	43	82
	Direction of test							
<u>Analytical properties</u>								
Specific gravity		1.160	0.943	0.948	0.931	0.921	1.477	1.480
Ash (db) ^f , %		7.33	0.10	0.03	0.00	0.04	12.30	13.21
Volatiles, %		0.34	0.06	0.14	0.09	0.18	0.45	0.19
Extractables (db) ^f , %		23.64	...	0.00	3.60	2.07	13.69	13.43
Solvent ^g		MEK	...	MEK	MEK	MEK	DMK	DMK
<u>Physical properties</u>								
Average thickness, mil		37	103	32	9	31	33	61
Tensile at yield, psi	Machine	...	2715	3745	1490	1455	...	...
	Transverse	...	2640	3815	1175	1455	...	...
Tensile at yield, ppi	Machine	...	306.5	118.4	14.2	41.6	...	...
	Transverse	...	291.9	122.9	10.7	41.8	...	...
Tensile at break, psi	Machine	1865	2185	2610	2990	2085	1910	1835
	Transverse	1790	2195	2355	2940	1975	1660	1675
Tensile at break, ppi	Machine	67.2	246.5	81.3	28.4	59.7	65.9	113.8
	Transverse	66.3	231.4	75.8	26.8	56.6	56.0	100.2
Elongation at break, %	Machine	475	750	100	510	535	330	390
	Transverse	500	675	125	675	575	310	410
Set after break, %	Machine	11	640	85	395	435	8	10
	Transverse	10	585	107	535	470	6	9
Stress at 100% elongation, psi	Machine	375	1965	2635	1490	1375	490	405
	Transverse	300	1920	2385	1175	1265	430	360
Stress at 100% elongation, ppi	Machine	13.5	221.7	82.2	14.2	39.4	16.9	25.1
	Transverse	11.2	212.3	74.7	10.7	36.2	14.5	21.5
Stress at 200% elongation, psi	Machine	915	1980	...	1610	1385	1105	875
	Transverse	795	1945	...	1165	1300	970	705
Stress at 200% elongation, ppi	Machine	32.9	223.5	...	15.3	39.5	38.1	54.3
	Transverse	29.5	215.2	...	10.6	37.2	32.7	42.2
Modulus of elasticity, psi	Machine	...	78,600	150,150	19,400	21,960	...	...
	Transverse	...	78,700	158,750	24,400	24,870	...	...
Tear strength (Die C), lb	Machine	7.27	...	40.17	4.07	14.96	5.40	11.57
	Transverse	7.16	...	36.00	3.54	13.91	5.43	10.70
Tear strength (Die C), ppi	Machine	196	...	1215	420	516	171	183
	Transverse	195	...	1110	365	479	170	178
Puncture resistance:								
Thickness, mil		37	99	32	9.6	31	33	60
Maximum force-average, lb		29.2	131.0	51.2	13.7	33.5	30.6	53.9
Deformation at puncture, in.		1.17	0.33	0.25	0.79	0.51	1.14	1.29
Hardness, Durometer points		52A	95A	90A	86A	93A	57A	57A
		...	59D	60D	41D	38D	...	...

continued . . .

TABLE F-2 (CONTINUED)

Polymer ^b		Neoprene	Polybutylene ^c	Polyester	Polypropylene ^c	PVC	PVC
Compound type ^d		XL	CX	CX	CX	TP	TP
Fabric, type		...	...	...	...	...	...
Thread count, epi		...	...	...	...	...	...
Nominal thickness, mil		37	8	7	33	30	20
Matrecon FML serial number ^e		90	98	75	106	11	17
	Direction of test						
Analytical properties							
Specific gravity		1.390	0.915	1.236	0.904	1.276	1.254
Ash (db) ^f , %		4.67	0.08	0.38	0.04	6.14	5.81
Volatiles, %		0.37	0.12	0.26	0.01	0.15	0.44
Extractables (db) ^f , %		21.46	4.42	2.74	0.44	33.90	34.11
Solvent ^g		DMK	MEK	MEK	MEK	CCl ₄ + CH ₃ OH	
Physical properties							
Average thickness, mil		37	8	7	33	30	20
Tensile at yield, psi	Machine	...	...	...	5015	...	...
	Transverse	...	...	...	5020	...	...
Tensile at yield, ppi	Machine	...	...	...	162.5	...	...
	Transverse	...	...	...	160.9	...	...
Tensile at break, psi	Machine	2185	5625	6770	i	3005	2910
	Transverse	2010	5580	6765	3035	2750	2675
Tensile at break, ppi	Machine	80.9	42.8	47.4	i	90.2	56.7
	Transverse	74.4	44.6	47.4	99.5	82.5	52.2
Elongation at break, %	Machine	415	390	560	40	350	350
	Transverse	415	375	590	75	365	365
Set after break, %	Machine	26	346	340	16	91	70
	Transverse	25	331	370	50	106	83
Stress at 100% elongation, psi	Machine	565	2330	2715	...	1495	1360
	Transverse	550	2360	2455	3055	1345	1180
Stress at 100% elongation, ppi	Machine	21.0	17.7	19.0	...	44.9	26.5
	Transverse	20.4	18.9	17.2	100	40.4	23.0
Stress at 200% elongation, psi	Machine	1450	3035	2880	...	2140	1915
	Transverse	1225	3200	2585	...	1885	1690
Stress at 200% elongation, ppi	Machine	53.7	23.1	20.2	...	64.2	37.3
	Transverse	45.3	25.6	18.1	...	56.6	33.0
Modulus of elasticity, psi	Machine	...	...	...	190,900	...	...
	Transverse	...	...	...	184,300	...	...
Tear strength (Die C), lb	Machine	7.74	2.61	6.38	12.25	11.37	6.56
	Transverse	7.29	2.85	5.47	9.37	11.04	5.94
Tear strength (Die C), ppi	Machine	207	355	911	393	379	332
	Transverse	196	380	782	302	368	301
Puncture resistance:							
Thickness, mil		37	7.5	7.8	33	31	20
Maximum force-average, lb		44.9	13.9	29.9	60.3	38.6	25.30
Deformation at puncture, in.		1.01	0.66	1.30	0.65	0.64	0.70
Hardness, Durometer points		61A	94A	93A	...	80A	76A
		...	...	49D	68D	...	29D

continued . . .

TABLE F-2 (CONTINUED)

Polymer ^b		PVC	PVC	PVC	PVC	PVC	PVC
Compound type ^d		TP	TP	TP	TP	TP	TP
Fabric, type		...	...	...	...	...	...
Thread count, epi		...	...	...	...	...	...
Nominal thickness, mil		20	30	20	10	20	10
Matrecon FML serial number ^e		19	59	88	89	92	93
	<u>Direction of test</u>						
<u>Analytical properties</u>							
Specific gravity		1.231	1.280	1.255	1.308	...	1.283
Ash (db) ^f , %		3.65	6.97	2.80	5.67	5.84	4.94
Volatiles, %		0.05	0.31	0.17	0.03	0.06	0.12
Extractables (db) ^f , %		38.91	35.86	33.46	25.17	32.75	32.26
Solvent ^g				CCl ₄ + CH ₃ OH			
<u>Physical properties</u>							
Average thickness, mil		22	33	20	11	20	11
Tensile at break, psi	Machine	2495	2685	3395	3715	2435	3575
	Transverse	2335	2430	2910	3085	2145	3035
Tensile at break, ppi	Machine	52.2	87.5	67.9	40.9	48.7	38.1
	Transverse	49.0	79.2	58.2	33.9	42.9	33.4
Elongation at break, %	Machine	310	355	325	315	245	325
	Transverse	340	395	335	325	255	350
Set after break, %	Machine	55	45	102	195	43	98
	Transverse	71	56	101	205	48	117
Stress at 100% elongation, psi	Machine	1410	1020	1870	1845	1515	1750
	Transverse	1250	970	1600	1530	1365	1420
Stress at 100% elongation, ppi	Machine	29.5	33.3	37.4	20.3	30.3	18.7
	Transverse	26.3	31.6	36.0	16.8	27.3	15.6
Stress at 200% elongation, psi	Machine	1935	1715	2610	2715	2170	2580
	Transverse	1675	1445	2190	2195	1885	2055
Stress at 200% elongation, ppi	Machine	40.5	55.9	52.2	29.9	43.4	27.5
	Transverse	35.1	47.1	43.8	24.1	37.7	22.6
Tear strength (Die C), lb	Machine	6.49	10.25	9.26	4.49	8.70	4.26
	Transverse	6.05	9.54	9.17	4.30	7.46	3.99
Tear strength (Die C), ppi	Machine	295	313	463	408	435	400
	Transverse	275	290	470	391	373	362
Puncture resistance:							
Thickness, mil		22	32	20	11	20	11
Maximum force-average, lb		24.0	40.0	28.6	17.0	27.4	15.9
Deformation at puncture, in.		0.71	0.75	0.56	0.48	0.62	0.55
Hardness, Durometer points		72A	73A	80A	82A	82A	78A
		...	26D	...	...	30D	...

^aMethods used for determining properties of the unexposed polymeric FMLs are listed in Table F-1. Note that all tensile and tear testing reported in this table was done at 20 ipm.

^bCPE = chlorinated polyethylene; CSPE = chlorosulfonated polyethylene; ELPO = elasticized polyolefin; EPDM = ethylene propylene rubber; PVC = polyvinyl chloride.

^cUnpigmented, i.e. compounded without a filler.

^dXL = crosslinked; TP = thermoplastic; CX = semicrystalline thermoplastic.

^eMatrecon identification number; R = fabric-reinforced.

^fdb = Dried basis.

^gMEK = methyl ethyl ketone; DMK = dimethyl ketone = acetone; CCl₄ + CH₃OH = 2:1 blend of carbon tetrachloride and methyl alcohol.

^hBulk of FMLs' strength is in the nylon fabric. The butyl coating over the fabric tended not to fail catastrophically, and no useful value could be obtained for tensile strength at ultimate break.

ⁱSheeting tended to fail after yielding and no value could be determined for a catastrophic failure.

Source: Haxo et al, 1985, pp 221-25.

TABLE F-3. PHYSICAL PROPERTIES OF UNEXPOSED SEMICRYSTALLINE POLYMERIC FMLS AND COMMERCIAL SHEETINGS TESTED AT TWO INCHES PER MINUTE^a

Polymer ^b		HDPE	HDPE ^c	LDPE ^c	LDPE ^c	Polypropylene ^c
Nominal thickness, mil		100	32	10	30	33
Matrecon FML serial number		99	105	21	108	106
	Direction of test					
<u>Physical properties</u>						
Tensile at yield, psi	Machine	2385	3695	1205	1270	4960
	Transverse	2460	4020	1015	1255	4785
Tensile at yield, ppi	Machine	265	111	11.1	37.7	162
	Transverse	244	121	9.7	36.9	159
Elongation at yield, %	Machine	15	17	28	20	7
	Transverse	15	22	18	18	6
Tensile at break, psi	Machine	3915	4270	2845	1690	5800
	Transverse	4440	3295	2645	1645	4570
Tensile at break, ppi	Machine	437	129	26.1	50.2	190
	Transverse	441	98.8	25.2	48.2	152
Elongation at break, %	Machine	925	825	490	515	665
	Transverse	1015	860	635	535	640
Set after break, %	Machine	819	715	365	400	560
	Transverse	900	715	515	430	545
Stress at 100% elongation, psi	Machine	1660	2725	1445	1230	3255
	Transverse	1720	2440	1105	1190	2820
Stress at 100% elongation, ppi	Machine	184	82.1	13.2	36.6	106
	Transverse	170	73.2	10.5	34.9	93.9
Stress at 200% elongation, psi	Machine	1655	2725	1610	1185	3400
	Transverse	1720	2460	1125	1145	3080
Stress at 200% elongation, ppi	Machine	184	82.1	14.8	35.2	111
	Transverse	170	73.9	10.7	33.6	103
Tear strength (Die C), lb	Machine	87.2	32.4	3.9	14.2	35.3
	Transverse	88.9	28.1	3.7	12.6	31.7
Tear strength (Die C), ppi	Machine	839	992	424	462	1082
	Transverse	850	897	400	421	987

^aTensile properties measured at 2 ipm in accordance with ASTM D638 using a special dumbbell test specimen. See Figure F-1 for dimensions of the special dumbbell. Tear resistance measured in accordance with ASTM D1004 at a test speed of 2 in. per minute.

^bHDPE = high-density polyethylene; LDPE = low-density polyethylene.

^cCompounded without pigment.

Source: Haxo et al, 1985, p 226.

- Chlorosulfonated polyethylene (CSPE).
- Epichlorhydrin rubber (ECO).
- Ethylene proplene rubber (EPDM).
- Neoprene (CR).
- Polybutylene (PB).
- Polyester Elastomer (PEL).
- Polyethylene:
 - Low-density (LDPE).
 - Linear low-density (LLDPE).
 - High-density (HDPE).
 - HDPE/EPDM-alloy (HDPE-A).
- Polyurethane (PU).
- Polyvinyl chloride (PVC).
- Elasticized polyvinyl chloride (PVC-E).
- Polyvinyl chloride--oil-resistant (PVC-OR).

Table F-4 presents, by type of sheeting, the methods used in the physical and analytical testing. Table F-5 presents the solvents used to extract the sheetings, and Table F-6 presents details on the procedures used in the tensile and tear resistance testing.

It should be noted that some of this testing was performed in conjunction with various exposure tests which require the testing of limited size samples after exposure to a waste test liquid. Thus, the methods cited for determining tensile properties and modulus elasticity were modified to allow for the testing of specimens smaller than those required in the respective methods. These specimen sizes were selected so that exposed and unexposed specimens could be tested in accordance with the same test procedures and so that the number of specimens that could be died out of the limited-size exposure samples could be maximized. Details are presented in Tables F-4 and F-6. The dimensions of the dumbbell used in testing the crosslinked and thermoplastic FMLs are presented in Figure F-1.

The results of testing the commercial FMLs are presented in Tables F-7 through F-10.

This appendix also presents information on six laboratory-prepared compounds, swelling data for which are presented in Section 5.4.2.3.1.

TABLE F-4. TEST METHODS^a USED TO DETERMINE PHYSICAL AND ANALYTICAL PROPERTIES OF POLYMERIC FMLS

Property	Sheeting without fabric reinforcement			Fabric reinforced
	Thermoplastic	Crosslinked	Semicrystalline	
<u>Analytical properties</u>				
Volatiles	MTM-1b	MTM-1b	MTM-1b	MTM-1b
Extractables	MTM-2c	MTM-2c	MTM-2c	MTM-2c
Ash	ASTM D297, Section 34	ASTM D297, Section 34	ASTM D297, Section 34	ASTM D297, Section 34
Specific gravity	ASTM D792, Method A	ASTM D297, Method A	ASTM D792, Method A	ASTM D792, Method A
<u>Physical properties</u>				
Thickness (average)	ASTM D638 ^d	ASTM D412 ^d	ASTM D638 ^d	ASTM D751, Section 6 ^d
Tensile properties ^e	ASTM D638	ASTM D412	ASTM D638 (modified) ^e	ASTM D751, Method B
Tear resistance ^e	ASTM D1004 (modified) ^e	ASTM D624, Die C	ASTM D1004	ASTM D751, Tongue Method (8 x 8-in. test specimen) ^e
Modulus of elasticity	na ^f	na ^f	ASTM D882, Method A (modified) ^g	na ^f
Hardness (Durometer A or D)	ASTM D2240	ASTM D2240	ASTM D2240	ASTM D2240
Puncture resistance	FTMS 101C, Method 2065	FTMS 101C, Method 2065	FTMS 101C, Method 2065	FTMS 101C, Method 2065

^aSee references of this appendix for the sources and titles of the test methods.

^bMatrecon Test Method-1. See Appendix G.

^cMatrecon Test Method-2. See Appendix E. Solvents used to extract polymeric FMLs are presented in Table F-5.

^dReported thickness values are the averages of all the values measured on test specimens used in the physical property testing.

^eDetails of tensile and tear resistance testing are presented in Table F-6.

^fna = Not applicable.

^gMeasured using 0.5 x 6-in. strip specimens with an initial jaw separation of 2.0 in. at the standard strain rate of 0.1 in./in. min. Using a specimen size large enough so that specimens would be tested with an initial jaw separation of 10.0 in. as specified by ASTM D882-83 would result in higher values.

Source: Haxo et al, 1988, p 113.

TABLE F-5. SOLVENTS USED FOR EXTRACTION OF POLYMERIC FMLS

Polymer	Extraction solvent
Chlorinated polyethylene (CPE)	n-Heptane
Chlorosulfonated polyethylene (CSPE)	Acetone
Epichlorohydrin rubber (ECO)	Methyl ethyl ketone
Ethylene propylene rubber (EPDM)	Methyl ethyl ketone
Ethylene vinyl acetate (EVA)	Ethyl alcohol
Neoprene (CR)	Acetone
Polybutylene (PB)	Methyl ethyl ketone
Polyester elastomer (PEL)	n-Heptane
Polyethylene:	
Low-density (LDPE)	Methyl ethyl ketone
Linear low-density (LLDPE)	Methyl ethyl ketone
High-density (HDPE)	Methyl ethyl ketone
HDPE/EPDM-alloy (HDPE-A)	Methyl ethyl ketone
Polyurethane (PU)	n-Heptane
Polyvinyl chloride (PVC)	2:1 blend of carbon tetrachloride and methyl alcohol
Elasticized polyvinyl chloride (PVC-E)	Methyl alcohol
Polyvinyl chloride--oil-resistant (PVC-OR)	2:1 blend of carbon tetrachloride and methyl alcohol

Source: Haxo et al, 1988, p 114.

TABLE F-6. DETAILS OF TENSILE AND TEAR RESISTANCE TEST METHODS USED IN TESTING

Test and test conditions	Sheeting without fabric reinforcement			Sheeting with fabric reinforcement
	Crosslinked	Thermoplastic	Semicrystalline	
Tensile properties				
Method	ASTM D412	ASTM D638	ASTM D638	ASTM D751, Method B
Type of specimen	"Special" dumbbell ^a	"Special" dumbbell ^a	ASTM D638 Type IV dumbbell	1-in. wide strip and 2-in. jaw separation
Jaw separation rate	20 ipm ^b	20 ipm ^b	2 ipm ^b	12 ipm ^b
Tear resistance				
Method	ASTM D624	ASTM D1004	ASTM D1004	ASTM D751, Tongue Method
Type of specimen	Die C	Die C ^c	Die C ^c	8 x 8-in. test specimen ^d
Speed of test	20 ipm ^b	20 ipm ^b	2 ipm ^b	12 ipm ^b

^aSee Figure F-1.

^bipm = inches per minute.

^cRequired test specimen is the same as Die C from ASTM D624.

^dNational Sanitation Foundation, 1985, p A-4.

Source: Haxo et al, 1988, p 117.

TABLE F-7. ANALYTICAL AND PHYSICAL PROPERTIES OF CHLORINATED POLYETHYLENE, CHLOROSULFONATED POLYETHYLENE, AND EPICHLOROHYDRIN RUBBER FMLS

Polymer ^a		CPE	CPE	CPE	CSPE	CSPE	ECO
FML number ^b		195	335R	378R	169R	174R	178
Nominal thickness, mil		30	40	...	30	36	60
Type of compound ^c		TP/AM	TP/AM	TP/AM	TP/AM	TP/AM	XL/AM
Thread count, epi ^d		na	9x9	9x9	8x8	10x10	na
	<u>Direction of test</u>						
<u>Analytical properties</u>							
Specific gravity		1.26	1.312	1.333	1.297	1.364	1.458
Ash-db, %		...	15.98	...	2.77	27.37	4.50
Volatiles, %		0.12	0.40	0.25	0.39	0.15	0.55
Extractables-db, %		14.85	4.48	7.94	11.29	7.15	7.36 ^e
<u>Physical properties</u>							
Average thickness, mil		30.8	39.8	35.0	27.9	37.7	66.9
Tensile of fabric at break, ppi	Machine	...	134.3	194.4	33.0	190.0	...
	Transverse	...	133.6	164.4	31.7	185.0	...
Elongation of fabric at break, %	Machine	...	31	29	25	24	...
	Transverse	...	30	32	26	32	...
Tensile at break, psi	Machine	1575	...	...	...	...	1050
	Transverse	1405	...	...	...	...	1120
Tensile at break, ppi	Machine	48.4	39.8	51.0	31.8	33.4	70.5
	Transverse	43.2	26.3	164.0	30.9	30.0	76.1
Elongation at break, %	Machine	315	570	39	275	125	215
	Transverse	440	340	32	285	155	200
Stress at 100% elongation, psi	Machine	1110	...	...	...	...	685
	Transverse	585	...	...	...	...	775
Stress at 100% elongation, ppi	Machine	34.0	29.7	...	23.9	32.5	46.0
	Transverse	18.0	20.3	...	22.4	28.1	52.6
Stress at 200% elongation, psi	Machine	1295	...	...	...	...	1035
	Transverse	760	...	...	...	...	1120
Stress at 200% elongation, ppi	Machine	39.8	31.2	...	30.9	...	69.6
	Transverse	23.3	23.5	...	29.3	...	76.2
Tear strength-tongue, lb	Machine	...	...	83.1 ^f	15.4	142.0	...
	Transverse	...	...	78.4 ^f	28.6	107.0	...
Tear strength-Die C, ppi	Machine	268	...	...	...	...	162
	Transverse	215	...	...	...	...	165
Puncture resistance:							
Thickness, mil		31.0	39.6	...	29.0	37.6	67.2
Maximum force-average, lb		38.1	50.7	...	27.2	68.0	40.0
Deformation at puncture, in.		0.86	0.31	...	0.67	0.30	0.68
Hardness, Durometer points		82A	69A	79A	85A	67A	64A
Hardness, Durometer points		28D	...	...	34D	...	...

^aCPE = chlorinated polyethylene; CSPE = chlorosulfonated polyethylene; ECO = epichlorohydrin rubber.

^bSerial number assigned by Matrecon to each lot of sheeting received; R = fabric-reinforced sheeting.

^cTP = thermoplastic; AM = amorphous; XL = crosslinked.

^depi = ends per inch.

^eWith methyl ethyl ketone.

^fMaximum peak values obtained before delamination and tearing in the opposite direction occurred.

Source: Haxo et al, 1988 p 119.

TABLE F-8. ANALYTICAL AND PHYSICAL PROPERTIES OF ETHYLENE PROPYLENE RUBBER, ETHYLENE VINYL ACETATE, NEOPRENE, POLYBUTYLENE, AND POLYESTER ELASTOMER FMLS

Polymer ^a		EPDM	EVA	Neoprene	PB	PEL	PEL
FML number ^b		232	308A	168	221A	316	323
Nominal thickness, mil		60	20	33	30	20	20
Type of compound ^c		XL/AM	TP/AM	XL/AM	CX	TP/CX/AM	TP/CX/AM
	<u>Direction of test</u>						
<u>Analytical properties</u>							
Specific gravity		1.166	0.951	1.500	0.907	1.149	1.253
Ash-db, %		8.40	0.76	13.65	0.41	0.24	...
Volatiles, %		0.47	0.05	0.81	0.10	0.18	0.24
Extractables-db, %		22.78	0.75	11.23	3.68	1.09	±0.6
<u>Physical properties</u>							
Average thickness, mil		58.6	20.3	32.0	28.0	20.1	20.4
Tensile at yield, psi	Machine	...	...	...	1925	960	3330
	Transverse	...	...	...	1865	950	3180
Elongation at yield, %	Machine	...	...	...	20	55	25
	Transverse	...	...	...	20	48	25
Tensile at break, psi	Machine	1780	3655	1990	5885	6080	8500
	Transverse	1705	3500	1800	5330	5750	8410
Tensile at break, ppi	Machine	103.5	74.5	60.9	159.9	122.9	175.1
	Transverse	97.8	71.1	54.8	146.6	115.0	170.0
Elongation at break, %	Machine	425	615	340	405	889	539
	Transverse	465	770	325	430	851	534
Stress at 100% elongation, psi	Machine	445	880	480	1930	920	2770
	Transverse	355	725	450	1785	905	2700
Stress at 100% elongation, ppi	Machine	26.0	18.0	14.7	52.4	18.6	14.3
	Transverse	20.5	14.7	13.6	49.1	18.1	13.7
Stress at 200% elongation, psi	Machine	965	1025	1110	3005	955	2860
	Transverse	815	790	1020	2449	945	2880
Stress at 200% elongation, ppi	Machine	56.2	20.9	33.9	81.6	19.3	14.7
	Transverse	46.8	16.0	31.1	68.5	18.9	14.6
Modulus of elasticity, psi	Machine	...	...	...	36,300	...	...
	Transverse	...	...	...	36,100	...	...
Tear strength-Die C, ppi	Machine	204	336	148	559	500	972
	Transverse	214	363	142	547	523	991
Puncture resistance:							
Thickness, mil		59.5	20.4	33.4	28.9	20.0	21.2
Maximum force-average, lb		49.9	50.0	32.0	55.6	41	67
Deformation at puncture, in.		1.05	2.08	0.88	0.72	1.85	0.97
Hardness, Durometer points		62A	30A	57A	89A	37A	59A
Hardness, Durometer points		20D	...	...	43D	...	...

