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Field Verification of Liners from Sanitary Landfills

EMCON Associates, San Jose, CA

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16. ABSTRACT

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FIELD VERIFICATION OF LINERS FROM SANITARY LANDFILLS

by

EMCON Associates
San Jose, California 95112

Contract No. 68-03-2824

Project Officer

Robert Landreth
Solid and Hazardous Waste Research Division
Municipal Environmental Research Laboratory
Cincinnati, Ohio 45268

MUNICIPAL ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
CINCINNATI, OHIO 45268

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FOREWORD

The U.S. Environmental Protection Agency was created because of increasing public and government concern about the dangers of pollution to the health and welfare of the American people. Noxious air, foul water, and spoiled land are tragic testimonies to the deterioration of our natural environment. The complexity of that environment and the interplay of its components require a concentrated and integrated attack on the problem.

Research and development is that necessary first step in problem solution, and it involves defining the problem, measuring its impact, and searching for solutions. The Municipal Environmental Research Laboratory develops new and improved technology and systems to prevent, treat, and manage wastewater and hazardous waste pollutant discharges from municipal and community sources, to preserve and treat public drinking water supplies, and to minimize the adverse economic, social, health, and aesthetic effects of pollution. This publication is one of the products of that research and is a most vital communications link between the researcher and the user community.

This report investigates the physical properties and integrity of liners from sanitary landfills that have been in operation for 3 to 9 years. Results will be of special interest and use to regulatory agencies and to owners, operators, and designers of landfill facilities.

Francis T. Mayo
Director
Municipal Environmental Research
Laboratory

ABSTRACT

Liner specimens from three existing landfill sites were collected and examined to determine the changes in their physical properties over time and to validate data being developed through laboratory research. Samples examined included a 15-mil PVC liner from a sludge lagoon in New England, a 30-mil PVC liner from a landfill in New York State, and four liners from a landfill test site in Boone County, Kentucky--chlorosulfonated polyethylene (CSPE), low-density polyethylene (LDPE), clay, and chlorinated polyethylene (CPE).

The 15-mil PVC liner from the New England sludge lagoon lost plasticizers whether it was exposed to sludge only, weather only, or both. But the most severe loss of plasticizer and stiffening was exhibited by samples that had been exposed to weather only.

The 30-mil PVC liner from the New York landfill had stiffened and probably lost plasticizer after exposure to weather for 3 years. But the material was still extensible and had not become brittle as is often the case with exposed PVC liners.

The remaining four liners from Boone County, Kentucky, came from two different test cells. The CSPE, LDPE, and clay liners were all from Test Cell 1. The CSPE liner was swollen and soft and had adsorbed considerable amounts of leachate after 9 years of exposure to attenuated leachate. Nonetheless, its properties were relatively normal for a CSPE material. The LDPE liner appeared to be unaffected by its 9 years of exposure to full-strength leachate. These samples showed little swelling and normal properties for a 6- to 7-mil LDPE liner. The clay liner was shown to have contained the leachate effectively. No cracking, channeling, or unusual changes in texture or consistency were noted. The CPE liner from Test Cell 2 showed significant absorption of the leachate it had contained, however, its properties were relatively good. CPE samples that had been exposed to weather only for 9 years showed significantly higher tensile strength, moduli, and puncture resistance than did the leachate-exposed samples.

This report was submitted in fulfillment of Contract No. 68-03-2824 by EMCON Associates under the sponsorship of the U.S. Environmental Protection Agency. This report covers the period August 1979 to June 1982, and work was completed as of June 1982.

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SECTION 1

INTRODUCTION

When municipal solid waste (MSW) is landfilled, ground and surface waters must be protected from leachates--liquid that has percolated through the waste and has become contaminated with extracted, dissolved, or suspended materials. The use of impervious barriers to intercept and control leachate offers a promising means of reducing or eliminating such pollution, and it is recommended by the U.S. Environmental Protection Agency (EPA) for consideration as a control mechanism.

Containment systems have traditionally been lined to prevent the excessive seepage of liquids into the ground. Clay, wood, concrete, asphalt, and metal linings were used in the past in a wide variety of applications. In the last 30 years, synthetic impervious lining materials have been developed. Among these are polyethylene (PE), polyvinyl chloride (PVC), chlorosulfonated polyethylene (CSPE), butyl rubber, high density polyethylene (HPDE), and various asphalt cement mixtures.