^aEPDM = ethylene propylene rubber; EVA = ethylene vinyl acetate; PB = polybutylene; PEL = polyester elastomer.

^bSerial number assigned by Matrecon to each lot of sheeting received.

CTP = thermoplastic; AM = amorphous; CX = semicrystalline; XL = crosslinked.

Source: Haxo et al, 1988, p 120.

TABLE F-9. ANALYTICAL AND PHYSICAL PROPERTIES OF LOW-DENSITY POLYETHYLENE, LINEAR LOW-DENSITY POLYETHYLENE, HIGH-DENSITY POLYETHYLENE, AND HIGH-DENSITY POLYETHYLENE ALLOY FMLS

Polymer ^a		LDPE	LLDPE	HDPE	HDPE	HDPE	HDPE-A
FML number ^b		309A	284	184	263	305	181
Nominal thickness, mil		20	30	30	80	30	30
Type of compound ^c		CX	CX	CX	CX	CX	CX
	<u>Direction of test</u>						
<u>Analytical properties</u>							
Specific gravity		0.938	0.929	0.951	0.953	0.954	0.949
Ash-db, %		...	0.07	0	...	0.69	0.32
Volatiles, %		0.07	0.09	0.13	0.13	0.22	0.11
Extractables-db, %		1.85	0.65	0.73	≤0.60	0.98	2.09
<u>Physical properties</u>							
Average thickness, mil		22.9	34.4	29.2	82.8	27.9	33.5
Tensile at yield, psi	Machine	...	1505	3885	3030	2540	1975
	Transverse	...	1540	4495	2910	2820	2070
Elongation at yield, %	Machine	...	23	20	20	25	20
	Transverse	...	23	15	20	25	15
Tensile at break, psi	Machine	2660	5360	5215	4260	4110	3915
	Transverse	2765	5420	3830	4275	4390	3945
Tensile at break, ppi	Machine	59.3	185	146	350	114	130
	Transverse	61.4	186	107	359	123	129
Elongation at break, %	Machine	470	765	930	805	760	875
	Transverse	575	800	745	845	770	910
Stress at 100% elongation, psi	Machine	1625	1505	2810	2100	2090	1635
	Transverse	1495	1470	2755	1970	1945	1640
Stress at 100% elongation, ppi	Machine	36.2	52.0	78.6	173	58.2	54.5
	Transverse	33.2	50.5	77.1	165	54.7	53.8
Stress at 200% elongation, psi	Machine	1705	1430	2830	2085	2125	1640
	Transverse	1485	1405	2830	1965	1975	1650
Stress at 200% elongation, ppi	Machine	38.0	49.4	79.2	171	59.1	54.6
	Transverse	33.0	48.1	79.2	165	55.5	54.2
Modulus of elasticity, psi	Machine	25,700	49,000	122,000	98,500	...	59,900
	Transverse	29,100	45,800	150,000	91,700	90,800	65,100
Tear strength-Die C, ppi	Machine	496	613	892	854	764	760
	Transverse	442	601	864	846	725	732
Puncture resistance:							
Thickness, mil		23.9	34.7	30.1	81.9	28.0	33.5
Maximum force-average, lb		28.8	60.2	48.0	109.2	43.4	45.5
Deformation at puncture, in.		0.71	1.13	0.65	0.55	0.77	0.56
Hardness, Durometer points		...	91A	94A	...	...	90A
Hardness, Durometer points		42D	47D	60D	57D	52D	51D

^aLDPE = low-density polyethylene; LLDPE = linear low-density polyethylene; HDPE = high-density polyethylene; HDPE-A = HDPE/ethylene propylene rubber alloy.

^bSerial number assigned by Matrecon to each lot of sheeting received.

^cCX = semicrystalline.

Source: Haxo et al, 1988, p 121.

TABLE F-10. ANALYTICAL AND PHYSICAL PROPERTIES OF POLYURETHANE, POLYVINYL CHLORIDE, ELASTICIZED POLYVINYL CHLORIDE, AND OIL-RESISTANT POLYVINYL CHLORIDE FMLS

Polymer ^a		Polyurethane	PVC	PVC-E	PVC-OR
FML number ^b		351	153	176R	144
Nominal thickness, mil		...	30	30	30
Type of compound ^c		TP/AM	TP/AM	TP/AM	TP/AM
Thread count, epi ^d		na	na	20x20	na
	<u>Direction of test</u>				
Analytical properties					
Specific gravity		1.118	1.263	1.219	1.356
Ash-db, %		...	5.31	5.12	10.82
Volatiles, %		0.65	0.38	0.44	0.21
Extractables-db, %		1.50	34.57	9.13	30.97
Physical properties					
Average thickness, mil		15.0	29.4	36.1	32.8
Tensile at fabric break, ppi	Machine	...	...	342	...
	Transverse	...	...	349	...
Elongation at fabric break, %	Machine	...	...	24	...
	Transverse	...	...	22	...
Tensile at break, psi	Machine	7775	2860	...	2655
	Transverse	7040	2540	...	2275
Tensile at break, ppi	Machine	134	94.3	342	86.0
	Transverse	122	83.9	349	74.9
Elongation at break, %	Machine	500	315	24	365
	Transverse	525	335	22	355
Stress at 100% elongation, psi	Machine	1020	1495	...	1235
	Transverse	955	1315	...	1085
Stress at 100% elongation, ppi	Machine	17.6	49.2	...	40.1
	Transverse	16.5	43.5	...	35.7
Stress at 200% elongation, psi	Machine	1305	2120	...	1800
	Transverse	1145	1835	...	1560
Stress at 200% elongation, ppi	Machine	22.5	70.0	...	58.3
	Transverse	19.8	60.6	...	51.3
Tear strength-Die C, ppi	Machine	420	346	...	323
	Transverse	446	343	...	277
Puncture resistance:					
Thickness, mil		15.0	33.3	36.3	33.0
Maximum force-average, lb		72.2	44.3	101.5	33.9
Deformation at puncture, in.		2.00	0.69	0.32	0.66
Hardness, Durometer points		86A	73A	93A	72A
Hardness, Durometer points		33D	28D	42D	24D

^aPVC = polyvinyl chloride; PVC-E = elasticized polyvinyl chloride; PVC-OR = oil-resistant polyvinyl chloride.

^bSerial number assigned by Matrecon to each lot of sheeting received; R = fabric-reinforced sheeting.

^cTP = thermoplastic; AM = amorphous.

^dna = Not applicable.

Source: Haxo et al, 1988, p 122.

The composition of the these compounds and information on their molding conditions and their extractables content are presented in Tables F-11 and F-12. These compounds include four CSPE compositions, a nitrile rubber composition, and a PVC composition plasticized with di(ethylhexyl) phthalate. Among the four CSPE compositions are three gum compounds that contain no filler but vary in the level of crosslinking. The fourth CSPE composition contains 100 parts of carbon black similar to that used in CSPE liner compounds.

REFERENCES

- ASTM. Annual Book of ASTM Standards. Issued annually in several parts. American Society for Testing and Materials, Philadelphia, PA:
- D297-81. "Methods for Rubber Products--Chemical Analysis," Section 09.01.
 - D412-83. "Test Methods for Rubber Properties in Tension," Sections 08.01, 09.01, and 09.02.
 - D624-86. "Test Method for Rubber Property--Tear Resistance," Section 09.01.
 - D638-84. "Test Method for Tensile Properties of Plastics," Section 08.01.
 - D751-79. "Methods of Testing Coated Fabrics," Section 09.02.
 - D792-66(1979). "Test Methods for Specific Gravity and Density of Plastics by Displacement," Section 08.01.
 - D882-83. "Test Method for Tensile Properties of Thin Plastic Sheet-ing," Section 08.01.
 - D1004-66(1981). "Test Method for Initial Tear Resistance of Plastic Film and Sheeting," Section 08.01.
 - D2240-86. "Test Method for Rubber Property--Durometer Hardness," Sections 08.02 and 09.01.
- Haxo, H. E., R. S. Haxo, N. A. Nelson, P. D. Haxo, R. M. White, and S. Dakessian. 1985. Liner Materials Exposed to Hazardous and Toxic Wastes. EPA-600/2-84/169 (NTIS No. PB 85-121 333). U.S. Environmental Protection Agency, Cincinnati, OH. 256 pp.
- Haxo, H. E., R. S. Haxo, N. A. Nelson, P. D. Haxo, R. M. White, and S. Dakessian. 1986. Liner Materials Exposed to Toxic and Hazardous Wastes. Waste Management and Research 4:247-264.

TABLE F-11. COMPOSITION OF LABORATORY-PREPARED COMPOUNDS OF CSPE, NITRILE RUBBER, AND POLYVINYL CHLORIDE^a

Ingredient	CSPE				Nitrile rubber	PVC
	DOY-3 ^b	DOZ-2 ^b	DPO ^b	DPP ^b	DPN ^b	DPQ ^b
CSPE (Hypalon 45)	100	100	100	100	...	...
Nitrile rubber (Hycar 1052-30)	...	...	...	...	100	...
PVC (Geon 135)	...	...	...	...	...	100
Di(ethylhexyl) phthalate	...	...	...	...	...	50
MT black	...	100	...	...	...	...
MgO (Maglite D)	4	4	10	4	...	...
Peroxide (Varox powder)	...	...	6	1.5	...	...
HVA-2 ^c	...	...	2	0.5	...	...
Lead stearate	...	...	...	...	...	2.0
Stearic acid (F300)	...	...	...	...	1.0	0.2
ZnO (Protox 168)	...	...	...	...	5.0	...
TMTDS ^d (Tuex)	...	...	...	...	3.5	...
Carbowax 4000	1.5	1.5	...	...	...	...
Pentaerythritol	3.0	...	...	...	...	...
Tetrone A ^e	<u>2.0</u>	<u>...</u>	<u>...</u>	<u>...</u>	<u>...</u>	<u>...</u>
Total	110.5	205.5	118.0	106.0	109.5	152.2

^aFormulation in parts by weight.

^bMatrecon identification code.

^cHVA-2 = N,N-m-phenylenedimaleimide (DuPont), a curing adjuvant for CSPE.

^dTMTDS = tetramethyl thiuram disulfide.

^eTetrone A = dipentamethylene thiuram hexasulfide, accelerator or sulfur source.

Source: Haxo et al, 1988, p 115.

TABLE F-12. MOLDING CONDITIONS AND EXTRACTABLES
OF THE LABORATORY-PREPARED COMPOUNDS

Item	CSPE				Nitrile rubber	PVC
	DOY-3 ^a	DOZ-2 ^a	DPO ^a	DPP ^a	DPN ^a	DPQ ^a
Molding conditions ^b						
Temperature, °C	160	160	150	140	150	150
Time, min.	25	60	20	40 ^c	40	^d
Extractables ^e , %	5.9	<1.0	6.8	1.9	1.0	34.3

^aMatrecon identification number.

^bMolded in small slabs of 25 to 30-mil thickness.

^cCooled in the press.

^dCooled immediately after filled mold was placed in a press.

^eExtractables of the composition were calculated based upon their respective formulations. The polymer component was assumed to be nonextractable.

Source: Haxo et al, 1988, p 116.

- Haxo, H. E., T. P. Lahey, and M. L. Rosenberg. 1988. Factors in Assessing the Compatibility of FMLs and Waste Liquids. EPA/600/2-88/017 (NTIS No. PB 88-173-372/AS). U.S. Environmental Protection Agency, Cincinnati, OH. 143 pp.
- National Sanitation Foundation (NSF). 1985. Standard Number 54: Flexible Membrane Liners. Rev. Standard. National Sanitation Foundation, Ann Arbor, MI.
- U.S. General Services Administration. 1980. Method 2065: Puncture Resistance and Elongation Test (1/8-Inch Probe Method). In: Federal Test Method Standard 101C. U.S. General Services Administration, Washington, D.C.

APPENDIX G

PROCEDURE FOR DETERMINATION OF THE VOLATILES OF EXPOSED AND UNEXPOSED FMLS [MATRECON TEST METHOD 1 (MTM-1) - AUGUST 1982]

Editorially Revised November 1987

SCOPE

This test can be performed on unexposed polymeric FMLs and on FML samples that have been exposed to a leachate or other liquid.

SIGNIFICANCE

This test can be used to determine the volatiles of an unexposed FML or the volatile fraction absorbed by an exposed FML, including water, volatile oils, and solvents. Moisture is removed by heating specimens in individual desiccators at 50°C. Organic volatiles are then removed by heating specimens for 2 hours at 105°C in an air-circulating oven. The composition of the organic volatiles can be determined by headspace gas chromatographic analysis of vapors sampled from a sealed can in which a specimen has been heated. Nonvolatile dissolved or absorbed components of a specimen can be determined by the extractables test which is run after the volatiles have been removed (see Appendix E, Matrecon Test Method 2). The volatiles should be determined as soon as possible after exposed samples have been removed from exposure and measured for weight and dimensional changes, or, for unexposed samples, as soon as possible after they have been received by the testing facility. By identifying the orientation of the disk with respect to the sheeting at the time it was died out, the grain of the sheeting can be established.

DEFINITIONS

Volatiles are the fraction of weight lost by a specimen during the specified heating process described below.

APPARATUS

- Two-inch interior diameter circular die.
- Analytical balance.
- Air oven.
- Individual desiccators with CaCl₂.

TEST SPECIMEN

Two-inch diameter disks died out of an FML sample.

NUMBER OF TEST SPECIMENS

All determinations should be run in duplicate.

PROCEDURE

1. Draw a line on the sheeting to mark "grain" or machine direction. If the "grain" is unknown, draw a random straight line on the sheeting.
2. Die out a 2-in. diameter disk so that the line falls approximately in the middle of the specimen.
3. Weigh specimen in tared, closed container to the nearest 0.0001 g. Record weight as the "as-received weight."
4. Place each specimen in an individual desiccator with CaCl_2 as the desiccant. Place the desiccator in a 50°C oven for four days.
5. Remove desiccator from oven and cool for 20 minutes at room temperature. Weigh specimen to 0.0001 g. Record weight as the "desiccated weight."
6. Dry specimen on Teflon screen for 2 hours in a circulating air oven heated to 105±2°C.
7. Cool specimen in desiccator for 20 minutes and weigh on analytical balance to 0.0001 g; record weight as the "oven-dried weight."
8. Measure diameter in machine and transverse directions. Record to 0.001 inches.
9. If machine direction is unknown, find and record largest and smallest diameter of disk. Mark small diameter as the machine direction on disk as shown in Figure G-1. Use the dried disk to determine the orientation of the sheeting from which it was died out.
10. Retain specimens for additional testing, e.g. specific gravity, thermogravimetry, extractables, GC, IR, ash content, etc.

Note 1: For cases in which the grain direction of the FML sample is known, Steps 1, 8, and 9 can be eliminated.

Note 2: For cases in which an unexposed FML sample is being tested, the "as-received weight" can be determined directly (Step 3). In addition, Steps 4 and 5 can also be eliminated.

Note 3: If the specific gravity of a highly swollen, exposed FML sample is to be determined, the volatiles may need to be removed from the test specimens more gradually than they are in the above test procedure to prevent blisters from forming. Specimens can be allowed to dehydrate for 1 week in moving air before being placed in an oven heated to 50°C, or they can be allowed to come to constant weight at 50°C before being placed in and oven heated to 105°±2°C.

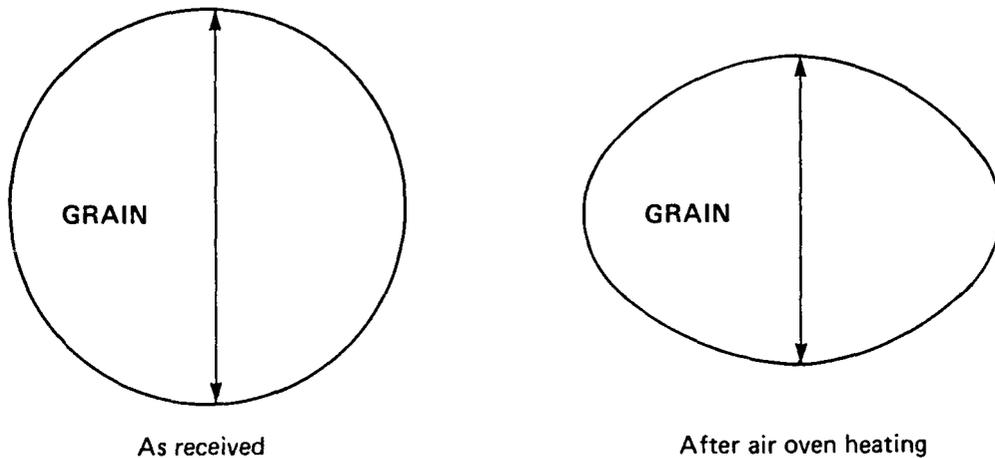


Figure G-1. Machine direction determination.

CALCULATIONS

Calculate the percent volatiles as follows:

$$\text{Volatiles after desiccation, \%} = [(A - B)/A] \times 100 \quad , \quad (G-1)$$

$$\text{Volatiles after } 105^{\circ}\text{C heating, \%} = [(B - C)/A] \times 100 \quad , \quad (G-2)$$

and

$$\text{Total volatiles, \%} = [(A - C)/A] \times 100 \quad , \quad (G-3)$$

where

A = grams of specimen, "as-received weight,"

B = grams of specimen, "desiccated weight," and

C = grams of specimen, "oven-dried weight."

REPORT

- Identification of the FML.
- In the case of exposed FMLs, the exposure conditions and the length of exposure.
- Results of volatiles calculations.

APPENDIX H

TUB TEST OF POLYMERIC FMLS

Editorially Revised November 1987

SIGNIFICANCE

The tub test exposes polymeric FMLs under conditions that simulate some of the conditions that exist in a lined surface impoundment in which a liner is in contact with a waste liquid and is not covered with soil. The effects of exposure to sun, temperature changes, ozone, and other weather factors can be assessed simultaneously with the effect of a given waste on a specific FML. The level of the waste is allowed to fluctuate so that an area of the liner is subjected to the effects of both the waste and weather intermittently. This alternating of conditions, which is especially harsh on FMLs and other liner materials, is encountered in the field.

SUMMARY OF METHOD

A small tub, lined with a polymeric FML is partially filled with a waste liquid and exposed to the weather for an unspecified length of time. The condition of the FML is monitored during exposure. At the end of exposure, the condition of the FML is assessed. The physical and analytical properties of selected areas of the liner are determined.

APPLICABLE DOCUMENTS

- ASTM D297, "Methods for Rubber Products - Chemical Analysis."
- ASTM D412, "Test Methods for Rubber Properties in Tension."
- ASTM D624, "Test Method for Rubber Property - Tear Resistance."
- ASTM D638, "Test Method for Tensile Properties of Plastics."
- ASTM D751, "Standard Methods of Testing Coated Fabrics."
- ASTM D882, "Test Methods for Tensile Properties of Thin Plastic Sheeting."
- ASTM D1004, "Test Method for Initial Tear Resistance of Plastic Film and Sheeting."

- ASTM D2240, "Test Method for Rubber Property - Durometer Hardness."
- ASTM D3421, "Recommended Practice for Extraction and Analysis of Plasticizer Mixtures from Vinyl Chloride Plastics."
- FTMS 101C, Method 2065, "Puncture Resistance and Elongation Test (1/8-inch Radius Probe Method)."
- Matrecon Test Method 1, "Procedure for Determination of the Volatiles of Exposed and Unexposed Polymeric FMLs" (see Appendix G).
- Matrecon Test Method 2, "Procedure for Determination of the Extractables Content of Exposed and Unexposed Polymeric FMLs" (see Appendix E).

EQUIPMENT AND SUPPLIES

- Plywood tub. The suggested tub design is as follows: The tub should be constructed of 0.75-in. exterior grade plywood with sides sloping outward at a 1 horizontal:2 vertical slope. The inside base should measure 7 x 12 in., and the opening at the top should measure 19.75 x 24.5 inches. A sketch of this design is presented in Figure H-1.
- Chicken-wire cover to fit over tub to prevent birds from bathing in the wastes (Figure H-2).
- Lined catch basin fitted with a drain designed to prevent waste overflow or leaks from contacting the roof top (Figure H-2). The suggested catch basin dimensions are 8 ft x 6 ft x 4 inches.
- Corrugated plastic cover to fit over tub during rainy weather. The cover should be capable of being secured to the catch basin.
- Label for the liner specimen.
- Stress-strain machine suitable for measuring tensile strength, tear resistance, and puncture resistance in accordance with the appropriate methods.
- Jig for testing puncture resistance in accordance with FTMS 101C, Method 2065.
- Air-circulating oven.
- Dial or digital micrometer.
- Analytical balance.
- Two-inch interior-diameter circular die.

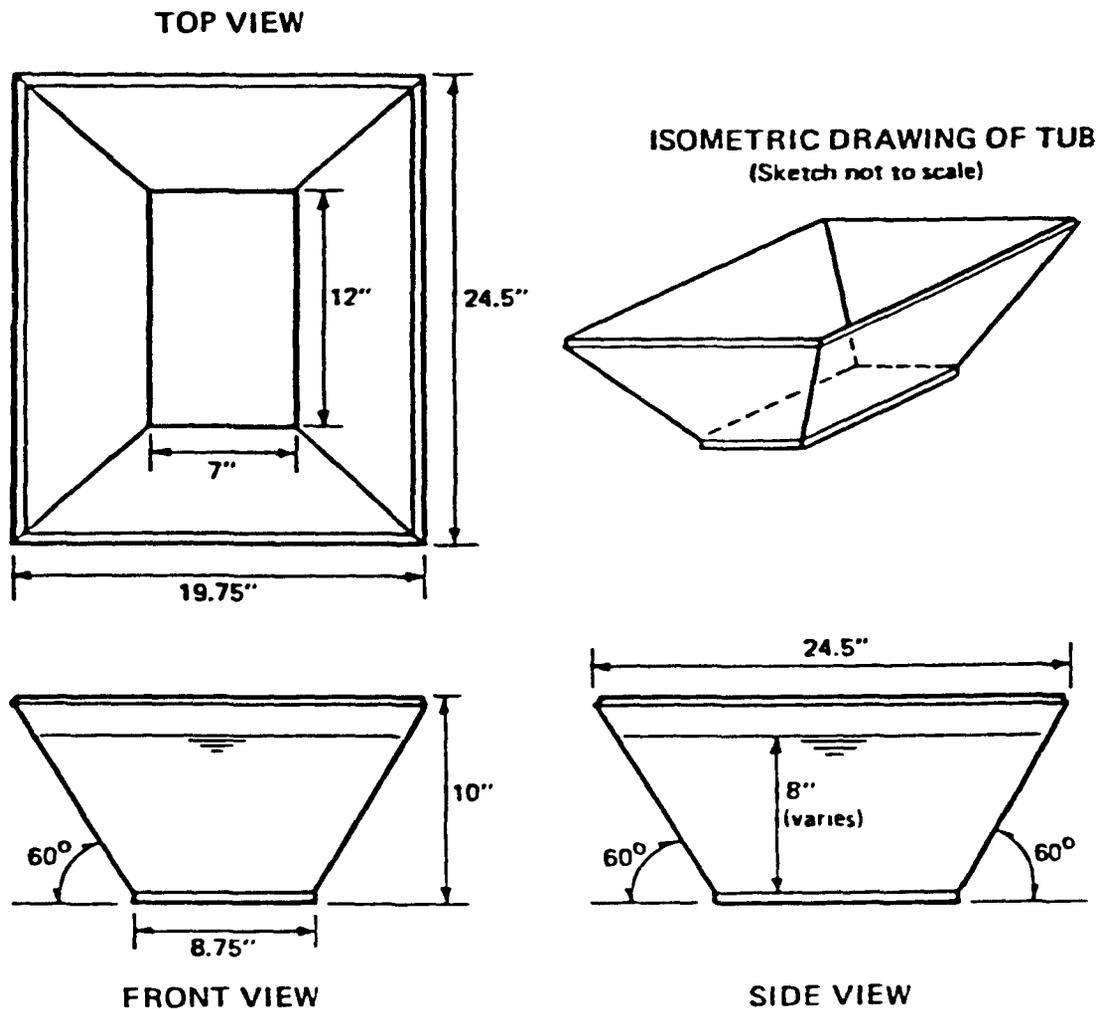


Figure H-1. Tub used in the outdoor exposure of polymeric FMLs in contact with wastes. The tub is lined with an FML and filled from 3/4 to 7/8 full with a waste liquid. The liquid level is allowed to fluctuate (Source: Haxo et al, 1985, p 157).

- Dies for cutting tensile and tear specimens as required.
- Individual desiccators with calcium chloride (CaCl_2).
- Soxhlet extractor (ASTM D3421) or rubber extraction apparatus (ASTM D297) and associated extraction apparatus including extraction thimbles and flasks (see Matrecon Test Method 2, presented in Appendix E).
- Meter stick or similar device to measure waste depth.
- Thermometers.

- pH meter.
- Conductivity meter.

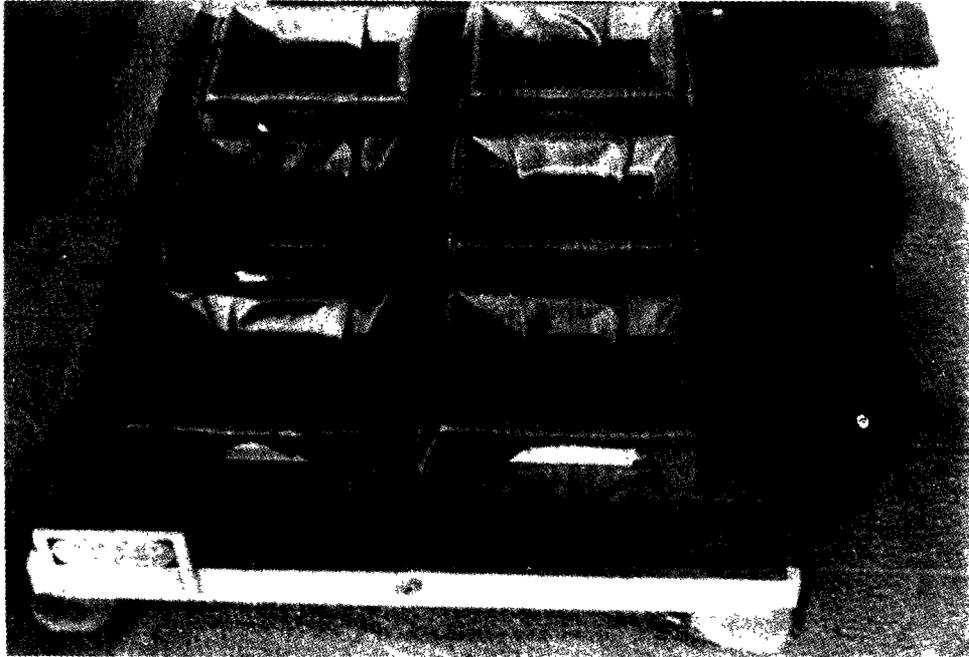


Figure H-2. The open exposure tubs lined with polymeric FMLs and partially filled with waste liquids. They are covered with chicken-wire and placed in a lined shallow basin. During rainy weather these cells are protected by a corrugated plastic cover. (Source: Haxo et al, 1985, p 158).

TEST SPECIMEN

Piece of FML, large enough to fold over edges of the tub; approximate size 4 ft x 4 feet. A seam should be incorporated into the center of the FML sample in accordance with the supplier's instructions. Fabricate the seam so that there is sufficient free overlap to perform peel testing. For materials that need proprietary equipment for seaming, a sample supplied by a fabricator with a field seam already incorporated in it is acceptable. Sufficient FML should be retained to perform baseline testing of both the sheeting and the seam.

PROCEDURE

- Obtain a representative sample of the waste liquid. Note if waste classifies or separates. Determine the pH, electrical conductivity,

and total solids of the waste sample. A more extensive waste analysis may also be required.

- Perform the following tests on an unexposed sample of the polymeric FML from the same roll as the sheeting used in fabricating the tub liner:
 - Volatiles, Matrecon Test Method 1 (Appendix G).
 - Extractables with suitable solvent, Matrecon Test Method 2 (Appendix E).
 - Tear resistance, machine and transverse directions, five specimens each direction. See Table H-1 for appropriate test method and recommended speed of test.
 - Puncture resistance, five specimens, FTMS 101C, Method 2065.
 - Tensile properties, machine and transverse directions, five specimens each direction. See Table H-1 for appropriate test method, recommended test specimen, speed of test, and values to be reported. The dumbbell recommended for testing unreinforced FMLs is presented in Figure H-3.
 - Modulus of elasticity, machine and transverse directions, 5 specimens each direction, ASTM D882 (modified), semicrystalline FMLs only, using 0.5 x 8-in. strip specimens with a 4.0-in. gage length extended at the standard initial strain rate of 0.1 in/in. min. (Note: Testing specimens with a 10.0-in. gage length as specified by ASTM D882 results in higher values.)
 - Hardness, Duro A (Duro D if Duro A reading is greater than 80), ASTM D2240.
 - Seam strength in shear mode, 5 specimens, ASTM D882, with 1-in. wide strips at a jaw separation rate of 2 ipm. ASTM D638 Type I specimens may be substituted for the 1-in. wide strip specimens if it is necessary to concentrate stress on the seam area. Report the locus of break for the tested specimens.
 - Seam strength in peel mode, 5 specimens, ASTM D413, in 90° peel with 1-in. wide strips at a jaw separation rate of 2 ipm. ASTM D638 Type I specimens may be substituted for the 1-in. wide strip specimens if it is necessary to concentrate stress on the seam area. Report the locus of break for the tested specimens.
- Drape the FML specimen over a tub and fold it so that the specimen fits the inside contours and edges of the tub. Allow the excess sheeting to hang freely over the edges of the tub. Attach an identification tag to one corner of the tub liner.

TABLE H-1. RECOMMENDATIONS FOR TENSILE AND TEAR TESTING FOR TUB TEST

Test	FML without fabric reinforcement				
	Crosslinked	Thermoplastic	Semicrystalline	Fabric-reinforced	
Tensile properties Method	ASTM D412	ASTM D638	ASTM D638	ASTM D751, Method B	
Type of specimen	Special dumbbell ^a	Special dumbbell ^a	Special dumbbell ^a	1-in. wide strip and 2-in. jaw separation	
Speed of test	20 ipm	20 ipm	2 ipm	12 ipm	
Values to be reported	Tensile strength, psi	Tensile strength, psi	Tensile stress at yield, psi	Tensile at fabric break, ppi	
	Elongation at break, %	Elongation at break, %	Elongation at yield, %	Elongation at fabric break, %	
	Tensile set after break, %	Tensile set after break, %	Tensile strength at break, psi	Tensile at ultimate break, ppi	
	Stress at 100, 200, and 300% elongation, psi		Stress at 100, 200, and 300% elongation, psi	Elongation at break, %	Elongation at ultimate break, %
				Tensile set after break, %	Tensile set after break, %
				Stress at 100, 200, and 300% elongation, psi	Stress at 100, 200, and 300% elongation, ppi
Tear resistance Method	ASTM D624	ASTM D1004	ASTM D1004	b	
Type of specimen	Die C	Die C ^c	Die C ^c	...	
Speed of test	20 ipm	20 ipm	2 ipm	...	

^aSee Figure H-3.

^bNo tear resistance test is recommended for fabric-reinforced FMLs in the tub test because of sample-size constraints.

^cTest specimen required in ASTM D1004 is the same as Die C from ASTM D624.

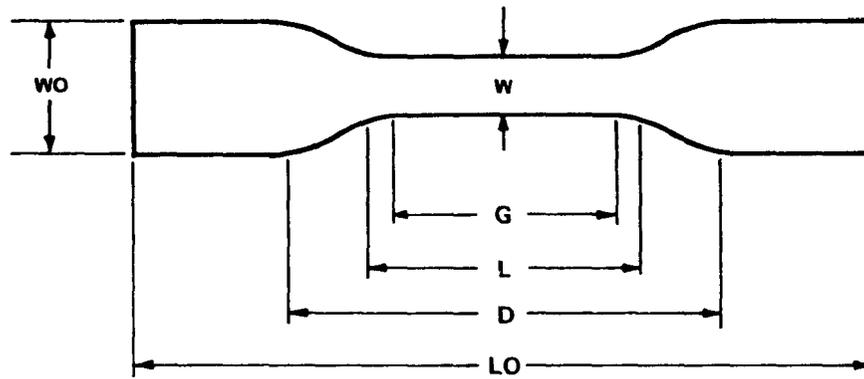


Figure H-3. Die for special dumbbell. Dimensions are as follows:

W - Width of narrow section	0.25 in.
L - Length of narrow section	1.25 in.
WO - Width overall	0.625 in.
LO - Length overall	3.50 in.
G - Gage length	1.00 in.
D - Distance between grips	2.00 in.

The width of the narrow section of this specimen, W, is the same as that of the ASTM D412 Die C dumbbell and the ASTM D638 Type IV dumbbell. It should be noted that these two dumbbells essentially have the same dimensions. The length of the narrow section, L, and the overall length, LO, of the ASTM D412 Die C/ASTM D638 Type IV dumbbell are, respectively, 1.30 in. and 4.50 inches.

- Place the lined tub in the catch basin so that it is oriented in a specific direction. It is recommended that the length of the seam runs in a north-south direction so that part of the seam can be exposed to as much sunlight as possible. Fill the tub 3/4 to 7/8 full with the waste liquid. Approximately 4.5 gal of waste is required to fill the suggested tub design to the recommended height. Cover the tub with chicken-wire to prevent birds from bathing in the waste.
- During exposure, monitor the ambient temperature and the level and temperature of the waste at regular intervals. At the same time, inspect the tubs for cracking, opening of seams, and other forms of FML deterioration. Cover the tubs during rainy periods to prevent waste overflow. Add water to the tub when the waste level drops below 4 inches. In the case of an oily waste, water that has accumulated from dew may need to be pumped from the bottom of the tub. Liquid removed from the tub should be analyzed for pH, electrical conductivity, percent solids, and other parameters as appropriate. During rainy periods, water in the catch basin should be monitored for pH and conductivity to indicate whether there is leakage from a tub containing a highly acidic or a highly alkaline waste.

- The tub exposure should be discontinued at the end of a predetermined exposure period or if the liner shows significant signs of deterioration. Exposure for several years is recommended. The following procedure should be used in dismantling the tub:
 - Examine the tub liner and the waste. Record observations regarding the waste appearance and, if it has stratified, the depth of the layers. Record observations on the condition of the tub liner. In particular, check for effects of weathering at the upper edge of the tub and places where the liner has been folded. Photograph the tub.
 - Scoop out the waste. If the waste has stratified, take care to remove each layer separately so as not to disturb the layer(s) below. Save the waste for analyses.
 - Record observations on the areas of the liner that were exposed to the waste. Note swelling, discoloration, deposits, condition of the seams. Note any sludge still remaining on the liner. Determine the area of the liner that was exposed intermittently to the weather and the waste. Using a wax pencil, indicate this area on the liner.
 - Detach the liner from the plywood tub and record any observations regarding the back of the liner. Note any moisture, discoloration, and the condition of the seam. Scoop any remaining sludge off the liner. Using a wax pencil, indicate the directional orientation of the tub liner, i.e. the north, south, east, and west sides of the liner. Also mark the top edge of the tub and waste-phase depths on the liner.
 - Lay the liner flat and photograph it. Make a drawing of the liner. Indicate on the drawing the tub edge, waste-phase levels, bottom area, folds, any signs of FML deterioration such as cracks, etc.
 - Clean off the liner. Seal the liner in a polyethylene bag to prevent loss of volatiles.
- Cut a 1-in. wide strip across the width of the liner parallel to the seam so that the strip runs from one edge of the liner along an area of the liner that was exposed on the bottom of the tub to the other edge. Measure the thickness of the strip using a dial or digital gage every 0.5 inches. Graph the results.
- Based on the condition of the liner, determine the areas for testing. Suggested areas for testing include:
 - North side (side facing south), exposed only to weather (including the sun).

- North side (side facing south), exposed intermittently to the waste and the weather (including the sun).
 - Bottom, exposed only to the waste.
 - South side (side facing north), exposed intermittently to the waste and the weather (not including the sun).
 - South side (side facing north), exposed only to the weather (not including the sun).
- Perform the following tests on the selected areas of the exposed FML as soon as possible after the liner has been removed from exposure:
- Volatiles, Matrecon Test Method 1 (Appendix G).
 - Extractables, with the same solvent used to determine the extractables of the unexposed sample, Matrecon Test Method 2 (Appendix E).
 - Tear resistance, machine and transverse directions, a minimum of two specimens each direction per tested area. See Table H-1 for appropriate test method and recommended speed of test.
 - Puncture resistance, a minimum of two specimens per tested area, FTMS 101C, Method 2065.
 - Tensile properties, machine and transverse directions, a minimum of two specimens each direction per tested area. See Table H-1 for appropriate test method, recommended test specimen, speed of test, and values to be reported. The dubbell recommended for testing unreinforced FMLs is presented in Figure H-3.
 - Hardness, Duro A (Duro D if Duro A reading is greater than 80), ASTM D2240.
 - Modulus of elasticity, machine and transverse directions, a minimum of two specimens each direction per tested area, ASTM D882 (modified), semicrystalline FMLs only, using 0.5 x 8-in. strip specimens with a 4.0-in. gage length extended at the standard initial strain rate of 0.1 in./in. minute.
 - Seam strength in shear mode, a minimum of two specimens, ASTM D882, at a jaw separation rate of 2 ipm with the same type of specimen used to test the unexposed seam sample. Report locus of break for the tested specimens.
 - Seam strength in peel mode, a minimum of two specimens, ASTM D413, in 90° peel at a jaw separation rate of 2 ipm with the same type of specimen used to test the unexposed seam sample.

Note: Test specimens cut from the seam of the exposed liner should be alternated between peel and shear test specimens.

A drawing of an exposed liner including the layout pattern for sampling the liner is presented in Figure H-4.

- Analyze the waste using the appropriate parameters.

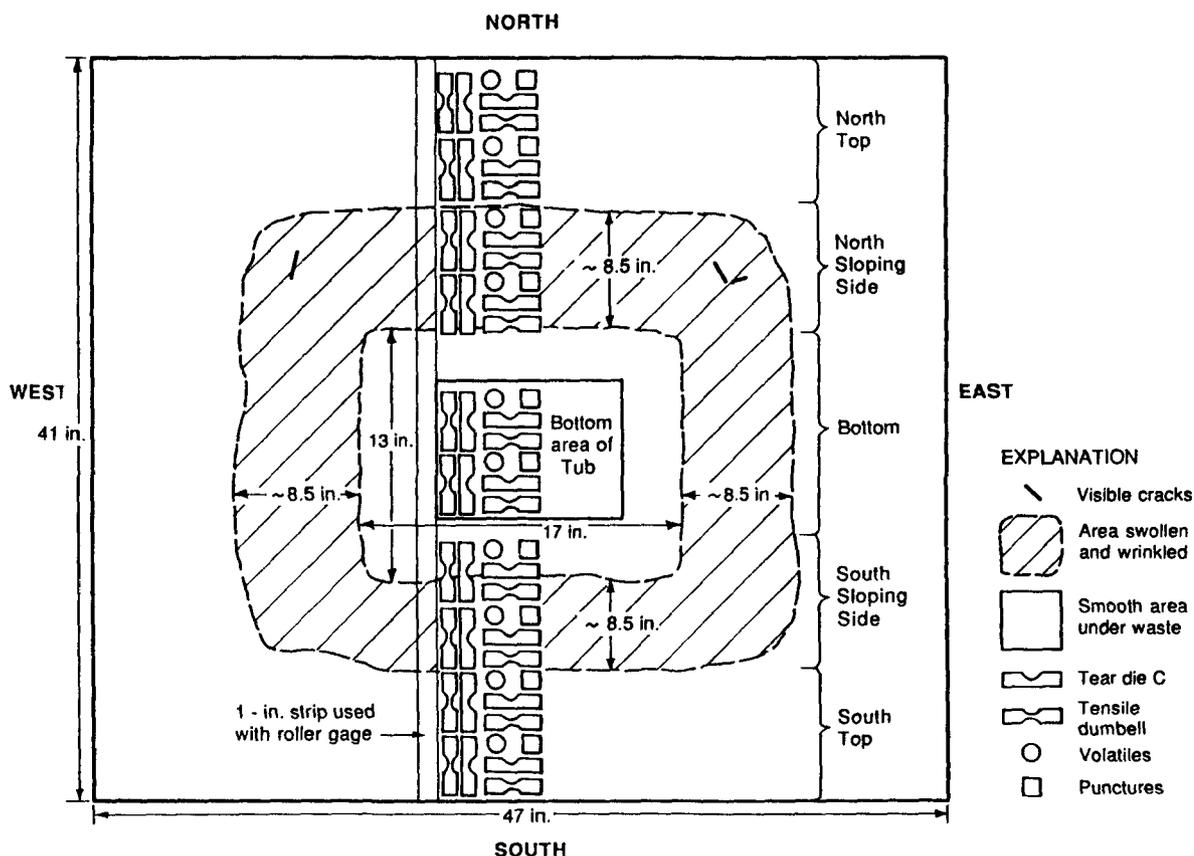


Figure H-4. Drawing of an exposed liner showing locations where the test specimens were cut and the directional orientation in which the liner was exposed. Location of strip for measuring thickness across specimens is also shown. Note that this FML sample did not include a seam. (Source: Haxo et al, 1985, p 163).

REPORT

- Summarize the results of monitoring the tub. Include observations on the appearance of the tub liner and the waste at the end of the exposure period.

- Summarize the results of testing the tub liner as follows:
 - Report test values for volatiles of the unexposed FML and the tested exposure areas.
 - Report test values for extractables of the unexposed FML and the tested exposed areas. Report the solvent used to perform the extractions.
 - Report test values for tear resistance and tensile properties of the unexposed FML and percent retention of the unexposed properties for each of the tested exposed areas.
 - Report test values for puncture resistance of the unexposed FML and the tested exposed areas.
 - Report test values for hardness of the unexposed FML and the change in points from the test values obtained on the unexposed FML for each of the tested exposed areas.
 - Report test values for the seam strength in peel and shear modes of the unexposed sample and for each of the tested exposed areas. Include a description of the seam system and a description of the manner in which the test specimens broke.
 - Present a drawing of the exposed liner indicating the exposed areas, any signs of FML deterioration, and the pattern used for cutting test specimens from the liner.
 - Present the thickness profile of the 1-in. wide strip cut from the liner.
 - Report the procedures used in performing the testing.
- Summarize the results of testing the waste liquid.

REFERENCE

Haxo, H. E., R. S. Haxo, N. A. Nelson, P. D. Haxo, R. M. White, and S. Dakessian. 1985. Liner Materials Exposed to Hazardous and Toxic Wastes. EPA/600/2-84/169 (NTIS No. PB-85-121333). Cincinnati, OH: U.S. Environmental Protection Agency. 256 pp.

APPENDIX I
DESIGN OF THE PIPE NETWORK FOR
LEACHATE COLLECTION SYSTEMS

A primary or secondary leachate collection system in a double liner system for the containment of hazardous wastes typically consists of:

- A drainage layer.
- A filter layer.
- A strategically-placed network of perforated pipe for transporting leachate or waste liquid from the drainage layer to the sump/manhole system from which the liquid is withdrawn.
- A bedding layer for the pipe network.
- A sump/manhole system which allows collection of the leachate or waste liquid and access to the pipe network for inspection and possible repairs throughout the monitoring periods.
- Mechanical and electrical equipment for conveying the leachate from the collection system to a separate storage or treatment area and for monitoring and controlling the level of leachate above the liner.

The pipe can be installed either in a trench condition or in a condition in which the pipe projects above the liner. The function of the primary leachate collection system at landfills and waste piles is to minimize the head of leachate on the top liner during operation of the unit and during the post-closure care period. The collection and removal system is required by present EPA regulations to be capable of maintaining a leachate head of less than 1 ft. The function of the secondary leachate collection system between the two liners is to detect and collect liquids that have leaked through the top liner and remove them for treatment and/or disposal.

This appendix discusses the flow capacity, sizing, structural stability, and deflection of pipe used in a pipe network for leachate collection systems with particular emphasis on primary leachate collection systems. A series of charts and tables is presented for use in the design and analysis of pipe networks. Various types of pipes are discussed in Section 4.2.7.

I.1 FLOW CAPACITY

As indicated in Chapter 7, the spacing of the collection pipes in a collection system above the top liner influences the maximum head of leachate on the base of a landfill or waste pile, given a uniform rate of leachate percolation through a saturated fill and the permeability of the medium through which the leachate is withdrawn. Figure I-1 can be used to select the required pipe spacing given an allowable leachate head (<1 ft) over the base of the unit. Figure I-2 shows the flow that must be carried in a collection pipe for various percolation rates and collection pipe spacings. With the required flow known, Figure I-3 can be used to select pipe sizes. Designs incorporating 6-in. diameter perforated pipes spaced 50 to 200 ft apart will effectively minimize head on the liner in most cases (EPA, 1985).

I.2 STRUCTURAL STABILITY OF PIPE

I.2.1 Introduction

Pipes installed at the bottom of a containment unit for collecting leachate and conveying it to withdrawal wells can be subjected to high loading of waste fills, which can rise several hundred feet above the pipe.

Leachate collection pipes beneath containment units generally are installed in one of two conditions (1) a trench condition or (2) a positive projecting condition. These installation conditions are shown in Figure I-4. In analyzing the structural stability of pipe under an imposed loading, the pipe is considered either a rigid or flexible conduit. Examples of rigid conduits are concrete and cast iron pipe. Polymeric and fiberglass pipes are examples of flexible pipe. Because a landfill environment can be highly corrosive, polymeric pipe materials are generally selected for use in leachate control systems due to their relatively inert properties. This section of this appendix discusses the structural stability of flexible pipe in landfill applications.

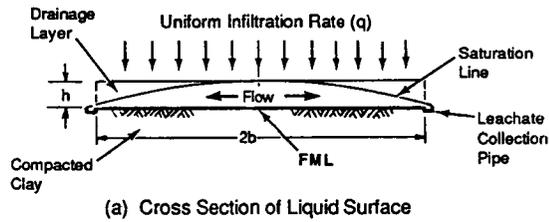
I.2.2 Loads Acting on Pipe

Loads are determined for one of two conditions: a trench condition or a positive projecting condition.

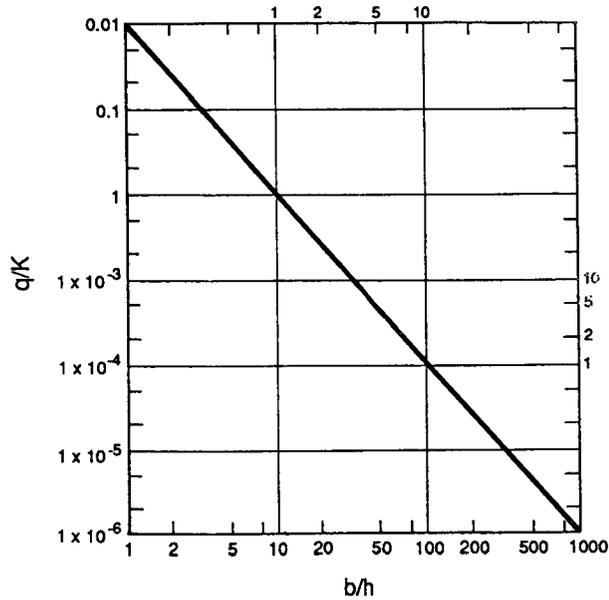
I.2.2.1 Trench Condition (Figure I-4)--

This condition is assumed to exist whenever the top of the pipe is located below the ground surface. Load on the pipe is caused by both the waste fill and the trench backfill. These two components of the total vertical pressure on the pipe are computed separately and then added to obtain the total vertical pressure acting on the top of the pipe. The waste fill is assumed to develop a uniform surcharge pressure, q_f , at the base of the unit. The magnitude of q_f is given by the expression:

$$q_f = (\omega_f)(H_f),$$



(a) Cross Section of Liquid Surface



(b) q/K vs. b/h for Drainage Material

For leachate flow conditions represented in Figure a, the following equation approximates the flow net solution:

$$q/K = \left(\frac{h}{b}\right)^2$$

where,

q = uniform infiltration rate

K = coefficient of permeability (i.e. of drainage layer above liner)

h = head of leachate above liner

b = width of area contributing to leachate collection pipe.