A major concern with liners is the possiblity of their degradation after prolonged exposure to leachate, which might chemically or physically attack liner materials. Unfortunately, no method of laboratory testing presently exists to predict the field service life of various liners. Strong circumstantial evidence indicates that liner life can exceed 20 years: Research to date shows only minimal physical changes in liner materials exposed to landfill leachate. But clearly, more study is needed.

OBJECTIVES

The primary objective of this project was to obtain specimens of liners from existing landfills to determine the changes in their physical properties as a function of age and to validate data being developed through laboratory research. Specifically, the program was to achieve the following goals:

1. Determine the nature, extent, and causes of any changes in the liners after prolonged exposure to the landfill environment.

2. Improve the ability to select liners by developing information on their strengths and weaknesses under a variety of conditions.

3. Assist regulatory agencies by providing information that could be used to develop site location and performance standards for waste disposal permit programs.

The project consisted of the following three tasks:

1. Obtaining liner samples and repairing the liner material after sample removal.

2. Testing and evaluating the samples.

3. Comparing original liner material with the removed samples.

Special regard was given to the problems associated with field research of this type. For example, the ideal test site was one that could provide sufficient information on soils and on hydrogeologic and engineering design. The protocol for obtaining a sample of the landfill liner was selected so as not to interfer with the liner's ability to contain leachate.

SECTION 2

CONCLUSIONS AND RECOMMENDATIONS

CONCLUSIONS

All liners provided effective containment of leachate, even after considerable length of service and exposure. Though the polymeric liners experienced swelling and absorption of leachate, their physical properties remained relatively unaffected. Weathering of polymers caused stiffening and loss of plasticizer, suggesting that a protective soil cover is important for such liners. The clay liner experienced some leakage, but this problem was apparently the result of accidental puncture during test cell construction.

Investigations like this one are vital to determining whether or not liners are preventing damage to the environment. Most liners are installed with the assumption that they will function as protective barriers indefinitely. Such is not always the case, however, and actual sampling of such liners is needed to determine their integrity, especially after the liner has been in contact with the leachate for some time.

Detecting liner failure and its causes is hampered greatly by the lack of records and data on site preparation, liner installation procedures, protection of completed liners, and landfill operations. Availability of such data is critical to predicting the containment capabilities of waste disposal sites.

RECOMMENDATIONS

1. Standards for testing liner materials should be established to determine longevity under various conditions and to guide the selection of liner materials.

2. Regulatory agencies should be encouraged to prepare guidance documents incorporating minimum design and construction standards and specifications for liner installation at various types of disposal facilities.

3. Surveillance, inspection, or certification procedures should be introduced to attest to correct liner selection and installation.

4. A more extensive liner testing and sampling data bank should be developed to ensure that the information is available both to regulatory agencies and to site designers, owners, and operators.

5. Site owners should be provided with assurances of anonymity and protection from certain legal liabilities in return for participation in investigations of this nature. Such assurances might require that financial support be given to site owners to correct problems discovered during sampling. The cost of insurance protection should be incorporated directly as a project cost.

SECTION 3

METHODS AND MATERIALS

SITE SELECTION

Thirty candidate sites were originally identified as possible choices for study. The criterion for the ideal test site was that it should have complete data and records available in the following categories:

1. Liner design and installation techniques

2. Methods of site operation

3. Type, age, and thickness of wastes in the landfill

4. Occurrence, quantity, and character of leachate

5. Soils, geology, and groundwater.

The original scope of work called for samp s of several types of liners (clay, asphalt, and polyvinyl chloride) from at least four landfills. Unfortunately, however, most operators of the 30 selected sites declined to participate in the study because of legal considerations. The final field testing program was therefore restricted to liner materials obtained from three sites:

1. A New England sludge lagoon (15-mil PVC liner),

2. A landfill in New York State (30-mil PVC liner), and

3. An EPA field site in Boone County, Kentucky (BCFS) (a chlorosulfonated polyethylene [CSPE] liner, a low-density polyethylene [LDPE] liner, a clay liner, and a chlorinated polyetheylene [CPE] liner).