Example for a 1-ft thickness of permeable material overlying FML liner:

$$q = 2 \text{ in./month} = .00548 \text{ ft/d}$$

$$K (\text{sand}) = 2 \times 10^{-2} \text{ cm/sec} = 50 \text{ ft/d}$$

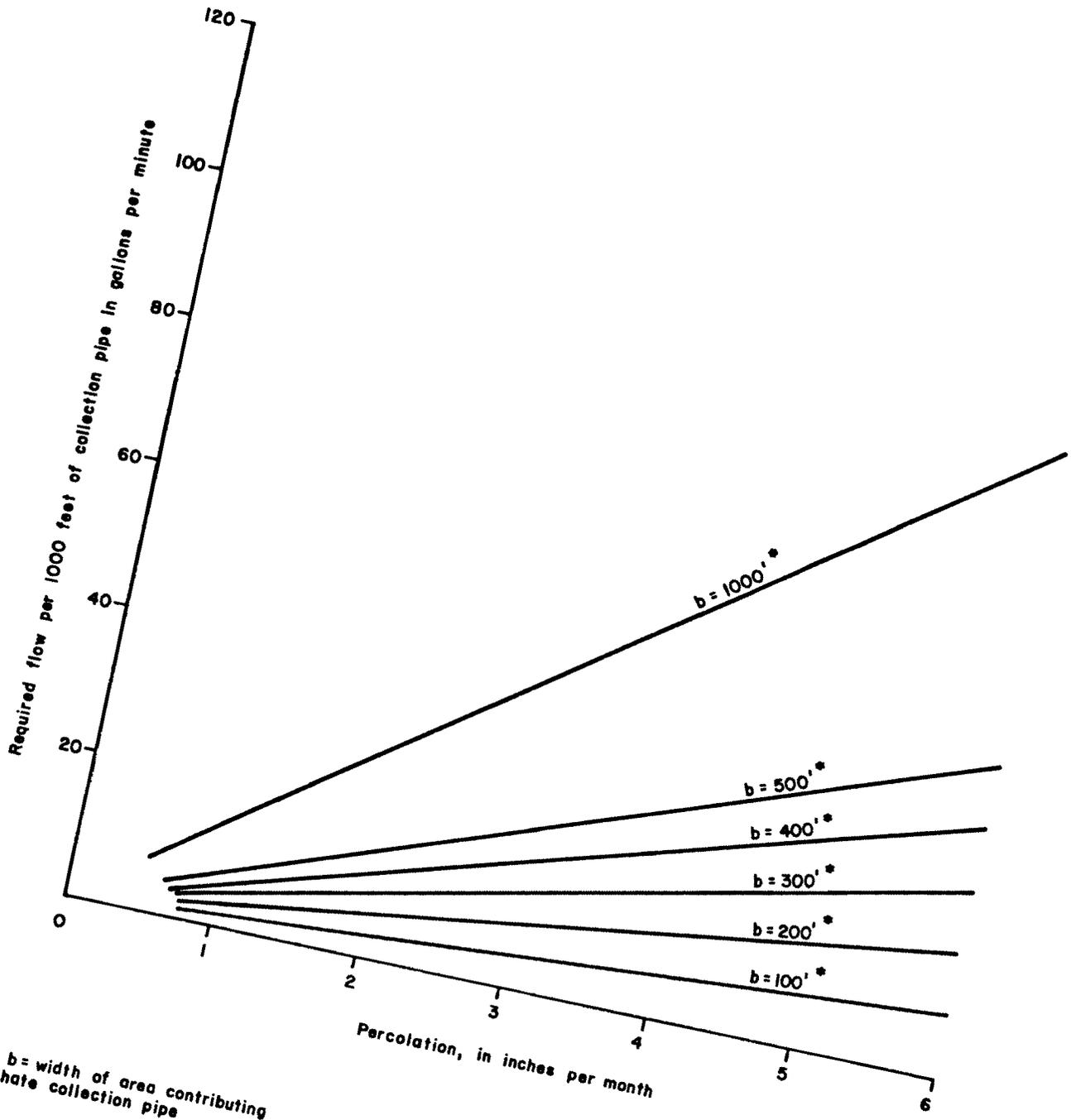
$$b = 100 \text{ ft and } q/K = 1 \times 10^{-4}$$

from chart,

$$b/h = 100$$

therefore, the head (h) acting on the liner = 1 ft.

Figure I-1. Determination of leachate head on FML liners using flow net solution (Cedergren, 1967). Figure (b) is a log-log plot with subdivisions shown on the right and top of graph. Methods of estimating leachate production rate, i.e. uniform infiltration rate, are discussed in Section 7.3.1.1.7.



*Where b = width of area contributing to leachate collection pipe

Figure I-2. Required capacity of leachate collection pipe.

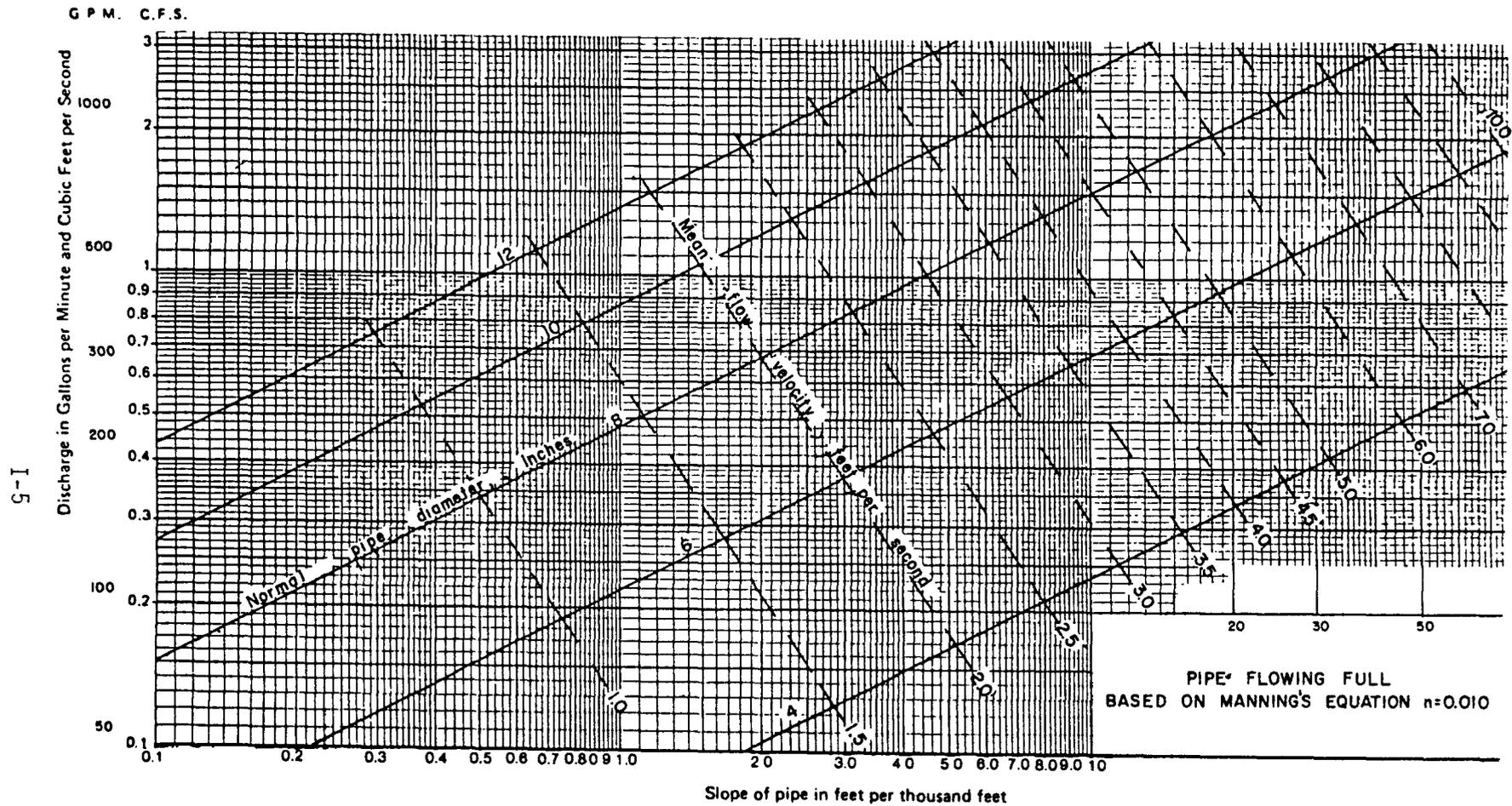
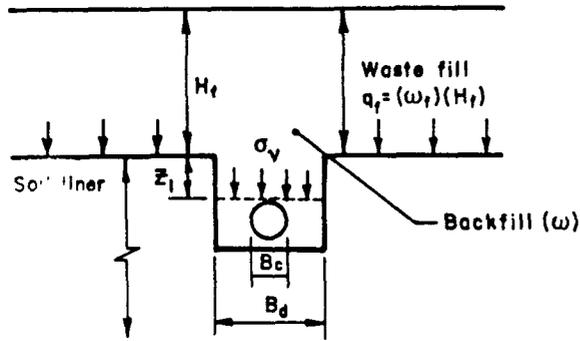
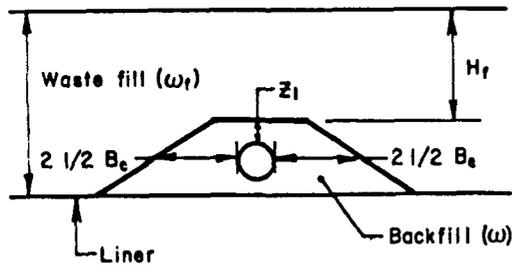


Figure I-3. Sizing of leachate collection pipe (Plastic Pipe Institute, 1975). It should be noted that the EPA draft Minimum Technology Guidance document requires a minimum 2% slope (EPA, 1985).



a) TRENCH CONDITION



b) PROJECTING CONDITION

Equations for determining the vertical pressure acting on the pipe:

For TRENCH CONDITION:

$$\sigma_v = B_d \omega C_D + q_f C_{u.s.}$$

$$\text{Where: } C_D = \frac{[1 - e^{-2K\mu(z/B_d)}]}{2K\mu}$$

$$C_{u.s.} = e^{-2K\mu(z/B_d)}$$

$$W = \sigma_v B_c$$

For PROJECTING CONDITION:

$$\sigma_v = (\omega_f)(H_f) + \omega z_1$$

DEFINITIONS:

- ω = unit weight of backfill
- ω_f = unit weight of waste fill
- H_f = height of waste fill
- q_f = vertical pressure at the bottom of the waste fill
- σ_v = vertical pressure at the top of the pipe
- W = force per unit length of pipe
- z_1 = height of backfill above the pipe
- B_d = width of trench
- B_c = outside diameter of pipe
- K = lateral pressure coefficient of backfill
- μ = coefficient of friction between backfill and the walls

Figure I-4. Pipe installation--conditions and loading (Clarke, 1968).

where

q_f = vertical pressure at the base of the unit due to waste fill (lb/sq ft),

ω_f = unit weight of the waste fill (lb/cu ft); for example, values range between 45 and 65 lb/cu ft for municipal solid waste with soil cover, and

H_f = height of waste fill (ft).

The value of the vertical pressure at the top of the pipe due to the waste fill may be determined from the following equation:

$$\sigma_{v1} = q_f C_{\mu s}.$$

The term $C_{\mu s}$, a load coefficient, is a function of the ratio of the depth of the trench, Z , (measured from the ground surface to the top of the pipe) to the width of the trench, B_d , and of the friction between the backfill and the sides of the trench. It may be calculated from the following equation or obtained from Figure I-5.

$$C_{\mu s} = e^{-2K\mu'(Z/B_d)},$$

where

K = lateral pressure coefficient of the trench backfill,

μ' = coefficient of friction between backfill and the walls of the trench,

Z = depth of trench from original ground surface to top of pipe (ft), and

B_d = width of trench at top of pipe (ft).

The product of $K\mu'$ is characteristic for a given combination of backfills in natural (in place) soil. Maximum values for typical soils are presented in ASCE Manual of Practice, No. 37. Those values of $K\mu'$ representing soils in which flexible pipes are likely to be installed are:

<u>Type of soil</u>	<u>Maximum value of $K\mu'$</u>
Sand and gravel	0.165
Saturated top soil	0.150
Clay	0.130
Saturated clay	0.110

The value of the vertical pressure at the top of the pipe due to the trench backfill may be determined from the following equation developed by Marston:

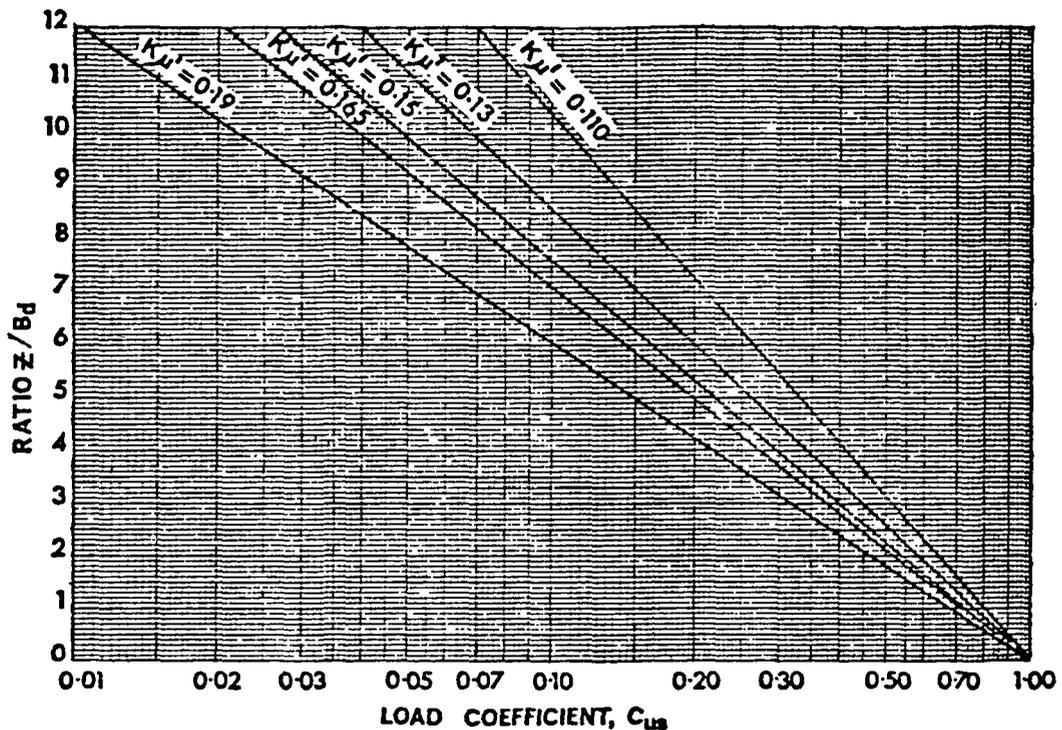
$$\sigma_{v2} = (B_d)(\omega)(C_d)$$

ω = unit weight of trench backfill (lb/cu ft).

The term C_d also is a load coefficient which is a function of the ratio Z/B_d and the friction between the backfill and sides of the trench. It may be computed from the following equation or obtained from Figure I-6.

$$C_d = \frac{1 - e^{-2K\mu'(Z/B_d)}}{2K\mu'}$$

where the terms are as defined above.



Values of load coefficient C_{us} (trench uniform surcharge)

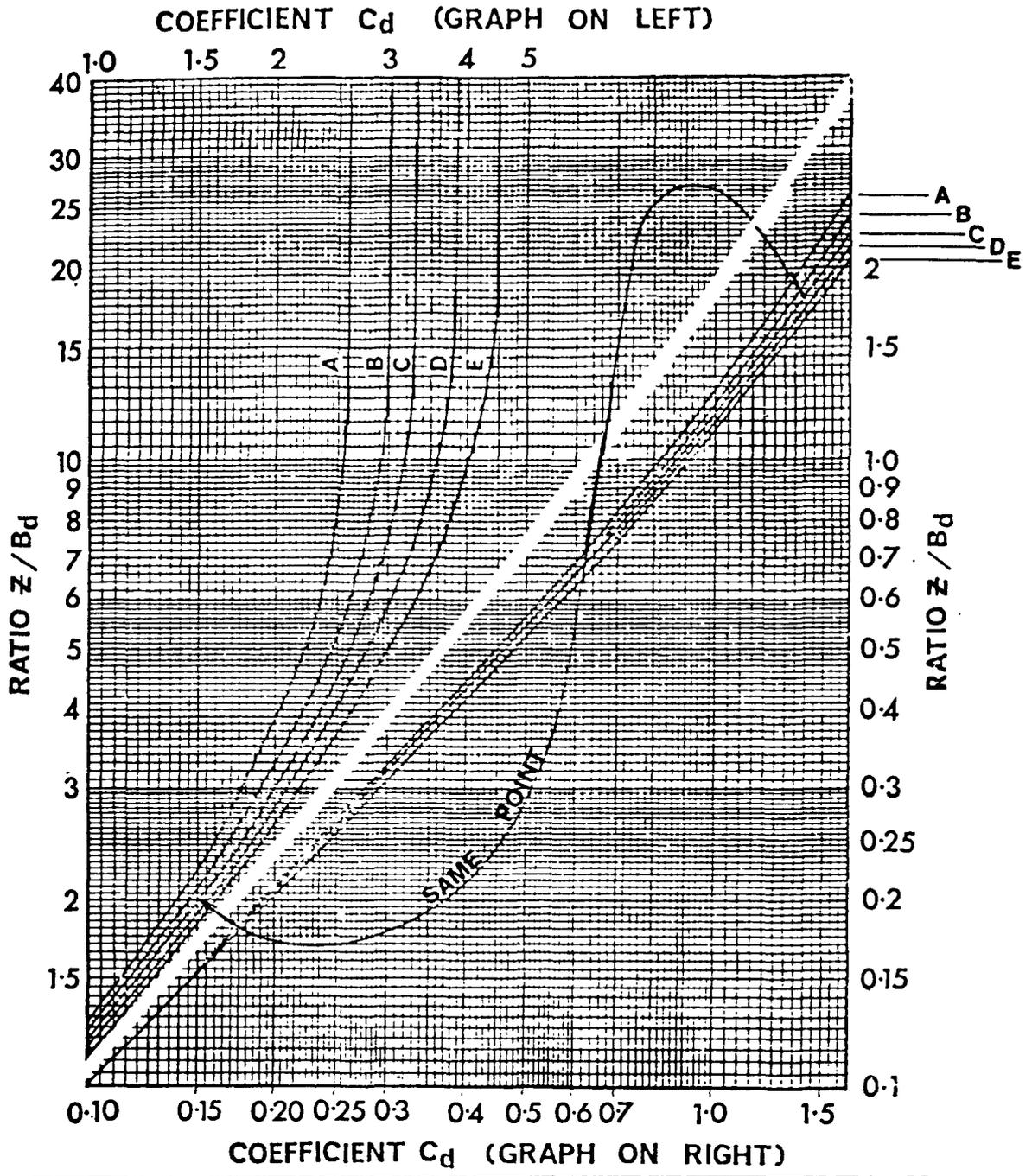
Figure I-5. Trench condition--pipe load coefficient C_{us} (trench uniform surcharge) (Clarke, 1968).

The total vertical pressure is equal to:

$$\sigma_v = \sigma_{v1} + \sigma_{v2} = qf C_{us} + B_d \omega C_d$$

The force per unit length of the pipe is equal to:

$$W = \sigma_v B_c,$$



- A— C_d for $K\mu' = 0.19$, for granular materials without cohesion
- B— C_d for $K\mu' = 0.165$ max. for sand and gravel
- C— C_d for $K\mu' = 0.150$ max. for saturated top soil
- D— C_d for $K\mu' = 0.130$ ordinary max. for clay
- E— C_d for $K\mu' = 0.110$ max. for saturated clay

Values of load coefficient C_d (back fill)

Figure I-6. Trench condition--pipe load coefficient C_d (Clarke, 1968).

where

W = force per unit length of pipe, and

B_C = outside diameter of pipe.

I.2.2.2 Positive Projecting Condition (Figure I-4)--

This condition is assumed to exist whenever the top of the pipe is at or above the level of the bottom of the unit. In this case, the load on the pipe can be assumed to be equal to the weight of a prism of overlying waste fill with a width B_C and height H_f plus the weight of a similar prism of gravel backfill above the pipe; because the pressure due to the gravel backfill typically will be small compared to the pressure due to the waste fill, the vertical pressure on the top of the pipe can be assumed to be equal to the unit weight of the waste fill multiplied by the distance from top of the waste fill to top of pipe, thus:

$$\sigma_v = (\omega_f)(H_f).$$

I.2.2.3 Perforated Pipe--

Perforations will reduce the effective length of pipe available to carry loads and resist deflection. The effect of perforations can be taken into account by using an increased load per nominal unit length of the pipe. If l_p equals the cumulative length in inches of perforations per foot of pipe, the increased vertical stress to be used equals:

$$(\sigma_v)_{\text{design}} = \frac{12}{12-l_p} \times (\sigma_v)_{\text{actual}}.$$

I.2.3 Deflection

A well-accepted formula for calculating flexible pipe deflection under earth loading is that developed by Spangler. This equation, also known as the Iowa formula, is presented together with suggested values for its various constants in the 1970 edition of the American Society of Civil Engineers (ASCE) Manual of Practice, No. 37, Chapter 9, Section E, Subsection 1, and is as follows:

$$\Delta y = D_e \frac{KW r^3}{EI + 0.061 E' r^3}$$

where,

Δy = horizontal and vertical deflection of the pipe (in.),

D_e = a factor, generally taken at a conservative value of 1.5, compensating for the lag or time dependent behavior of the soil/pipe systems (dimensionless),

W = vertical load acting on the pipe per unit of pipe length (lb/in.),

r = mean radius of the pipe (in.),

E = modulus of elasticity of the pipe materials (psi),

E' = modulus of passive soil resistance (psi) (normally estimated to be 300 psi for soils of Proctor density of 65%, and 700 psi for soils of Proctor density of at least 90%),

K = bedding constant, reflecting the support the pipe receives from the bottom of the trench (dimensionless) (a conservative value generally taken is 0.10), and

I = moment of inertia of pipe wall per unit of length (in.⁴/in.); for any round pipe, $I = t^3/12$ where t is the average thickness (in).

The equation can be rewritten to express pipe deflection as a decimal fraction of the pipe diameter, B_C , and to relate it to the vertical stress on the pipe as follows:

$$\frac{W}{B_C} = \sigma_v = \frac{(\Delta y)(EI + 0.061E'r^3)}{(B_C)(D_e K r^3)}$$

Solutions to this equation are shown graphically in Fig. J-7 where the quantity $\sigma_v/(\Delta y/B_C)$ has been plotted against the passive soil modulus E'. The relationship between $\sigma_v/(\Delta y/B_C)$ and E' has been shown for four plastic pipes: 4 and 6-in. Schedule 40 and 4 and 6-in. Schedule 80 PVC pipe. In computing the quantity EI for these pipes, a reduced modulus was used to account for creep of the plastic pipe. A value equal to 142,000 psi was used to correspond to the modulus at 50 years under sustained loading (see Janson, 1974). Also shown is the relationship for EI = 0. This would represent a relationship between $\sigma_v/(\Delta y/B_C)$ and E', if the stiffness of the pipe is neglected.

In addition to using the chart to check the adequacy of a given pipe, the chart can be used to determine the necessary value of EI/r^3 which the pipe must have for given values of $\sigma_{max}/(\Delta y/B_C)$ and E'. Although it is customary to use either 300 or 700 psi for the value of the modulus of passive soil resistance, it should be noted that the modulus of elasticity of a coarse grained soil (sand or gravel) increases with increasing pressure (or depth in the ground). Thus, it should be expected that the modulus of passive soil resistance also would increase with increasing pressure or depth of fill.

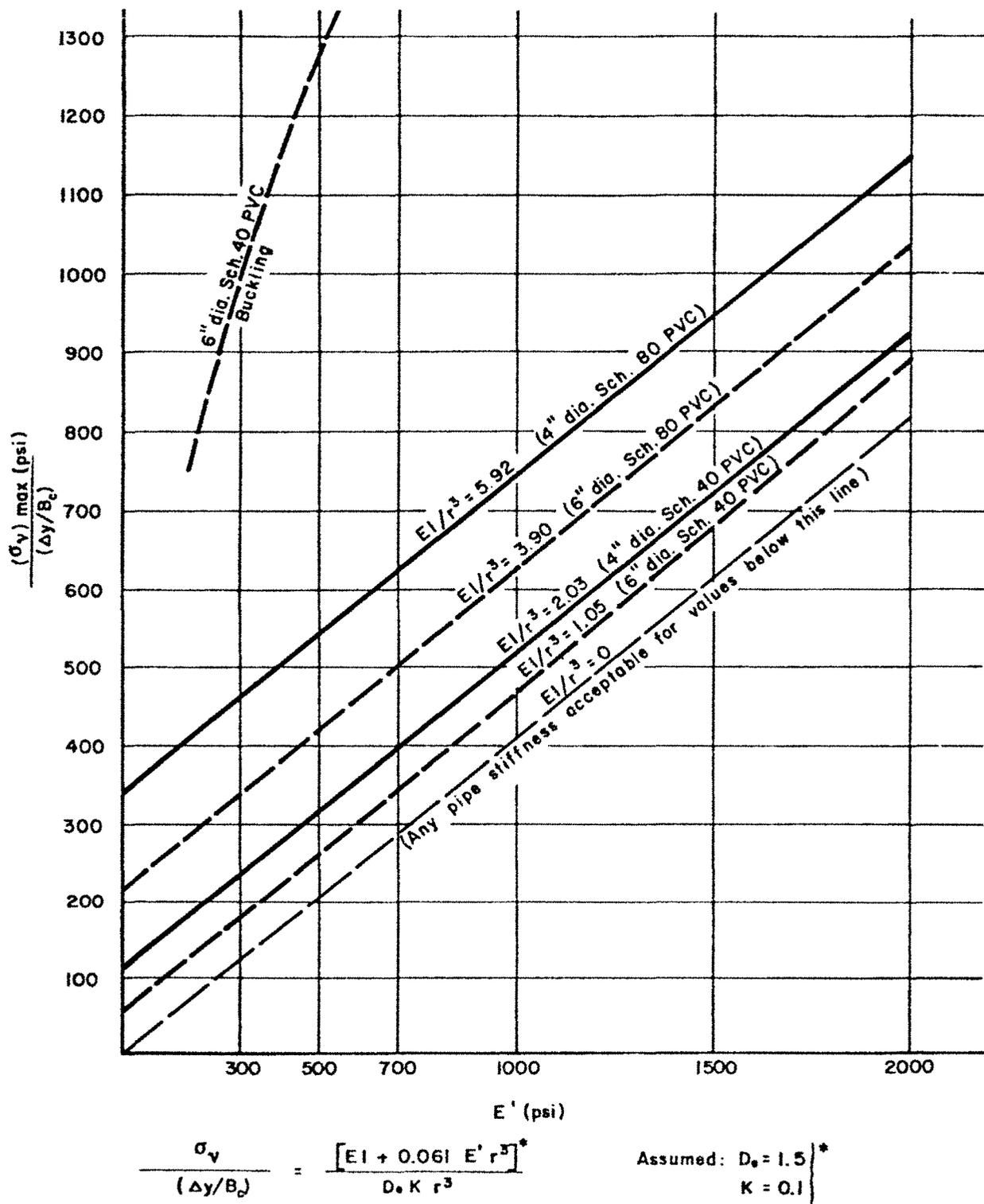


Figure I-7. Selection of pipe strength. (Source: ASCE, 1969).

The term EI in Spangler's equation reflects the pipe's contribution to the total resistance to deflection under load offered by the pipe/soil system. This term, known as the pipe's Stiffness Factor, is related to the pipe's behavior under parallel plate loading as per ASTM D2412, "External Loading Properties of Plastic Pipe by Parallel Plate Loading," by the following expression:

$$EI = 0.149r^3(F/\Delta y),$$

where

E, I and r are as previously defined:

F = the recorded load (lb/linear in.) required to produce a pipe deflection Δy , and

Δy = the pipe's deflection (in.).

Minimum values of the term $F/\Delta y$, called Pipe Stiffness, are set according to Pipe DR (dimension ratio) by the ASTM PVC Sewer Pipe Specifications D3033 and D3034. The DR represents the ratio of the pipe's average outside diameter to its minimum wall thickness. Thus, for each DR there is a corresponding minimum specified value of $F/\Delta y$.

The above expression for EI can be substituted into the previous equation for deflection to obtain the following:

$$\frac{\sigma_v}{(\Delta y/B_c)} = \frac{(0.149F/W_y) + 0.061E'}{D_e K}$$

Solutions to this equation can be made on a graph similar to Figure I-7 where the quantity $\sigma_v/(\Delta y/B_c)$ is plotted against the soil modulus E' for several values of $F/\Delta y$.

1.2.4 Buckling Capacity

The capacity of a buried plastic drain pipe to support vertical stresses may be limited by buckling. Estimates of the vertical stresses at which buckling of the 6-in. Schedule 40 PVC pipe (the most flexible of the four pipes shown) will occur are indicated by the curve in Figure I-7. For the four pipes shown, buckling would not be a controlling factor. However, it could be a controlling factor, depending on the flexibility of the pipe and the modulus of passive soil resistance. Specific information for other sizes and pipe materials proposed for use in the collection system should be secured from the pipe manufacturer.

1.2.5 Compressive Strength

The capacity of the pipe to support vertical stresses may be influenced by the circumferential compressive strength of the pipe. The designer or

reviewer should secure up-to-date information on circumferential compressive strength characteristics from the manufacturer of the type of pipe proposed for use.

I.2.6 Construction Loadings

A pipe correctly designed to withstand loading from a high fill can fail from loading received during construction. Although only a fraction of a stationary wheel or tracked vehicle load applied at the ground surface over a trench is transmitted to a pipe through the trench backfill, the percentage increases rapidly as the vertical distance between the loaded surface and the top of the pipe decreases. In addition, moving loads cause impact loading which is generally considered to have a 1.5 to 2.0 multiplier effect over stationary loading.

In general, equipment should not cross leachate collection drains installed in trenches with shallow cover or in projecting installations. When equipment must be routed across a drain, impact loading can be minimized by mounding material over the pipe to provide a vertical separation of 4 ft between the loaded surface and the top of the pipe.

I.2.7 Procedures for Calculating Required Pipe Strength

The procedures used to select the proper strength pipe are illustrated in the following examples:

Trench Installation (Figures I-5 and I-8)

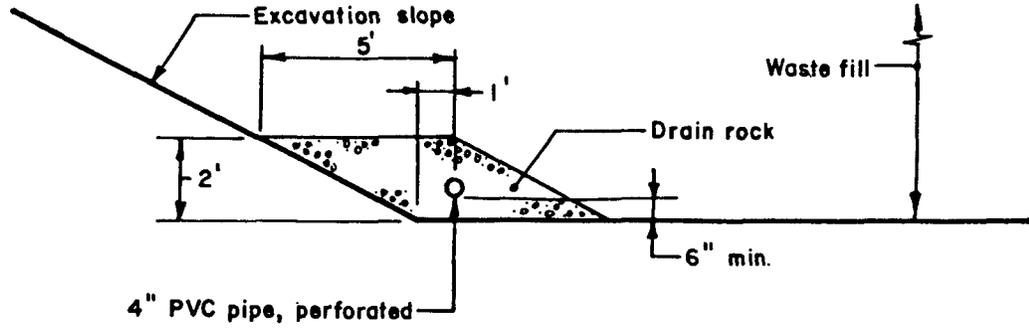
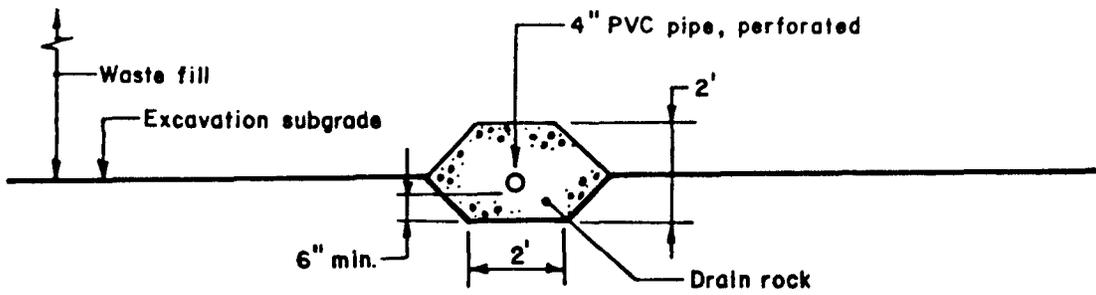
Given: $Z = 1 \text{ ft} - 8 \text{ in.}$ $H_f = 100 \text{ ft waste fill}$
 $B_d = 1 \text{ ft} - 6 \text{ in.}$ $\omega_f = 50 \text{ pcf}$
 $K_{\mu'} = 0.19$ $\gamma = 110 \text{ pcf}$
pipe diameter = 4 in.

Determine: Required pipe strength/schedule.

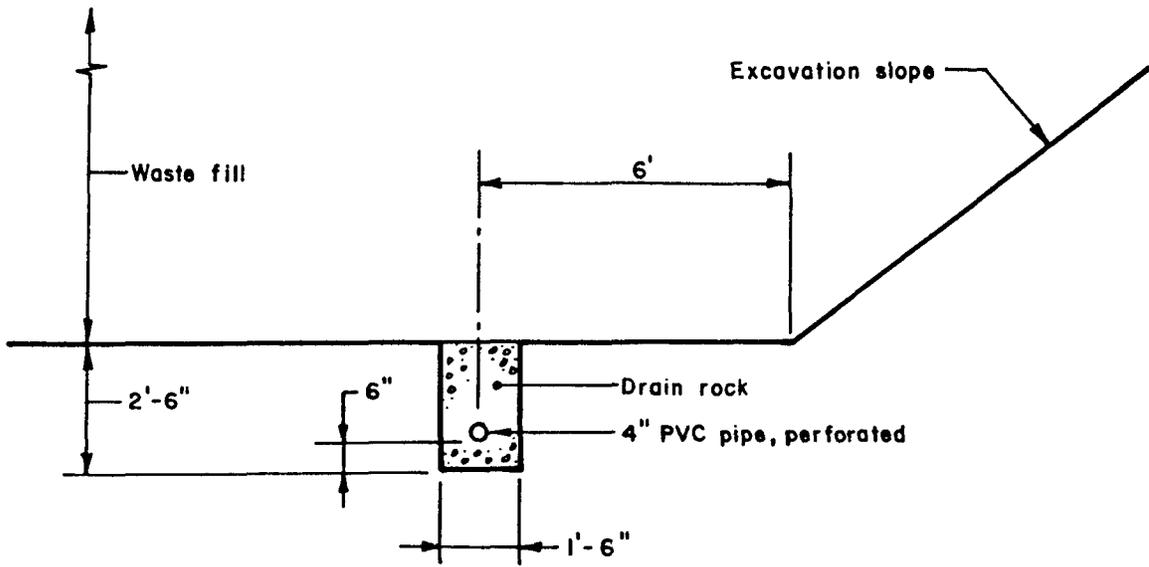
Step 1 - Determine the maximum vertical pressure σ_v (psi) acting on the top of the pipe:

$$\frac{Z}{B_d} = \frac{1.67}{1.5} = 1.11, \text{ and}$$

$$q_f = (\omega_f) H_f = 100 (50) \\ = 5000 \text{ psf.}$$



PROJECTING INSTALLATIONS



TRENCH INSTALLATION

Figure I-8. Typical leachate collection drains.

From Fig. I-5, $C_{\mu S} = 0.64$ and Fig. I-8, $C_d = 0.9$;

then

$$\begin{aligned}\sigma_v &= (\omega)(B_d)(C_d) + (q_f)(C_{\mu S}) \\ &= (110)(1.5)(0.9) + (5000)(0.64) \\ &= 3348 \text{ psf} = 23.3 \text{ psi} = \sigma_v \text{ max.}\end{aligned}$$

Step 2 - Select the appropriate modulus of passive soil resistance E' (psi). For gravel bedding use 300 to 700 psi.

Step 3 - Select allowable pipe deflection ratio $\Delta y/B_C$. Use 0.05 to 0.1.

Step 4 - Determine the quantity $\frac{\sigma_v \text{ max}}{\Delta y/B_C}$, where $\sigma_v \text{ max}$ is in psi.

From Fig. I-7, the following information is obtained:

$\Delta y/B_C$	$\sigma_v \text{ max}/(\Delta y/B_C)$	E'	
		300	700
0.05	466	4-in. Sch 80 adequate	4-in. or 6-in. Sch 80 adequate
0.1	233	4-in. Sch 40 or 6-in. Sch 80 adequate	Any pipe

Positive Projecting Installation (see Figures I-4 and I-8)

Given: $Z_1 = 6$ in.; other parameters given as in example above.

Determine: Required pipe strength/schedule.

Step 1 - Determine the maximum vertical pressure σ_v (psi) acting on the top of the pipe:

$$\begin{aligned}\sigma_v &= \omega_f H_f + \omega Z_1 = (50)(100) + (110)(0.5) = \\ &5055 \text{ psf} = 35.1 \text{ psi} = \sigma_v \text{ max.}\end{aligned}$$

Steps 2, 3, and 4 as given under Trench Installation.

From Fig. I-7, the following information is obtained:

$\Delta y/B_C$	$\sigma_{V \max}/(\Delta y/B_C)$	E'	
		300	700
0.05	466	4-in. Sch 80 adequate	4-in. or 6-in. Sch 80 adequate
0.1	233	4-in. Sch 40 or 6-in. Sch 80 adequate	Any pipe

I.3 REFERENCES

- ASCE and Water Pollution Control Federation. 1969. Design and Construction of Sanitary and Storm Sewers. ASCE Manuals and Reports on Engineering Practice No. 37. NY. 332 pp.
- ASTM. Annual Book of ASTM Standards. American Society for Testing and Materials, Philadelphia, PA. Issued annually in several parts:
- D2112. "Test Method for Oxidation Stability of Inhibited Mineral Insulating Oil by Rotating Bomb."
- D3033. "Specification for Type PSP Poly(Vinyl Chloride) (PVC) Sewer Pipe and Fittings."
- D3034. "Specification for Type PSM Poly(Vinyl Chloride) (PVC) Sewer Pipe and Fittings."
- Cedergren, H.R. 1967. Seepage, Drainage, and Flow Nets. John Wiley and Sons, Inc., NY. 534 pp.
- Clarke, N. W. B. 1968. Buried Pipelines, A Manual of Structural Design and Installation. Maclaren and Sons, London. 309 pp.
- Janson, L. 1974. Plastic Pipe in Sanitary Engineering. Celanese Piping Systems, Hillard, OH.
- Spangler, M. G., and R. L. Handy. 1973. Soil Engineering. 3rd ed. Int. Educational Publishers, NY. 748 pp.

APPENDIX J

ANALYSES OF HAZARDOUS WASTES USED IN EXPOSURES REPORTED BY HAXO

This appendix summarizes the results of analyzing wastes used in the exposure tests performed by Haxo et al (1985 and 1986). In these tests, a variety of FMLs were exposed to a series of hazardous wastes under different test conditions including exposure in one-sided exposure cells, tub tests, pouch tests, and immersion tests. The results of these tests are summarized in Chapter 5 in the following sections:

- Section 5.4.1.2, "Exposure to Hazardous Wastes in One-Sided Exposure Cells."
- Section 5.4.1.4, "Exposure in Tub Tests."
- Section 5.4.1.6.2, "Tests of FML Pouches Containing Hazardous Waste Liquids."
- Section 5.4.2.2, "Immersion of FMLs in Hazardous Wastes and Selected Test Liquids."

The results of analyzing the wastes used in those exposure test are presented in Table I-1.

REFERENCES

- ASTM. Annual Book of ASTM Standards. Issued annually in several parts. American Society for Testing and Materials, Philadelphia, PA:
- D92-85. "Test Method for Flash and Fire Points by Cleveland Open Cup," Sections 04.04, 05.01, and 10.03.
 - D2007-69. "Test Method for Characteristic Groups in Rubber Extender and Processing Oils by the Clay-Gel Adsorption Chromatographic Method," Sections 05.02, 09.01, and 10.03.
 - D2983-85. "Test Method for Low-Temperature Viscosity of Automotive Fluid Lubricants Measured by Brookfield Viscometer," Section 05.02.

TABLE J-1. ANALYSES OF HAZARDOUS WASTES USED IN EXPOSURES REPORTED BY HAXO

Phases and tests	Wastes ^a								
	Acidic		Alkaline		"Lead Waste" ^b (W-14)	Oily waste			Pesti- cide
	"HFL" (W-10)	"HNO ₃ -HF- HOAc" ^b (W-9)	"Stop Water" (W-4)	"Spent Caustic" ^b (W-2)		"Slurry Oil" (W-15)	"Oil Pond 104" ^b (W-5)	"Weed Oil" (W-7)	"Weed Killer" ^b (W-11)
Separation of phases									
Phase I, aqueous insoluble organic liquid, weight %	0	0	0	0	10.4	98	89	20.6	0
Phase II, aqueous phase, weight %	100	100	100	95.1	86.2	0	0	78.4	99.5
Phase III, solid phase, weight %	0	0	0	4.9	3.4	2.0	11	0	0.5
Phase I - Organic									
Weight %	0	0	0	0	10.4	98	89	20.6	0
Flash point ^c , °C	...	...	...	...	<20	174	157	...	...
Viscosity ^d , cP									
At 20°C	...	...	...	...	...	3200	300	...	...
At 30°C	...	...	...	...	...	660	124	...	...
Water content, %	...	...	...	...	...	0	17	...	...
Organic group ^e									
Asphaltenes, %	...	...	...	...	...	13.1	9.6	...	...
Polar compounds, %	...	...	...	...	...	14.0	18.6	...	...
Saturated hydrocarbons, %	...	...	...	...	...	13.1	37.9	...	...
Aromatics, %	...	...	...	...	...	59.7	339	...	...
Lead, mg/L	...	...	...	...	530	...	170 ^f	...	...
Phase II - Aqueous									
pH	3.3	1.1	13.1	11.3	7.6	...	...	7.5	3.1
Electrical conductivity, mmho/cm	29	155	129	155	...	...	...	...	3.2
Weight %	100	100	100	95.1	86.2	0	0	78.4	99.5
Solids in solution, %									
Total	2.48	0.77	22.43	22.07	0.9	...	...	1.81	0.78
Volatile	0.9	0.12	5.09	1.61	0.35	...	...	1.0	0.46
Solids, total g/L	...	140	...	234.5	3.23	...	...	9.10	6.78
Volatiles, g/L	...	15	...	24.2	1.62	...	...	3.45	3.32
Total dissolved, g/L	...	137	...	234.5	2.66	...	...	1.75	6.62
Volatiles dissolved, g/L	...	7.0	...	24.0	1.14	...	...	...	3.22
Total suspended, g/L	...	15.0	...	0.04	0.41	...	...	...	0.16
Volatiles suspended, g/L	...	9.0	...	0.01	0.28	...	...	...	0.10
Alkalinity, g CaCO ₃ /L	...	...	..	8.69	1.06/28	...	...	...	25
Oil and grease, g/L	...	0.0	...	0.02	0.15	...	...	...	0.05
Soluble volatile organics, mL/L	...	0.0	...	0.15	1.0	...	...	...	0.8
Lead, mg/L	...	28 ^f	...	5.0 ^f	13	...	...	...	1.4 ^f
Phase III - Solids									
Weight %	0	0	0	4.9	3.4	2.0	11.0	0	0.5
Flammability									
Flame	...	...	...	Yes	...	...	Yes	...	Yes
Color	...	...	...	Orange	...	...	...	...	Orange
Smoke	...	...	...	No	...	...	...	...	No
Solids, %									
Organic, %	...	...	...	8.9	22.5	...	78.9	...	50.4
Inorganic, %	...	...	...	91.1	77.5	...	21.1	...	49.6
Water extract, mg/g	...	...	...	122.4	43.8	...	11.2	...	3.5
pH	...	...	...	5.2	7.4	...	8.4	...	2.5

^aMatrecon waste serial number shown below identification.

^bAnalyzed after exposure. The "Oil Pond 104" waste was originally an oil-water slurry which eventually separated into oil and water layers. The initial water content was about 30%.

^cASTM D92.

^dASTM D2983.

^eASTM D2007-69, in percent by weight.

^fTotal lead content of the waste.

Source: Haxo et al, 1985, p 26.

Haxo, H. E., R. S. Haxo, N. A. Nelson, P. D. Haxo, R. M. White, and S. Dakessian. 1985. Liner Materials Exposed to Hazardous and Toxic Wastes. EPA-600/2-84/169 (NTIS No. PB 85-121-333). U.S. Environmental Protection Agency, Cincinnati, OH. 256 pp.

Haxo, H. E., R. S. Haxo, N. A. Nelson, P. D. Haxo, R. M. White, and S. Dakessian. 1986. Liner Materials Exposed to Toxic and Hazardous Wastes. Waste Management and Research 4:247-264.

APPENDIX K

SUGGESTED PROPERTY STANDARDS FOR REPRESENTATIVE FMLS AVAILABLE IN JULY 1988

In view of the lack of accepted standards to cover currently available FMLs for lining waste disposal impoundments, suggested standards for representative FMLs currently available (July 1988) are presented in this appendix. The values are preliminary and subject to change. They are based largely upon the properties and tests discussed in Chapter 4, particularly Section 4.2.2.5, and reflect some of the current efforts to develop standards.

These tables of values should not be used to select materials. Selection, as indicated in Chapters 4, 5, 7, and 8, should be based upon factors of compatibility, durability, etc. The tables are intended to be used as a means of assuring that the quality of the FML that is installed in the waste containment unit is the same as was tested in the compatibility tests.

The standards present values for different properties which can characterize the FMLs. By themselves, these standards are not adequate to predict long-term product performance, nor can they be used for engineering design purposes. For example, the low temperature resistance numbers represent qualities measured after a few minutes of exposure at a given temperature and should not be interpreted or extrapolated into installation temperature qualities or comparisons. Correlations of specific properties and tests with field performance of lining materials have not been established, but the results of the tests indicate the quality of the specific material under test. Performance test methods are being developed by ASTM Committee D35 on Geotextiles and Related Products for use in the design of containment facilities.

K-1. GENERAL REQUIREMENTS FOR THE MANUFACTURE OF FMLS

FMLs shall be first quality designed and manufactured for the purpose of lining waste disposal impoundments. They shall be manufactured of virgin polymers and specifically compounded of high quality ingredients to produce flexible, durable, watertight membranes. Compounding ingredients shall either be soluble in the polymer or, if solid, shall pass through a No. 325 sieve, i.e. have particle size of 44 μm or less. All ingredients should be well dispersed through the compound prior to being formed into membranes. No water soluble ingredients can be used in the compound; neither can the ingredients contain water-soluble components.

The resultant FMLs shall be free from dirt, oil, foreign matter, scratches, cracks, creases, bubbles, pits, tears, holes, pinholes, or other defects that may affect serviceability and shall be uniform in color, thickness, and surface texture. The sheeting shall be capable of being seamed both in the factory and in the field to yield seams that are as resistant to waste liquids as the sheeting.

Note: Recycling of clean scrap compound is allowed up to 5% by weight of the compound. The recycling of scrap containing fiber is generally not considered to be good practice; however, the effects of such recycling have not been established at this time and tests are underway to resolve this question.

K-2. SUGGESTED TEST METHODS AND REQUIRED PROPERTIES FOR REPRESENTATIVE LINERS

Suggested methods for testing FMLs for acceptance and quality control and required values for properties of representative liner materials are presented in the following six tables:

- K-1. Suggested Properties and Methods for Testing of FMLs for Standards and Specifications.
- K-2. Titles of ASTM Test Methods Specifications Used with FMLs.
- K-3. Suggested Standards for Unreinforced FMLs (Thermoplastic FMLs of CPE, PVC, and PVC-OR).
- K-4. Suggested Standards for Unreinforced FMLS (Polyethylene FMLs).
- K-5. Suggested Standards for Fabric-Reinforced FMLs (FMLs with Thermoplastic Coatings of CPE, CPE-A, and EIA).
- K-6. Suggested Standards for Fabric-Reinforced FMLs (Thermoplastic CSPE FMLs).

For quality control purposes, it is suggested that random samples be taken from each 10,000 square yards of sheeting; however, a minimum of five samples for quality control testing should be taken from each job. Each sample should be three by six feet and should include a factory seam if the FML requires factory fabrication. The minimum tests that should be performed for quality control purposes are those that are listed under mechanical properties.

Table K-1 presents all of the suggested test methods arranged by type of FML and by analytical properties, mechanical properties, and tests of the

TABLE K-1. SUGGESTED PROPERTIES AND METHODS^a FOR TESTING FMLs FOR STANDARDS AND SPECIFICATIONS

Property	Unreinforced FMLs		
	Thermoplastic polymers	Semicrystalline polymers	Fabric-reinforced FMLs ^b
Analytical properties			
Specific gravity/density	D792, Method A	D792, Method A/D1505	...
Volatile loss	D1203, Method A MTM-1 ^b	D1203, Method A MTM-1 ^b	D1203, Method A MTM-1 ^b
Extractables	MTM-2 ^b	MTM-2 ^b	MTM-2 ^{b,c}
Ash	D297, Section 34	D297, Section 34	D297, Section 34 (selvage)
Carbon black content	na ^d	TGA, D1603, or D4218	na
Carbon black dispersion	na	D3015	na
Melt index	na	D1239, Procedure A (Condition: 190/2.16)	na
Mechanical properties			
Thickness:			
Overall	D1593, Section 9.1.3	D1593, Section 9.1.3	D751, Section 7
Coating over scrim	na	na	Optically ^e
Minimum tensile properties (in both machine and transverse directions):			
Breaking strength of fabric	na	na	D751, Method A (grab)
Breaking elongation of fabric	na	na	D751, Method A (grab)
Tensile at yield	na	D638	na
Elongation at yield	na	D638	na
Tensile strength	D882, Methods A and B	D638	D751, Method A (grab)
Elongation at break	D882, Methods A and B	D638	D751, Method A (grab)
Modulus of elasticity	na	D638 or D882, Method A	na
Tear strength	D1004	D1004	D751, Method B (tongue) (8 in. x 8 in. specimen)
Hardness, Duro A or D	D2240	D2240	D2240 ^f
Hydrostatic resistance	D751, Method A, Procedure 1	D751, Method A, Procedure 1	D751, Method A, Procedure 1
Puncture resistance	FTMS 101C, Method 2065	FTMS 101C, Method 2065	FTMS 101C, Method 2031
Ply adhesion	na	na	D413, Method A
Strength of factory seams:			
Shear	D4545	D4545	D4545
Peel	D4545	D4545	D4545
Environmental and aging properties			
Dimensional stability	D1204 (15 minutes at 100°C)	D1204 (15 minute at 100°C)	D1204 (1 hour at 100°C)
Low temperature brittleness	D17909	D746, Procedure B9	D2136 ^h
Resistance to soil-burial for 120 d ⁱ	D3083, Section 9.5	D3083, Section 9.5	D3083, Section 9.5
Tensile at yield	na	D638	na
Tensile at fabric break	na	na	D751, Method A (grab)
Tensile at break	D882	D638	D751, Method A (grab)
Elongation at break	D882	D638	D751, Method A (grab)
Modulus of elasticity	na	D638	na
Ozone resistance at 40°C	D1149 100 ppm O ₃ 70% extension 7 days	D1149/D518 100 ppm O ₃ Bent loop 7 days	D1149/D518 100 ppm O ₃ Bent loop 7 days
Environmental stress-cracking	na	D1693	na
Water absorption	...	...	D471 (166 hours at 23°C) (166 hours at 70°C)
Water extraction	D3083, Section 9.6/ D1239	D3083, Section 9.6/ D1239	D3083, Section 9.6/ D1239

^aASTM unless otherwise noted. FTMS = Federal Test Method Standard; MTM = Matrecon Test Methods. Matrecon Test Method 1 is presented in Appendix G, and Matrecon Test Method 2 is presented in Appendix E.