SAMPLING METHODS

The sampling program was designed with three objectives: (1) to obtain samples of the various in-place liner materials , (2) to sample indigenous soils beneath the liner, and (3) to repair the liner to preclude escape of leachate as a result of the temporary interruption of liner integrity. Samples of similar soils beyond the influence of the landfill were also to be collected and analyzed for purposes of background comparisons.

Clay Liner

The proposed methods involved the use of a hollow-stem auger (Figure 1), which bore to a point approximately 1.6 m (5 ft) above the anticipated depth of liner. A split-spoon sampler was to be driven beyond the auger in 46 cm (18 in.) increments, with the auger following every advance. The sampler was to be withdrawn after each advance to ascertain the refuse/clay interface. The auger would then be advanced to a depth of approximately 31 cm (1 ft) into the liner. Shelby tubes were to be driven into the clay and removed to obtain soil samples to a depth of 3.2 m (10 ft) below the refuse. After sampling, bentonite was to be placed in the boring as the auger was withdrawn to prevent escape of any leachate above the liner.

PVC Liners

One of the two sites selected with PVC liners (SII) was a relatively shallow fill; sampling was therefore accomplished by excavating through the refuse to the liner with a small backhoe. Shelby tubes were driven into the subsoil to obtain samples at depths below the liner. The other PVC site (SI) was a sludge pond. Excavation at this site was made with a front-end loader. Shelby tubes were also used for the soil samples.

TESTING AND EVALUATION METHODS

The testing and evaluation methods selected were tailored to the two types of liner materials to be sampled--clay and polymeric. Characteristics and properties of clay liners were to be compared with those for background soils to determine the nature of physical and mechanical changes at depth. Testing of polymeric materials included determination of permeability, thickness, tensile strength and elongation at break, hardness, tear strength, creep, water absorption or extraction, puncture resistance, and density.

Chemical tests on soil samples beneath the liners included analyses for pH, Hg, Pb, Zn, Cd, Fe, Cl, COD, Na, NH_4, K and Mg. This testing was designed to develop absorption data. Underlying soils were also subjected to physical tests for permeability, density and voids, water swell, and compressive strength.