^bWith thermoplastic coatings.

^cBoth selvage edge and fabric-reinforced FML.

^dna = not applicable.

^eOptical measurements made of a diagonal cut of the FML made with a razor blade. A box microscope with stage micrometer with mil divisions should be used.

^fOn selvage edge.

^gDetermination of the temperature at which membranes exhibit brittle failure under specified impact conditions.

^hBend specimen over 1/8-in. mandrel after four hours at the test temperature.

ⁱSize of buried specimens: 1 in. x 6 inches.

TABLE K-2. TITLES OF ASTM TEST METHODS AND SPECIFICATIONS^a
USED WITH FMLS

ASTM number	Title and pertinent sections
D297-81	Rubber Products - Chemical Analysis. Section 15-Density; Section 34-Referee Ash Method.
D412-80	Rubber Properties in Tension.
D413-82	Rubber Property - Adhesion to Flexible Substrate.
D471-79	Rubber Property - Effect of Liquids, Section 09.01.
D518-61 (1974)	Rubber Deterioration - Surface Cracking.
D573-81	Rubber - Deterioration in Air Oven.
D624-73	Rubber Property - Tear Resistance.
D638-84	Tensile Properties of Plastics.
D746-79	Brittleness Temperature of Plastics and Elastomers by Impact.
D751-79	Coated Fabrics.
D792-66 (1979)	Specific Gravity and Density of Plastics by Displacement.
D882-83	Tensile Properties of Thin Plastic Sheeting.
D1004-66 (1981)	Initial Tear Resistance of Plastic Film and Sheeting.
D1146-53 (1981)	Blocking Point of Potentially Adhesive Layers.
D1149-86	Rubber Deterioration - Surface Ozone Cracking in a Chamber (Flat Specimens).
D1203-67 (1981)	Loss of Plasticizer from Plastics (Activated Carbon Methods).
D1204-84	Linear Dimensional Changes of Nonrigid Thermoplastic Sheeting or Film at Elevated Temperature.
D1239-86	Flow Rates of Thermoplastics by Extrusion Plastometer.
D1239-55 (1982)	Resistance of Plastic Films to Extraction by Chemicals

continued . . .

TABLE K-2. CONTINUED

ASTM number	Title and pertinent sections
D1248-84	Specification for Polyethylene Plastics Molding and Extrusion Materials.
D1505-85	Density of Plastics by the Density-Gradient Technique, Section 08.01.
D1593-80	Specification for Nonrigid Vinyl Chloride Plastic Sheeting.
D1603-76 (1983)	Carbon Black in Olefin Plastics, Section 08.02.
D1693-70 (1980)	Environmental Stress-Cracking of Ethylene Plastics.
D1790-62 (1983)	Brittleness Temperature of Plastic Film by Impact.
D2136-66 (1984)	Coated Fabrics - Low-Temperature Bend Test.
D2240-81	Rubber Property - Durometer Hardness.
D3015-72 (1985)	Recommended Practice for Microscopical Examination of Pigment Dispersion in Plastic Compounds.
D3083-76 (1980)	Specification for Flexible Poly(Vinyl Chloride) Plastic Sheeting for Pond, Canal, and Reservoir Lining; Section 9.5, Soil Burial, Section 9.6; Water Extraction; Section 9.4 Pinholes and Cracks, Section 04.04.
D4218-82 (1986)	Carbon Black Content in Polyethylene Compounds by the Muffle Furnace Technique.
D4545-86	Practice for Determining the Integrity of Factory Seams Used in Joining Manufactured Flexible Sheet Geomembranes.

^aAs listed in the 1987 issue of the ASTM standards. Number in parentheses indicates the year of last reapproval by the committee with jurisdiction for the standard.

TABLE K-3. SUGGESTED STANDARDS FOR UNREINFORCED FMLS
Thermoplastic FMLs of Chlorinated Polyethylene, Polyvinyl Chloride, and Polyvinyl Chloride - Oil-Resistant

Property	ASTM test method ^a	Chlorinated polyethylene		Polyvinyl chloride ^b			PVC-ORC
		20	30	20	30	40	30
Nominal thickness, mil		20	30	20	30	40	30
Analytical properties							
Specific gravity	D792-A	1.20 minimum	1.20 minimum	1.24-1.30 range	1.24-1.30 range	1.24-1.30 range	1.20 minimum
Volatile loss, % (maximum)	D1203-A	0.5	0.5	0.9	0.7	0.55	0.5
Mechanical properties							
Thickness:							
Actual, mils (minimum)	D1593, Section 9.1.3	19	28.5	19	28.5	42.75	28.5
Minimum tensile properties in each direction:	D882						
Breaking factor, ppi width		34	43	46 (2300 psi)	69 (2300 psi)	92 (2300 psi)	69
Elongation at break, %		250	300	300	300	300	300
Stress at 100% elongation, ppi width		8	12	18 (900 psi)	27 (900 psi)	36 (900 psi)	27
Tear strength, lb (minimum)	D1004	3.5	4.5	6.0 (300 ppi)	8.0 (267 ppi)	10.0 (250 ppi)	8
Factory seam strength (minimum):							
In shear (ppi)	D4545/D3083/D882	27	34	36.8	55.2	82.8	55.2
In peel (ppi)	D4545/D413	10 ^d	10 ^d	10 ^d	10 ^d	10 ^d	10 ^d
Hydrostatic resistance, psi (minimum)	D751-A	75	100	60	82	95	82
Environmental and aging effects on properties							
Dimensional stability, % change (maximum)	D1204	16	16	5	5	5	5
Low temperature (brittleness temperature), °F (maximum)	D1790	-20	-20	-15	-20	-20	0
Resistance to soil-burial for 120 days (maximum % change from original value):	D3083						
Breaking factor		5	5	5	5	5	5
Elongation at break		20	20	20	20	20	20
Stress at 100% elongation		20	20	10	10	10	10
Water extraction, % (maximum)	D3083/D1239	-0.35	-0.35	-0.35	-0.35	-0.35	-0.35

^aFor more details regarding conditions and titles of test methods, see Tables K-1 and K-2.

^bFor waste containment purposes, the PVC FML should be of single-ply construction, having polyvinyl chloride as the sole polymer. The resin used should be a medium to medium-high molecular weight PVC homopolymer with a relative viscosity of 2.25 to 2.50. The plasticizer should be a dialkyl phthalate plasticizer made from a minimum average of C₉ molecular weight alcohols. To ensure low volatiles, it is suggested that the minimum average molecular weight of the plasticizer should be 410. The specific gravity (at 20/20°C) of the plasticizer should be 0.964 to 0.972, and the refractive index (at 20°C) should be 1.482 to 1.484. The PVC should be formulated to resist microbial attack. The PVC FML should be nonblocking in accordance with ASTM Method D1146.

^cPoly(vinyl chloride) - oil resistant.

^dOr film-tearing bond.

TABLE K-4. SUGGESTED STANDARDS FOR UNREINFORCED FMLS
Polyethylene FMLs

Property	Test method ^a	Polyethylene base compound	FMLs of different nominal thickness				
			30	40	60	80	100
Nominal thickness, mil		30-120	30	40	60	80	100
<u>Analytical properties</u>							
Density of base resin	D792/D1505	0.930-0.940	----->				
Carbon black content, %	D1603/TGA	2.0-2.5	----->				
Volatile loss, % (maximum)	D1203-A	0.1	----->				
<u>Mechanical properties</u>							
Thickness ^b , mil (minimum)	D1593, Section 9.1.3	...	27	36	52	72	90
Tensile properties, in each direction (minimum):	D638						
Tensile at yield		2500 psi	75	90	150	200	250
Elongation at yield, %		15	----->				
Tensile strength		4000 psi	120	160	240	320	400
Elongation at break, %		750	----->				
Modulus of elasticity, psi (minimum)	D638	100,000	----->				
Tear strength, lb (minimum)	D1004, Die C	750	22	30	45	60	75
Hydrostatic resistance	D751, Method A	8000	240	315	490	650	800
Puncture resistance	FTMS 101C, Method 2065	...	50	60	85	110	135
Hardness, Durometer points (Shore D)	D2240	55	----->				
Bonded seam strength and field seams:	D4545						
In shear		...	FTBC	FTBC	FTBC	FTBC	FTBC
In peel		...	FTBC	FTBC	FTBC	FTBC	FTBC
<u>Environmental and aging effects on properties</u>							
Dimensional stability ^d , % change (maximum)	D1204	3	3	3	3	3	3
Low temperature (brittleness temperature), °F (maximum)	D746	-40	----->				
Resistance to soil-burial for 120 days (maximum % change from original value):	D3083						
Tensile at yield		10	----->				
Elongation at yield		10	----->				
Tensile at break		10	----->				
Elongation at break		10	----->				
Modulus of elasticity		10	----->				
Ozone resistance at 40°C	D1149/D518 ^e	no cracks ^e	----->				
Environmental stress-cracking, hours, (minimum)	D1693, Condition C	>1500	----->				
Water absorption, % weight change (maximum)	D471	0.1	----->				

^aASTM unless otherwise noted. ASTM = American Society for Testing Materials; FTMS = Federal Test Method Standard. For more details regarding conditions and titles of test methods, see Tables K-1 and K-2.

^bTo ensure that the minimum thickness requirements are met, it is suggested that the thickness be measured at each foot across the FML sheet at the beginning and end of each roll.

^cSee Appendix N for location of break codes for the testing of seam strength; FTB = film tearing bond.

^dMaximum percent change in each direction in 15 min at 100°C.

^eNo cracks were visible at 7X magnification on bent loops exposed for 7 days in 100 ppm O₃.

TABLE K-5. SUGGESTED STANDARDS FOR FABRIC-REINFORCED FMLS
 FMLs with Thermoplastic Coatings of Chlorinated Polyethylene (CPE),
 Chlorinated Polyethylene-Alloy, (CPE-A) and Ethylene Interpolymer Alloy (EIA)

Property	ASTM test method ^a	CPE			CPE-A		EIA
Nominal thickness, mil		36 ^b	36 ^b	45	36	45	30
<u>Analytical properties</u>							
Volatile loss, % (maximum)	D1203, Method A	0.5	0.5	0.5	0.7	0.7	1.0
<u>Mechanical properties</u>							
Thickness:							
Overall ^c , mil (minimum)	D751	32	34	41	34	41	27
Coating over fabric, mils (minimum)	Optically	11	11	11	11	11	7
Minimum tensile properties (each direction):							
Breaking strength, lb	D751-A (grab)	120	200	200	200	250	400
Tear resistance, lb (minimum)	D751-B	25	35	75	60	70	125
Hydrostatic resistance, psi (minimum)	D751-A, Procedure 1	160	250	300	250	250	500
Ply adhesion (each direction), lb/in width (minimum)	D413-A	10 ^d	8 ^d	8 ^d	7 ^d	7 ^d	10 ^d
Factory seam strength (minimum):							
In shear (lb)	D751, Modified ^e	96	160	160	160	176	320
In peel (ppi)	D413	10 ^f	10^{f}	10^{f}	10^{f}	10^{f}	...
<u>Environmental and aging effects on properties</u>							
Dimensional stability (each direction), % change (maximum)	D1204	2	2	2	2	2	2
Low temperature (brittleness temperature), °F (maximum)	D21369	-40	-40	-40	-40	-40	-30
Tear resistance after air-oven aging for 30 days at 100°C lb (minimum)	D753/D751-B	20	25	25	25	25	90
Resistance to soil-burial for 120 days (maximum % change from original value):							
Breaking strength of fabric alone ^e	D3083	-25	-25	-25	-25	-25	-25
Breaking factor of unreinforced FML		-5	-5	-5	-5	-5	-10
Elongation at break of unreinforced FML		-20	-20	-20	-20	-20	-20
Stress at 100% elongation of unreinforced FML		+10	+10	+25	+25	+25	+15
Ozone resistance at 40°C (Bent loop at 100 ppm O ₃ for 7 days)	D1149/D518	...	...	...	...	...	no cracks ^h
Water extraction, % (maximum)	D3083	...	...	...	-0.35	-0.35	-0.35
Water absorption, % gain (maximum):							
14 days at 23°C	D471	...	...	...	...	...	1
14 days at 70°C		...	...	...	...	...	2

^aFor more details regarding conditions and titles of test methods, see Tables K-1 and K-2.

^bThese FMLs differ in their fabric reinforcement.

^cTo better ensure that the required thickness of the FML is achieved, it is recommended that thickness measurements of the FML be made very 6-in. across the width of the manufactured sheeting at the beginning and end of each roll.

^dOr film-tearing bond.

^eMeasured at 12 inches-per-minute, specimen 4-in. wide and with 4 1/2-in. on either side of seam.

^fOr ply separation in plane of the fabric.

91/8-in. Mandrel after 4 hours exposure at -40°C.

^hNo cracks were visible at 7X magnification.

TABLE K-6. SUGGESTED STANDARDS FOR FABRIC-REINFORCED FMLS
Thermoplastic Chlorosulfonated Polyethylene (CSPE) FMLs
Potable and Industrial Grades^a

Property	ASTM test method ^b	CSPE FML-type				
		A	B	C	B	C
Nominal thickness, mil		30	36	36	45	45
Analytical properties						
Volatile loss, % (maximum)	D1203	0.5	0.5	0.5	0.5	0.5
Mechanical properties						
Thickness:						
Actual, mil (minimum)	D751	27	27	34	41	41
Actual coating over scrim, mil (minimum)	Optically	11	11	11	11	11
Minimum tensile properties (each direction):						
Breaking strength of fabric, lbf	D751-A (Grab)	60 ^c	120	200	125	200 250 ^d
Tensile strength of unreinforced FML, lbf	D412	1200 1500 ^d	1200 1500^{d}	1200 1500^{d}	1200 1500^{d}	1200 1500^{d}
Elongation at break of unreinforced FML, %	D412	300	300	300	300	300
Tear resistance, lbf (minimum)	D751-B	10	25	60	30	70
Hydrostatic resistance, psi (minimum)	D751-A, Procedure 1	80	160	250	180	250
Ply adhesion (each direction), ppi (minimum)	D413-A	10	10	7	10	7
Factory seam strength (minimum):						
In shear, lbf	D751, Modified ^e	80	96	160 200 ^d	96 100 ^d	180 250 ^d
In peel, ppi	D413	10 ^f	10^{f}	10^{f}	10^{f}	10^{f}
Environmental and aging effects on properties						
Dimensional stability (each direction), % change (maximum)	D1204	7.5	2	2	3	2
Low temperature (brittleness temperature), °F (maximum)	D2136	-40	-40	-45	-40	-45
Tear resistance after air-oven aging for 30 days at 100°C, lbf (minimum)	D573/D571-B	5	20	25	25	25
Resistance to soil-burial for 120 days (maximum % change from original value):						
Breaking strength of fabric	D3083/D412	-25	-25	-25	-25	-25
Tensile strength of unreinforced FML		-5	-5	-5	-5	-5
Elongation at break of unreinforced FML		-20	-20	-20	-20	-20
Stress at 100% elongation of unreinforced FML		+20	+20	+30	+20	+30
Water absorption, % gain (maximum):						
14 days at 23°C	D471	1.5 ^d				
14 days at 70°C		30 ^d				

^aValues apply to both grades, except for those specifically noted for industrial grades only. The different types of FMLs are classified by the type of fabric that is used to reinforce the FML. A Type-A FML is typically reinforced with a 6 x 6 ends per inch (epi) fabric; a Type-B FML is typically reinforced with an 8 x 8 epi; and a Type-C FML is typically reinforced with a 10 x 10 epi fabric. Polyester fabric is used for reinforcement.

^bFor more details regarding conditions and titles of test method, see Tables K-1 and K-2.

^cCoating is stronger than the fabric and has a breaking strength of 100 lb for 30 mils and 150% minimum elongation at break.

^dApply to industrial grades of CSPE FMLs only.

^eMeasured at 12 inches per minute, specimen 4-1/2 in. on each side of seam and 4-in. wide.

^fOr film-tearing bond.

effects of environmental and aging conditions on properties. The types of polymeric FMLs are:

- Thermoplastic FMLs without fabric reinforcement.
- Semicrystalline FMLs without fabric reinforcement.
- Fabric-reinforced FMLs which include both FMLs with crosslinked coatings and those with thermoplastic coatings.

Note 1. No fabric-reinforced FMLs with crystalline coatings are currently available in thicknesses of 20 mils or greater.

Note 2. Inasmuch as crosslinked FMLs are not being produced or used for the lining of waste containment facilities suggested standards for these materials are not included.

Table K-2 lists the ASTM standards that are suggested for testing and evaluation of the FMLs. These methods are listed by number, giving their titles. Those that are practices or specifications are indicated; the rest are test methods.

Table K-3 presents the suggested standards for unreinforced FMLs based on thermoplastic polymer compositions, exclusive of polyethylene. The thermoplastic FMLs that are included in the table are based on CPE, PVC, and PVC-OR.

Table K-4 covers the suggested standards for polyethylene FMLs, which are available in thicknesses from 20 to 120 mils. For FMLs of polyethylene suggested values for properties, such as tensile at yield, tensile strength, tear resistance, and seam strength, vary proportionately with the thickness. Other properties such as specific gravity, volatile loss, elongation at yield, elongation at break, modulus of elasticity, dimensional stability, low temperature brittleness, resistance to soil-burial, ozone resistance, resistance to environmental stress-cracking, and water extraction are compound properties and are considered for these standards to be independent of the thickness of the FML.

Note: Inasmuch as the polyethylene used in the manufacture of FMLs is not high density by standard practice in the plastics industry, the term "high density" is not used. "High-density" polyethylene has a density of 0.941 and higher (see Chapter 4, Section 4.2.2.1.4).

Tables K-5 and K-6 present the suggested standards for representative fabric-reinforced flexible polymeric FMLs. Strength values for these FMLs depend upon the fabric reinforcement used. Fabric reinforcement increases

tensile strength, puncture resistance and tear resistance, and reduces shrinkage and elongation at break. Table K-5 covers those FMLs coated with thermoplastic chlorinated polyethylene and with ethylene interpolymer alloy. Table K-6 covers fabric-reinforced chlorosulfonated polyethylene lining materials. It covers both standard (potable grade) CSPE coated FMLs and the industrial grade of CSPE coating which has a lower water absorption than the standard grade. Minimum required values for potable and industrial-grade CSPE FMLs are equal except for breaking strength, strength of factory seams, and water absorption. Of particular importance in the assessing of fabric-reinforced FMLs is the adhesion between the top and bottom plies and the thickness of the coating above the fabric.

No required values are suggested for seam strength by dead weight test because of the lack of data. Dead weight tests are considered to be important for assessing adhesion in seams made both in the factory and in the field. These tests are particularly useful in assessing the durability of seams, as they keep the seam in the test specimen under constant load. ASTM Test Methods D413, "Adhesion to Flexible Substrate (Machine Method)" and D1876, "Peel Resistance of Adhesives (T-Peel Test)" appear to be the appropriate test methods for assessing peel strength of liner seams.

APPENDIX L

METHOD 9090 COMPATIBILITY TEST
FOR WASTES AND MEMBRANE LINERS

METHOD 9090

COMPATIBILITY TEST FOR WASTES AND MEMBRANE LINERS

1.0 SCOPE AND APPLICATION

1.1 Method 9090 is intended for use in determining the effects of chemicals in a surface impoundment, waste pile, or landfill on the physical properties of flexible membrane liner (FML) materials intended to contain them. Data from these tests will assist in deciding whether a given liner material is acceptable for the intended application.

2.0 SUMMARY OF METHOD

2.1 In order to estimate waste/liner compatibility, the liner material is immersed in the chemical environment for minimum periods of 120 days at room temperature ($23 \pm 2^\circ\text{C}$) and at $50 \pm 2^\circ\text{C}$. In cases where the FML will be used in a chemical environment at elevated temperatures, the immersion testing shall be run at the elevated temperatures if they are expected to be higher than 50°C . Whenever possible, the use of longer exposure times is recommended. Comparison of measurements of the membrane's physical properties, taken periodically before and after contact with the waste fluid, is used to estimate the compatibility of the liner with the waste over time.

3.0 INTERFERENCES (Not Applicable)

4.0 APPARATUS AND MATERIALS

NOTE: In general, the following definitions will be used in this method:

1. Sample -- a representative piece of the liner material proposed for use that is of sufficient size to allow for the removal of all necessary specimens.
2. Specimen -- a piece of material, cut from a sample, appropriately shaped and prepared so that it is ready to use for a test.

4.1 Exposure tank: Of a size sufficient to contain the samples, with provisions for supporting the samples so that they do not touch the bottom or sides of the tank or each other, and for stirring the liquid in the tank. The tank should be compatible with the waste fluid and impermeable to any of the constituents they are intended to contain. The tank shall be equipped with a means for maintaining the solution at room temperature ($23 \pm 2^\circ\text{C}$) and $50 \pm 2^\circ\text{C}$ and for preventing evaporation of the solution (e.g., use a cover equipped with a reflux condenser, or seal the tank with a Teflon gasket and use an airtight cover). Both sides of the liner material shall be exposed to the chemical environment. The pressure inside the tank must be the same as that outside the tank. If the liner has a side that (1) is not exposed to the

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waste in actual use and (2) is not designed to withstand exposure to the chemical environment, then such a liner may be treated with only the barrier surface exposed.

4.2 Stress-strain machine suitable for measuring elongation, tensile strength, tear resistance, puncture resistance, modulus of elasticity, and ply adhesion.

4.3 Jig for testing puncture resistance for use with FTMS 101C, Method 2065.

4.4 Liner sample labels and holders made of materials known to be resistant to the specific wastes.

4.5 Oven at $105 \pm 2^{\circ}\text{C}$.

4.6 Dial micrometer.

4.7 Analytical balance.

4.8 Apparatus for determining extractable content of liner materials.

NOTE: A minimum quantity of representative waste fluid necessary to conduct this test has not been specified in this method because the amount will vary depending upon the waste composition and the type of liner material. For example, certain organic waste constituents, if present in the representative waste fluid, can be absorbed by the liner material, thereby changing the concentration of the chemicals in the waste. This change in waste composition may require the waste fluid to be replaced at least monthly in order to maintain representative conditions in the waste fluid. The amount of waste fluid necessary to maintain representative waste conditions will depend on factors such as the volume of constituents absorbed by the specific liner material and the concentration of the chemical constituents in the waste.

5.0 REAGENTS (Not Applicable)

6.0 SAMPLE COLLECTION, PRESERVATION, AND HANDLING

6.1 For information on what constitutes a representative sample of the waste fluid, refer to the following guidance document:

Permit Applicants' Guidance Manual for Hazardous Waste Land Treatment, Storage, and Disposal Facilities; Final Draft; Chap. 5, pp. 15-17; Chap. 6, pp. 18-21; and Chap. 8, pp. 13-16, May 1984.

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7.0 PROCEDURE

7.1 Obtain a representative sample of the waste fluid. If a waste sample is received in more than one container, blend thoroughly. Note any signs of stratification. If stratification exists, liner samples must be placed in each of the phases. In cases where the waste fluid is expected to stratify and the phases cannot be separated, the number of immersed samples per exposure period can be increased (e.g., if the waste fluid has two phases, then 2 samples per exposure period are needed) so that test samples exposed at each level of the waste can be tested. If the waste to be contained in the land disposal unit is in solid form, generate a synthetic leachate (See Step 7.9.1).

7.2 Perform the following tests on unexposed samples of the polymeric membrane liner material at $23 \pm 2^\circ\text{C}$ and $50 \pm 2^\circ\text{C}$ (see Steps 7.9.2 and 7.9.3 below for additional tests suggested for specific circumstances). Tests for tear resistance and tensile properties are to be performed according to the protocols referenced in Table 1. See Figure 1 for cutting patterns for nonreinforced liners, Figure 2 for cutting patterns for reinforced liners, and Figure 3 for cutting patterns for semicrystalline liners. (Table 2, at the end of this method, gives characteristics of various polymeric liner materials.)

1. Tear resistance, machine and transverse directions, three specimens each direction for nonreinforced liner materials only. See Table 1 for appropriate test method, the recommended test speed, and the values to be reported.
2. Puncture resistance, two specimens, FTMS 101C, Method 2065. See Figure 1, 2, or 3, as applicable, for sample cutting patterns.
3. Tensile properties, machine and transverse directions, three tensile specimens in each direction. See Table 1 for appropriate test method, the recommended test speed, and the values to be reported. See Figure 4 for tensile dumbbell cutting pattern dimensions for nonreinforced liner samples.
4. Hardness, three specimens, Duro A (Duro D if Duro A reading is greater than 80), ASTM D2240. The hardness specimen thickness for Duro A is 1/4 in., and for Duro D it is 1/8 in. The specimen dimensions are 1 in. by 1 in.
5. Elongation at break. This test is to be performed only on membrane materials that do not have a fabric or other nonelastomeric support as part of the liner.
6. Modulus of elasticity, machine and transverse directions, two specimens each direction for semicrystalline liner materials only, ASTM D882 modified Method A (see Table 1).
7. Volatiles content, SW 870, Appendix III-D.
8. Extractables content, SW 870, Appendix III-E.

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TABLE 1. PHYSICAL TESTING OF EXPOSED MEMBRANES IN LINER-WASTE LIQUID COMPATIBILITY TEST

Type of compound and construction	Crosslinked or vulcanized	Thermoplastic	Semi-crystalline	Fabric-reinforced ^a
Tensile properties				
Method	ASTM D412	ASTM D638	ASTM D638	ASTM D751, Mtd B
Type of specimen	Dumbbell ^b	Dumbbell ^b	Dumbbell ^b	1-in. wide strip and 2- in. jaw separation
Number of specimens	3 in each direction	3 in each direction	3 in each direction	3 in each direction
Speed of test	20 ipm	20 ipm	2 ipm	12 ipm
Values to be reported	Tensile strength, psi Elongation at break, % Tensile set after break, % Stress at 100 and 200% elongation, psi	Tensile strength, psi Elongation at break, % Tensile set after break, % Stress at 100 and 200% elongation, psi	Tensile stress at yield, psi Elongation at yield, % Tensile strength at break, psi Elongation at break, % Tensile set after break, % Stress at 100 and 200% elongation, psi	Tensile at fabric break, ppi Elongation at fabric break, % Tensile at ultimate break, ppi Elongation at ultimate break, % Tensile set after break, % Stress at 100 and 200% elongation, ppi
Modulus of elasticity				
Method	c	c	ASTM D882, Mtd A	c
Type of specimen	...	...	Strip: 0.5-in. wide and 6-in. long at a 2-in. jaw separation	...
Number of specimens	...	...	2 in each direction	...
Speed of test	...	...	0.2 ipm	...
Values reported	...	...	Greatest slope of initial stress-strain curve, psi	...
Tear resistance				
Method	ASTM D624	ASTM D1004	ASTM D1004	d
Type of specimen	Die C	e	e	...
Number of specimens	3 in each direction	3 in each direction	2 in each direction	...
Speed of test	20 ipm	20 ipm	2 ipm	...
Values reported	Stress, ppi	Stress, ppi	Maximum stress, ppi	...
Puncture resistance				
Method	FTMS 101C, Method 2065	FTMS 101C, Method 2065	FTMS 101C, Method 2065	FTMS 101C, Method 2065
Type of specimen	2-in. square	2-in. square	2-in. square	2-in. square
Number of specimens	2	2	2	2
Speed of test	20 ipm	20 ipm	20 ipm	20 ipm
Values reported	Gage, mil Stress, lb Elongation, in.	Gage, mil Stress, lb Elongation, in.	Gage, mil Stress, lb Elongation, in.	Gage, mil Stress, lb Elongation, in.

^aCan be thermoplastic, crosslinked or vulcanized membrane.
^bSee Figure 3.
^cNot performed on this material.
^dNo tear resistance test is recommended for fabric-reinforced sheetings in the immersion study.
^eSame as ASTM D624, Die C.

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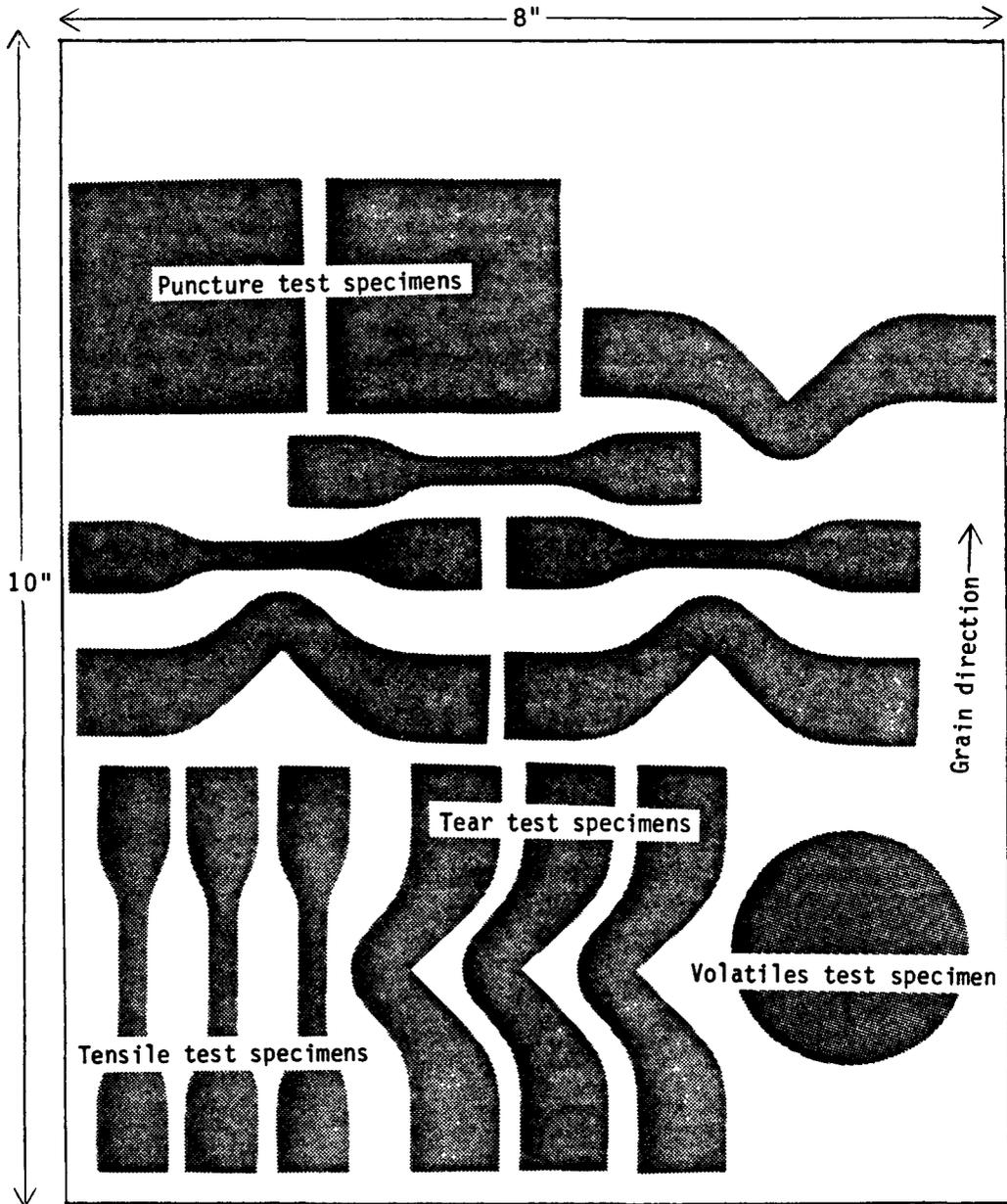


Figure 1. Suggested pattern for cutting test specimens from nonreinforced crosslinked or thermoplastic immersed liner samples.

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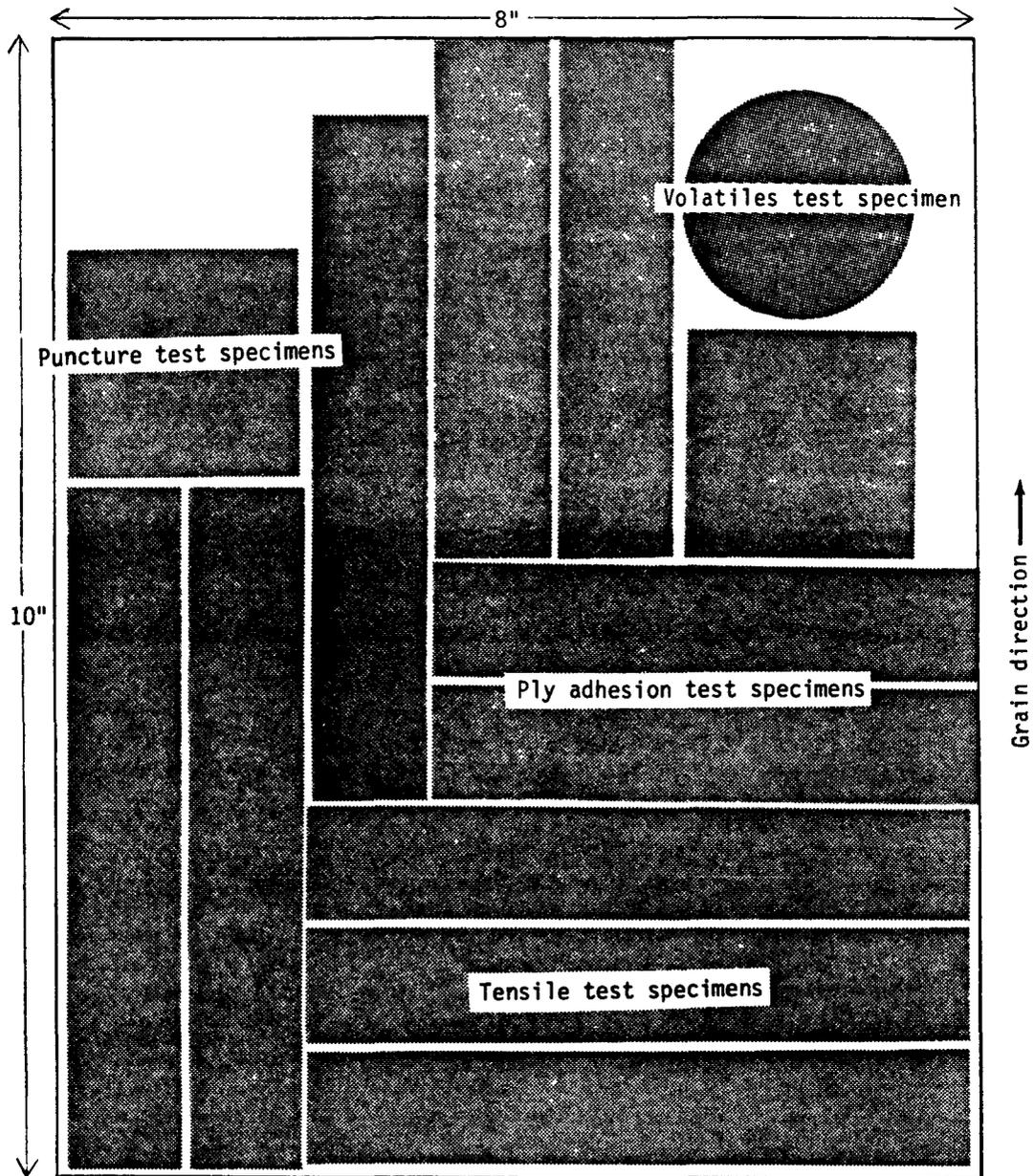


Figure 2. Suggested pattern for cutting test specimens from fabric reinforced immersed liner samples. Note: To avoid edge effects, cut specimens 1/8 - 1/4 inch in from edge of immersed sample.

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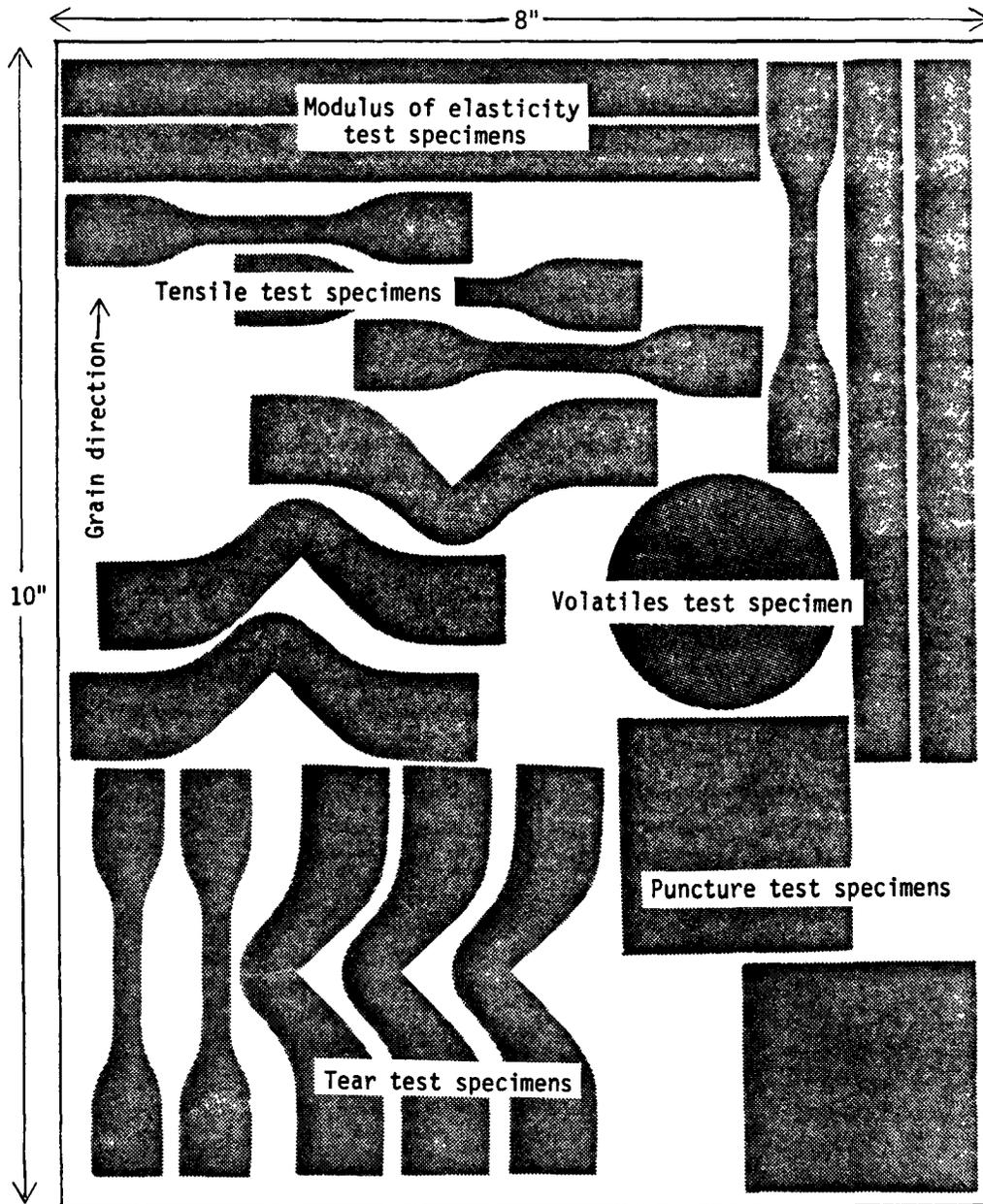
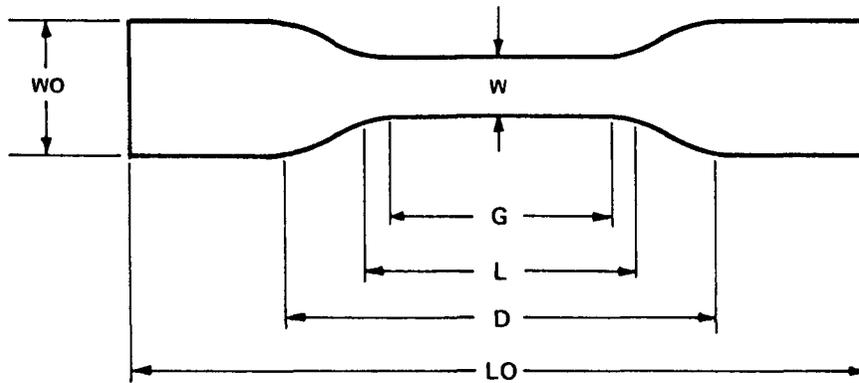


Figure 3. Suggested pattern for cutting test specimens from semicrystalline immersed liner samples. Note: To avoid edge effects, cut specimens 1/8 - 1/4 inch in from edge of immersed sample.

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W - Width of narrow section	0.25 inches
L - Length of narrow section	1.25 inches
WO - Width overall	0.625 inches
LO - Length overall	3.50 inches
G - Gage length	1.00 inches
D - Distance between grips	2.00 inches

Figure 4. Die for tensile dumbbell (nonreinforced liners) having the following dimensions.

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9. Specific gravity, three specimens, ASTM D792 Method A.
10. Ply adhesion, machine and transverse directions, two specimens each direction for fabric reinforced liner materials only, ASTM D413 Machine Method, Type A -- 180 degree peel.
11. Hydrostatic resistance test, ASTM D751 Method A, Procedure 1.

7.3 For each test condition, cut five pieces of the lining material of a size to fit the sample holder, or at least 8 in. by 10 in. The fifth sample is an extra sample. Inspect all samples for flaws and discard unsatisfactory ones. Liner materials with fabric reinforcement require close inspection to ensure that threads of the samples are evenly spaced and straight at 90°. Samples containing a fiber scrim support may be flood-coated along the exposed edges with a solution recommended by the liner manufacturer, or another procedure should be used to prevent the scrim from being directly exposed. The flood-coating solution will typically contain 5-15% solids dissolved in a solvent. The solids content can be the liner formula or the base polymer.

Measure the following:

1. Gauge thickness, in. -- average of the four corners.
2. Mass, lb. -- to one-hundredth of a lb.
3. Length, in. -- average of the lengths of the two sides plus the length measured through the liner center.
4. Width, in. -- average of the widths of the two ends plus the width measured through the liner center.

NOTE: Do not cut these liner samples into the test specimen shapes shown in Figure 1, 2, or 3 at this time. Test specimens will be cut as specified in 7.7, after exposure to the waste fluid.

7.4 Label the liner samples (e.g., notch or use metal staples to identify the sample) and hang in the waste fluid by a wire hanger or a weight. Different liner materials should be immersed in separate tanks to avoid exchange of plasticizers and soluble constituents when plasticized membranes are being tested. Expose the liner samples to the stirred waste fluid held at room temperature and at $50 \pm 2^\circ\text{C}$.

7.5 At the end of 30, 60, 90, and 120 days of exposure, remove one liner sample from each test condition to determine the membrane's physical properties (see Steps 7.6 and 7.7). Allow the liner sample to cool in the waste fluid until the waste fluid has a stable room temperature. Wipe off as much waste as possible and rinse briefly with water. Place wet sample in a labeled polyethylene bag or aluminum foil to prevent the sample from drying out. The liner sample should be tested as soon as possible after removal from the waste fluid at room temperature, but in no case later than 24 hr after removal.

7.6 To test the immersed sample, wipe off any remaining waste and rinse with deionized water. Blot sample dry and measure the following as in Step 7.3:

1. Gauge thickness, in.
2. Mass, lb.
3. Length, in.
4. Width, in.

7.7 Perform the following tests on the exposed samples (see Steps 7.9.2 and 7.9.3 below for additional tests suggested for specific circumstances). Tests for tear resistance and tensile properties are to be performed according to the protocols referenced in Table 1. Die-cut test specimens following suggested cutting patterns. See Figure 1 for cutting patterns for nonreinforced liners, Figure 2 for cutting patterns for reinforced liners, and Figure 3 for semicrystalline liners.

1. Tear resistance, machine and transverse directions, three specimens each direction for materials without fabric reinforcement. See Table 1 for appropriate test method, the recommended test specimen and speed of test, and the values to be reported.

2. Puncture resistance, two specimens, FTMS 101C, Method 2065. See Figure 1, 2, or 3, as applicable, for sample cutting patterns.

3. Tensile properties, machine and transverse directions, three specimens each direction. See Table 1 for appropriate test method, the recommended test specimen and speed of test, and the values to be reported. See Figure 4 for tensile dumbbell cutting pattern dimensions for nonreinforced liner samples.

4. Hardness, three specimens, Duro A (Duro D if Duro A reading is greater than 80), ASTM 2240. The hardness specimen thickness for Duro A is 1/4 in., and for Duro D is 1/8 in. The specimen dimensions are 1 in. by 1 in.

5. Elongation at break. This test is to be performed only on membrane materials that do not have a fabric or other nonelastomeric support as part of the liner.

6. Modulus of elasticity, machine and transverse directions, two specimens each direction for semicrystalline liner materials only, ASTM D882 modified Method A (see Table 1).

7. Volatiles content, SW 870, Appendix III-D.

8. Extractables content, SW 870, Appendix III-E.

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9. Ply adhesion, machine and transverse directions, two specimens each direction for fabric reinforced liner materials only, ASTM D413 Machine Method, Type A -- 180 degree peel.

10. Hydrostatic resistance test, ASTM D751 Method A, Procedure 1.

7.8 Results and reporting:

7.8.1 Plot the curve for each property over the time period 0 to 120 days and display the spread in data points.

7.8.2 Report all raw, tabulated, and plotted data. Recommended methods for collecting and presenting information are described in the documents listed under Step 6.1 and in related agency guidance manuals.

7.8.3 Summarize the raw test results as follows:

1. Percent change in thickness.
2. Percent change in mass.
3. Percent change in area (provide length and width dimensions).
4. Percent retention of physical properties.
5. Change, in points, of hardness reading.
6. The modulus of elasticity calculated in pounds-force per square inch.
7. Percent volatiles of unexposed and exposed liner material.
8. Percent extractables of unexposed and exposed liner material.
9. The adhesion value, determined in accordance with ASTM D413, Section 12.2.
10. The pressure and time elapsed at the first appearance of water through the flexible membrane liner for the hydrostatic resistance test.

7.9 The following additional procedures are suggested in specific situations:

7.9.1 For the generation of a synthetic leachate, the Agency suggests the use of the Toxicity Characteristic Leaching Procedure (TCLP) that was proposed in the Federal Register on June 13, 1986, Vol. 51, No. 114, p. 21685.

7.9.2 For semicrystalline membrane liners, the Agency suggests the determination of the potential for environmental stress cracking. The

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test that can be used to make this determination is either ASTM D1693 or the National Bureau of Standards Constant Tensile Load. The evaluation of the results should be provided by an expert in this field.

7.9.3 For field seams, the Agency suggests the determination of seam strength in shear and peel modes. To determine seam strength in peel mode, the test ASTM D413 can be used. To determine seam strength in shear mode for nonreinforced FMLs, the test ASTM D3083 can be used, and for reinforced FMLs, the test ASTM D751, Grab Method, can be used at a speed of 12 in. per min. The evaluation of the results should be provided by an expert in this field.

8.0 QUALITY CONTROL

8.1 Determine the mechanical properties of identical nonimmersed and immersed liner samples in accordance with the standard methods for the specific physical property test. Conduct mechanical property tests on nonimmersed and immersed liner samples prepared from the same sample or lot of material in the same manner and run under identical conditions. Test liner samples immediately after they are removed from the room temperature test solution.

9.0 METHOD PERFORMANCE

9.1 No data provided.

10.0 REFERENCES

10.1 None required.

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TABLE 2. POLYMERS USED IN FLEXIBLE MEMBRANE LINERS

Thermoplastic Materials (TP)

CPE (Chlorinated polyethylene)^a

A family of polymers produced by a chemical reaction of chlorine on polyethylene. The resulting thermoplastic elastomers contain 25 to 45% chlorine by weight and 0 to 25% crystallinity.

CSPE (Chlorosulfonated polyethylene)^a

A family of polymers that are produced by the reaction of polyethylene with chlorine and sulfur dioxide, usually containing 25 to 43% chlorine and 1.0 to 1.4% sulfur. Chlorosulfonated polyethylene is also known as hypalon.

EIA (Ethylene interpolymer alloy)^a

A blend of EVA and polyvinyl chloride resulting in a thermoplastic elastomer.

PVC (Polyvinyl chloride)^a

A synthetic thermoplastic polymer made by polymerizing vinyl chloride monomer or vinyl chloride/vinyl acetate monomers. Normally rigid and containing 50% of plasticizers.

PVC-CPE (Polyvinyl chloride - chlorinated polyethylene alloy)^a

A blend of polyvinyl chloride and chlorinated polyethylene.

TN-PVC (Thermoplastic nitrile-polyvinyl chloride)^a

An alloy of thermoplastic unvulcanized nitrile rubber and polyvinyl chloride.

Vulcanized Materials (XL)

Butyl rubber^a

A synthetic rubber based on isobutylene and a small amount of isoprene to provide sites for vulcanization.

^aAlso supplied reinforced with fabric.

TABLE 2. (Continued)

EPDM (Ethylene propylene diene monomer)^{a,b}

A synthetic elastomer based on ethylene, propylene, and a small amount of nonconjugated diene to provide sites for vulcanization.

CM (Cross-linked chlorinated polyethylene)

No definition available by EPA.

CO, ECO (Epichlorohydrin polymers)^a

Synthetic rubber, including two epichlorohydrin-based elastomers that are saturated, high-molecular-weight aliphatic polyethers with chloromethyl side chains. The two types include homopolymer (CO) and a copolymer of epichlorohydrin and ethylene oxide (ECO).

CR (Polychloroprene)^a

Generic name for a synthetic rubber based primarily on chlorobutadiene. Polychloroprene is also known as neoprene.

Semicrystalline Materials (CX)

HDPE - (High-density polyethylene)

A polymer prepared by the low-pressure polymerization of ethylene as the principal monomer.

HDPE - A (High-density polyethylene/rubber alloy)

A blend of high-density polyethylene and rubber.

LLDPE (Liner low-density polyethylene)

A low-density polyethylene produced by the copolymerization of ethylene with various alpha olefins in the presence of suitable catalysts.

PEL (Polyester elastomer)

A segmented thermoplastic copolyester elastomer containing recurring long-chain ester units derived from dicarboxylic acids and long-chain glycols and short-chain ester units derived from dicarboxylic acids and low-molecular-weight diols.

^aAlso supplied reinforced with fabric.

^bAlso supplied as a thermoplastic.

TABLE 2. (Continued)

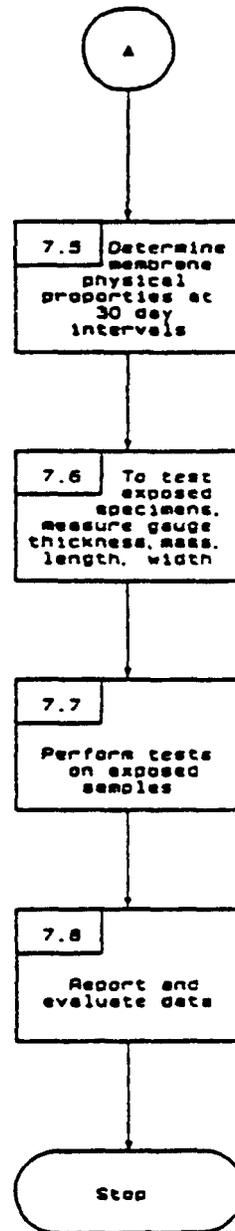
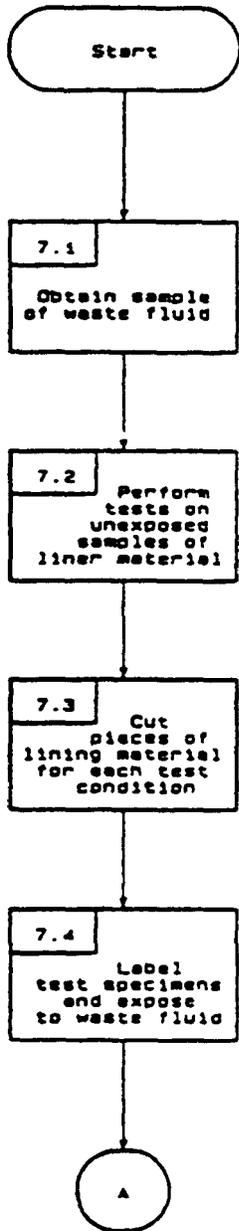
PE-EP-A (Polyethylene ethylene/propylene alloy)

A blend of polyethylene and ethylene and propylene polymer resulting in a thermoplastic elastomer.

T-EPDM (Thermoplastic EPDM)

An ethylene-propylene diene monomer blend resulting in a thermoplastic elastomer.

METHOD 9090
COMPATIBILITY TEST FOR WASTES AND MEMBRANE LINERS



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APPENDIX M

OBSERVATIONS AND TESTS FOR THE CONSTRUCTION QUALITY ASSURANCE AND QUALITY CONTROL OF HAZARDOUS WASTE DISPOSAL FACILITIES

This appendix lists observations that should be made and tests that should be performed for the construction quality assurance of the following components of hazardous waste disposal facilities:

- Foundations.
- Embankments.
- Low-permeability soil liner.
- Leachate collection system.

Methods for testing FMLs are presented and discussed in Chapter 4. This appendix is based on Appendix A of the EPA Technical Guidance Document, "Construction Quality Assurance for Hazardous Waste Land Disposal Facilities" (Northeim and Truesdale, 1986). Table M-1 lists the observations and tests by component.

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- D1556-82. "Test Method for Density of Soil in Place by the Sand-Cone Method," Section 04.08.
- D1557-78. "Test Methods for Moisture-Density Relations of Soils and Soil-Aggregate Mixtures Using 10-lb (4.54-kg) Rammer and 18-in. (457-mm) Drop," Section 04.08.
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- D2165-78(1983). "Test Method for pH of Aqueous Extracts of Wool and Similar Animal Fibers," Section 07.02.
- D2166-85. "Test Method for Unconfined Compressive Strength of Cohesive Soil," Section 04.08.
- D2216-80. "Method for Laboratory Determination of Water (Moisture) Content of Soil, Rock, and Soil-Aggregate Mixtures," Section 04.08.
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TABLE M-1. OBSERVATIONS AND TESTS FOR THE CONSTRUCTION QUALITY ASSURANCE
AND QUALITY CONTROL OF HAZARDOUS WASTE DISPOSAL FACILITIES

Facility component	Factors to be inspected	Inspection methods	Test method reference
Foundation	Removal of unsuitable materials	Observation	NA
	Proof rolling of subgrade	Observation	NA
	Filling of fissures or voids	Observation	NA
	Compaction of soil backfill	(See low-permeability soil liner component)	...
	Surface finishing/compaction	Observation	NA
	Sterilization	Supplier's certification and observation	NA
	Slope	Surveying	NA
	Depth of excavation	Surveying	NA
	Seepage	Observation	NA
	Soil type (index properties)	Visual-manual procedure Particle-size analysis Atterberg limits Soil classification	ASTM D2488 ASTM D422 ASTM D4318 ASTM D2487
Cohesive soil consistency (field)		Penetration tests	ASTM D3441
		Field vane shear test	ASTM D2573
		Hand penetrometer	Horslev, 1943
		Handheld torvane	Lanz, 1968
		Field expedient unconfined compression	TM 5-530 (U.S. of Army, 1971)

continued . . .

TABLE M-1 (CONTINUED)

Facility component	Factors to be inspected	Inspection methods	Test method reference
Embankments	Strength (laboratory)	Unconfined compressive strength	ASTM D2166
		Triaxial compression	ASTM D2850
	Dike slopes	Surveying	NA
	Dike dimensions	Surveying; observations	NA
	Compacted soil	(See foundation component)	...
M-6 Low-permeability soil liner	Drainage system	(See leachate collection system component)	...
	Erosion control measures	(See cover system component)	...
	Coverage	Observation	NA
	Thickness	Surveying; measurement	NA
	Clod size	Observation	NA
	Tying together of lifts	Observation	NA
	Slope	Surveying	...
	Installation of protective cover	Observation	NA
	Soil type (index properties)	Visual-manual procedure	ASTM D2488
		Particle-size analysis	ASTM D422
	Atterberg limits	ASTM D4318	
	Soil classification	ASTM D2487	

continued . . .

TABLE M-1 (CONTINUED)

Facility component	Factors to be inspected	Inspection methods	Test method reference
	Moisture content	Oven-dry method Nuclear method Calcium carbide (speedy) Frying pan (alcohol or gas burner)	ASTM D2166 ASTM D3017 AASHTO T217 Spigolon & Kelley, 1984
	In-place density	Nuclear methods Sand cone Rubber balloon Drive cylinder	ASTM D2922 ASTM D1556 ASTM D2167 ASTM D2937
	Moisture-density relations	Standard proctor Modified proctor	ASTM D698 ASTM D1557
	Strength (laboratory)	Unconfined compressive strength Triaxial compression Unconfined compressive strength for soil cement	ASTM D2166 ASTM D2850 ASTM D1633
	Cohesive soil consistency (field)	Penetration tests Field vane shear test Hand penetrometer Handheld torvane Field expedient unconfined compression	ASTM D3441 ASTM D2573 Horslev, 1943 Lanz, 1968 TM 5-530 (U.S. Dept. of Army, 1971)
	Permeability (laboratory)	Flexible wall	Daniel et al, 1984 Daniel et al, 1985 SW-846, Method 9100 (EPA, 1986)

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Continued . . .

TABLE M-1 (CONTINUED)

Facility component	Factors to be inspected	Inspection methods	Test method reference
	Permeability (field)	Large diameter single-ring infiltrometer Sai-Anderson infiltrometer	Day and Daniel, 1985 Anderson et al, 1984
	Susceptibility to frost damage	Susceptibility classification Soil-cement freeze-thaw test	Chamberlin, 1981 ASTM D560
	Volume change	Consolidometer (undisturbed or remolded sample) Soil-cement wet-dry test Soil-cement freeze-thaw test	Holtz, 1965 ASTM D559 ASTM D560
8-W	Leachate collection system:		
	- Granular drainage and filter layers	Thickness	NA
		Coverage	NA
		Soil type	Visual-manual procedure ASTM D2488 Particle-size analysis ASTM D422 Soil classification ASTM D2487
		Density	Nuclear methods ASTM D2922 Sand cone ASTM D1556 Rubber balloon ASTM D2167
		Permeability (laboratory)	Constant head ASTM D2434

continued . . .

TABLE M-1 (CONTINUED)

Facility component	Factors to be inspected	Inspection methods	Test method reference	
- Synthetic drainage and filter layers	Material type	Manufacturer's certification	NA	
	Handling and storage	Observation	NA	
	Coverage	Observation	NA	
	Overlap	Observation	NA	
	Temporary anchoring	Observation	NA	
	Folds and wrinkles	Observation	NA	
	Geotextile properties	Tensile strength		Horz, 1984
		Puncture or burst resistance		Horz, 1984
		Tear resistance		Horz, 1984
		Flexibility		Horz, 1984
Outdoor weatherability			Horz, 1984	
- Pipes	Material type	Short-term chemical resistance	Horz, 1984	
		Fabric permeability	Horz, 1984	
		Percent open area	Horz, 1984	
- Pipes	Material type	Manufacturer's certification	NA	
		Handling and storage	Observation	NA

continued . . .

TABLE M-1 (CONTINUED)

Facility component	Factors to be inspected	Inspection methods	Test method reference
	Location	Surveying	NA
	Layout	Surveying	NA
	Orientation of perforations	Observation	NA
Cast-in-place concrete structures	Sampling	Sampling fresh concrete	ASTM C172
	Consistency	Slump of portland cement	ASTM C143
	Compressive strength	Making, curing, and testing concrete specimens	ASTM C31
	Air content	Pressure method	ASTM C231
	Unit weight, yield, and air content	Gravimetric method	ASTM C138
	Form work inspection	Observation	NA
Electrical and mechanical equipment	Equipment type	Manufacturer's certification	NA
	Material type	Manufacturer's certification	NA
	Operation	As per manufacturer's instructions	NA
	Electrical connections	As per manufacturer's instructions	NA
	Insulation	As per manufacturer's instructions	NA
	Grounding	As per manufacturer's instructions	NA

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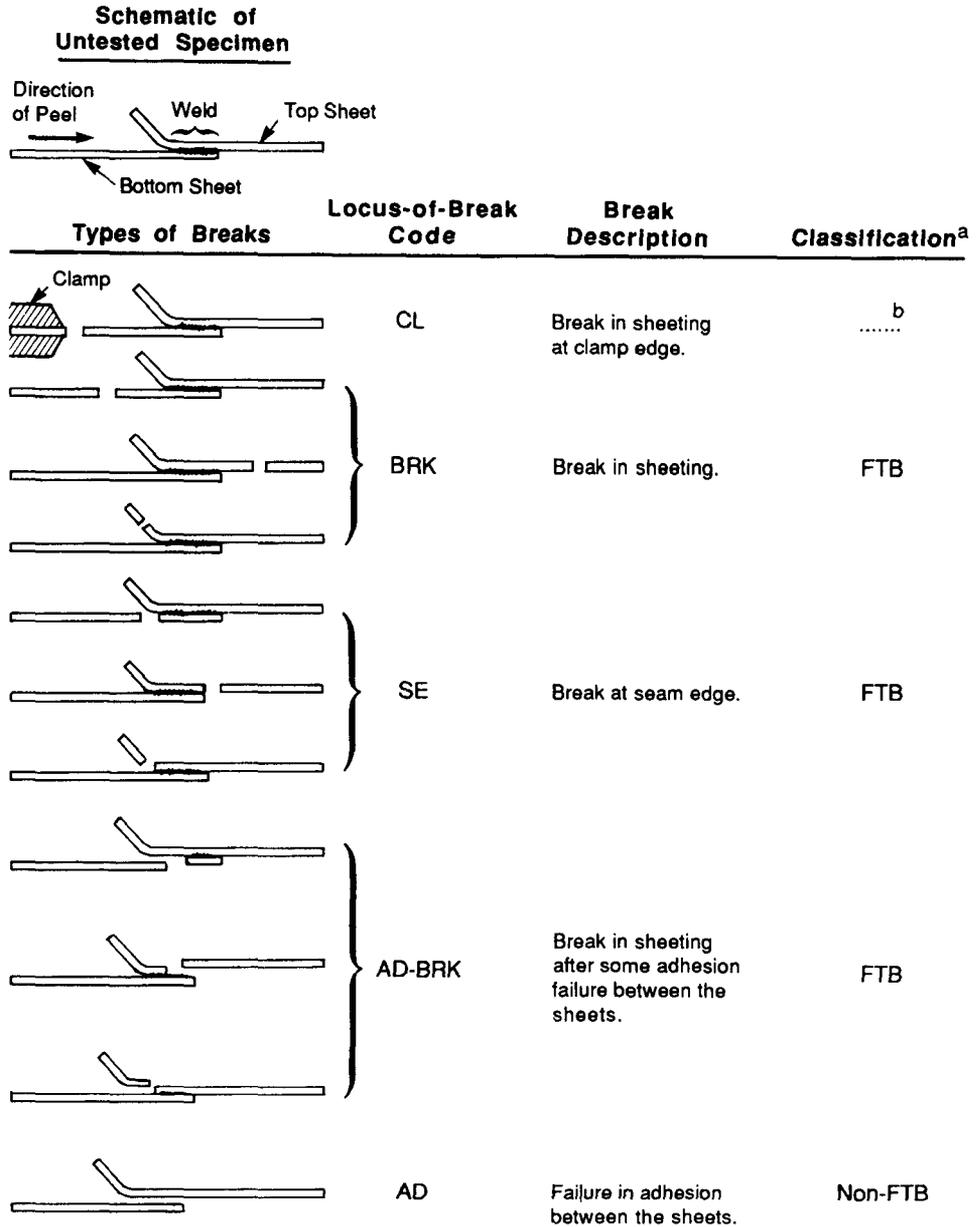
Source: Northeim and Truesdale, 1986, pp 83-88.

APPENDIX N

LOCUS-OF-BREAK CODES FOR VARIOUS TYPES OF FML SEAMS

This appendix presents locus-of-break codes for various types of FML seams. These codes can be used in reporting the results of CQA destructive seam testing. They have been found to be particularly useful in cases where the type of break is important for determining whether or not the tested seam meets specification, e.g. for determining whether or not there was a film-tearing bond when the tested specimens broke. These codes can be included in specifications for defining specific types of breaks that meet specification and for defining types of breaks that are not considered to reflect the quality of the seam, i.e. "no test" situations.

- Dielectric-welded or solvent-welded seams in unreinforced FMLs.
- Seams in three-ply fabric-reinforced FMLs.
- Fillet-extrusion weld seams in semicrystalline FMLs.
- Extrusion weld seams in semicrystalline FMLs.
- Dual-hot-wedge seams in semicrystalline FMLs.

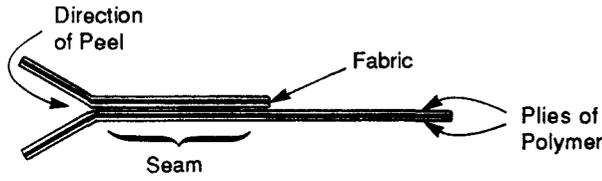


^a FTB = Film - Tear Bond.

^b Acceptance of CL - type breaks may depend on whether test values meet a minimum specification value. In general, though, a CL - type break should be considered a "no test". If specimens for a particular sample break consistently at the clamp edge, changes in the testing procedure should be considered, e.g. changing the clamp face, using a dumbbell - type specimen.

Figure N-1. Locus-of-break codes for dielectric-welded or solvent-welded seams in unreinforced FMLs tested for seam strength in shear and peel modes.

Schematic of a Seam of a 3-Ply Fabric-Reinforced FML

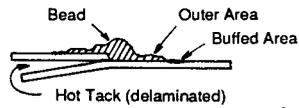


Types of Breaks	Locus-of-Break Code	Break Description	Classification ^a
	AD	Adhesion failure resulting in delamination in the plane of the bond.	Non - FTB
	DEL	Delamination in the plane of the scrim. (Applicable to peel only).	FTB
	AD-DEL	Delamination in the plane of the scrim after some delamination in the plane of the bond. (Applicable to peel only)	FTB
	BRK	Break in the sheet through both the fabric and the plies of polymer. Fabric break may precede break in sheeting.	FTB
	FP	Fabric pullout. Pullout of the threads parallel to the direction of test followed by break in the plies of polymeric sheeting.	No Test

^a FTB = Film - Tear Bond.

Figure N-2. Locus-of-break codes for seams in three-ply fabric-reinforced FMLs tested for seam strength in shear and peel modes.

Schematic of Untested Specimen



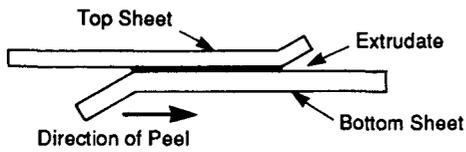
Types of Breaks	Locus-of-Break Code	Break Description	Classification ^a
	AD1	Failure in adhesion. Specimens may also delaminate under the bead and break through the thin extruded material in the outer area.	Non-FTB
	AD2	Failure in adhesion.	Non-FTB
	AD-WLD	Break through the fillet. Breaks through the fillet range from breaks starting at the edge of the top sheet to breaks through the fillet after some adhesion failure between the fillet and the bottom sheet.	Non-FTB ^b
	SE1	Break at seam edge in the bottom sheet. Specimens may break anywhere from the bead/outer area edge to the outer area/buffed area edge. (Applicable to shear only).	FTB
	SE2	Break at seam edge in the top sheet. Specimens may break anywhere from bead/outer area edge to the outer area/buffed area edge.	FTB
	SE3	Break at seam edge in the bottom sheet. (Applicable to peel only)	FTB
	BRK1	Break in the bottom sheeting. A "B" in parentheses following the code means the specimen broke in the buffed area. (Applicable to shear only).	FTB
	BRK2	Break in the top sheeting. A "B" in parentheses following the code means the specimen broke in the buffed area.	FTB
	AD-BRK	Break in the bottom sheeting after some adhesion failure between the fillet and the bottom sheet. (Applicable to peel only)	FTB
	HT	Break at the edge of the hot tack for specimens which could not be delaminated in the hot tack.	No Test

^aFTB = Film - Tear Bond.

^bAcceptance of AD-WLD breaks may depend on whether test values meet a minimum specification value and not on classification as a FTB or non-FTB break

Figure N-3. Locus-of-break codes for fillet-extrusion weld seams in semi-crystalline FMLs tested for seam strength in shear and peel modes.

Schematic of Untested Specimen



Location of Break	Locus-of-Break Code	Break Description	Classification ^a
	BRK	Break in sheeting outside weld area. Break can be in either the top or bottom sheet	FTB
	SE1	Break in top sheet at seam edge.	FTB
	SE2	Break in bottom sheeting at seam edge	FTB
	SE3	Break in bottom sheeting at seam edge. (Applicable to peel only).	FTB
	AD-BRK	Break in sheeting after some adhesion failure between extrudate and surface of the sheeting. Break can be in either the top or bottom sheet.	FTB
	AD	Failure in adhesion between the extrudate and the sheeting surface.	Non-FTB

^a FTB = Film - Tear Bond

Figure N-4. Locus-of-break codes for extrusion weld seams in semicrystalline FMLs tested for seam strength in shear and peel modes.

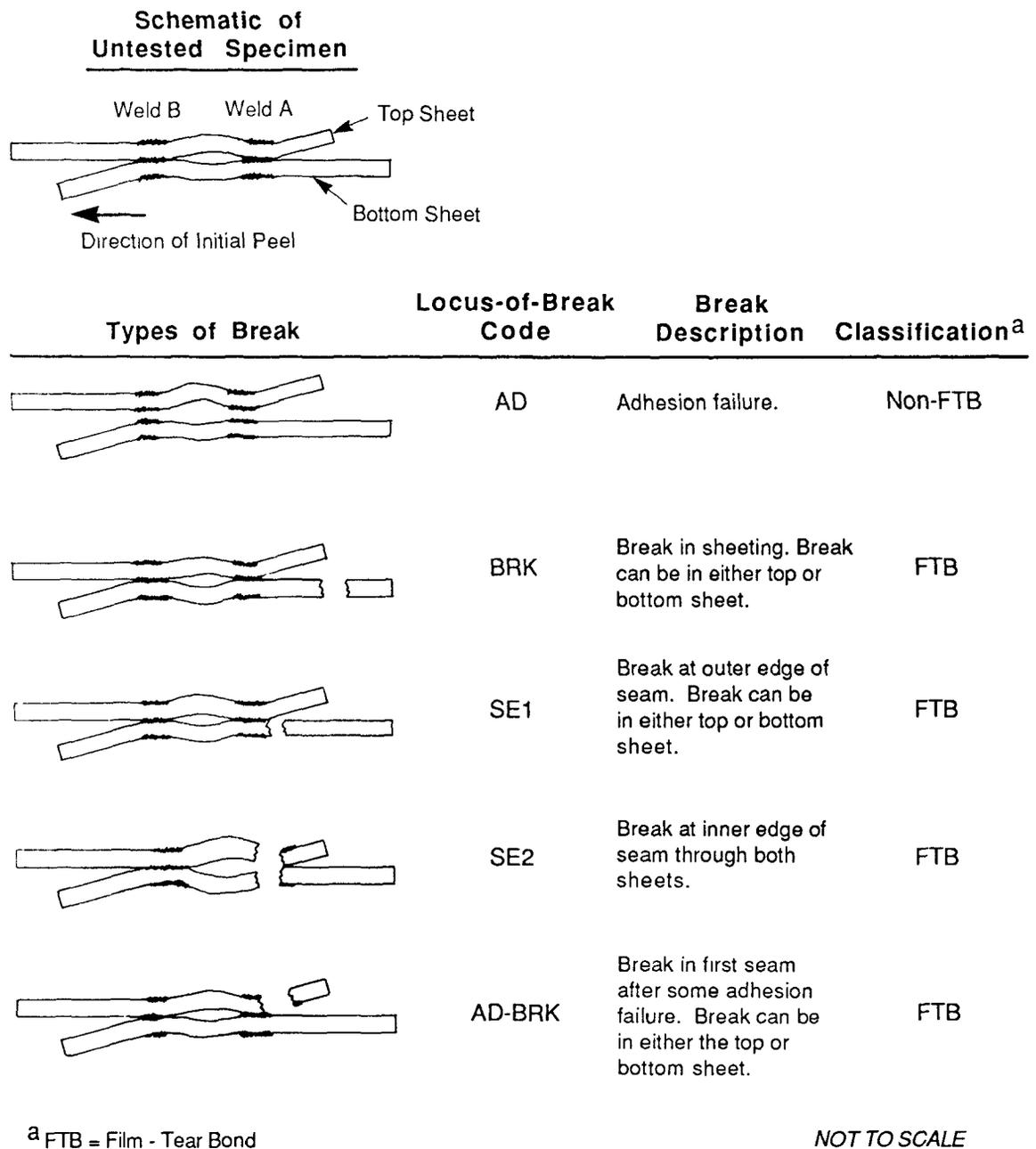


Figure N-5. Locus-of-break codes for dual hot-wedge seams in semicrystalline FMLs tested for seam strength in shear and peel modes. In cases where the Weld A fails in adhesion in a peel test, it is recommended that the test be stopped, that the specimen be replaced in the testing machine, and that Weld B be tested by peeling in the direction opposite to that used to Weld A.