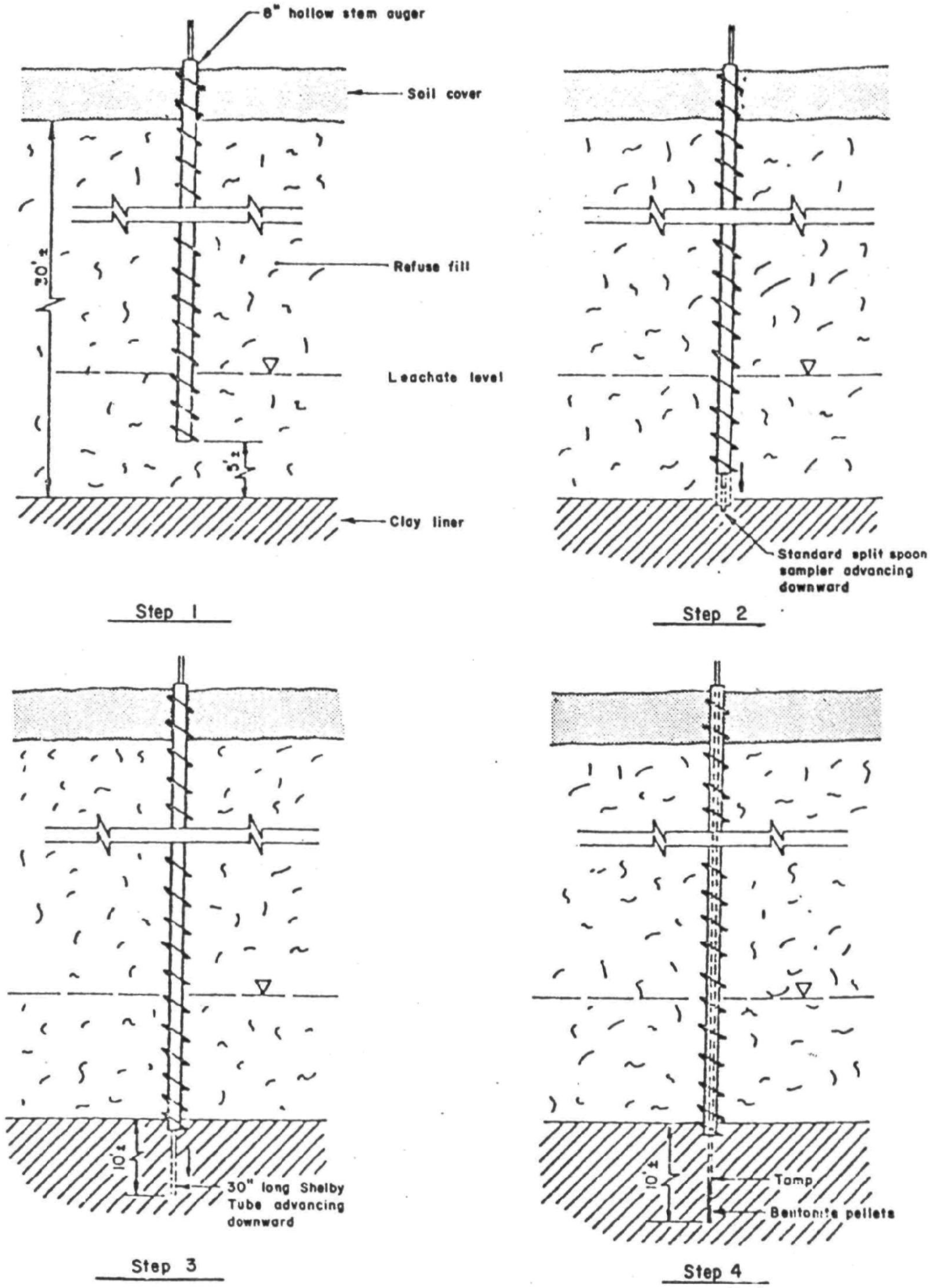

FIGURE 1. Proposed sampling and repair procedure for clay liner

SECTION 4

RESULTS AND PROCEDURES

Exposure conditions of the liners from the three sites varied. Some had been exposed only to the weather, and others had been buried under the waste. The exposure of the chlorinated polyethylene (CPE) liner under municipal solid waste (MSW) in Test Cell 2D at the BCFS most closely conformed with the desired site selection criterion detailed in Section 3 of the report. These requirements also were partially fulfilled by the exposure of the PVC liner at the New England Sludge Lagoon (SI). Quantification of the changes that had taken place in the PCV liner at the New York State Landfill (SII) was limited by the absence of test data on the original liner material.

NEW ENGLAND SLUDGE LAGOON (SI)

Site Conditions

The sludge lagoon at the solid waste disposal facility in New England is approximately 1.25 ha (3.1 acres) in area with a maximum depth of 5 m (16 ft). The lagoon is completely lined with a 15-mil PVC liner. The sludge was added to the lagoon at specific dumping areas along the perimeter levee and spread by gravitational pressure. The maximum distance to the centerline of the lagoon is approximately 55 m (180 ft).

The sewage sludge disposed of at the site consists of approximately 85 percent water and 15 percent suspended solids. A high pH of 10 to 11 is due to a high lime and ferric chloride content, which, along with other toxic chemical conditioning agents, constitutes up to 40 percent of the total filter cake. Chemical analyses of the sludge cake and the supernatant from the lagoon are presented in Tables 1 and 2.

Two major site visits were made--the first on October 18, 1979, and the second on June 9, 1980. The first visit was made to inspect and examine the site and to plan and arrange for the recovery of PVC liner samples of the PVC that had been exposed to the sludge. Some samples of bare, weather-exposed liner were also collected at this time. The second trip was made exclusively to recover liner samples.

TABLE 1. CHEMICAL ANALYSIS OF LAGOON SLUDGE CAKE*

Sample element	Sludge cake (mg/g dry sample)	Ash (ashed at 800°C) (mg/g ash)
Arsenic as As	0.357	<0.001
Cadmium as Cd	0.043	0.0025
Calcium as Ca	303.441	322.0
Chromium as Cr	0.714	0.115
Copper as Cu	1.071	0.38
Fluoride as F	0.011	--
Iron as Fe	82.465	43.1
Lead as Pb	1.071	0.12
Magnesium as Mg	11.781	10.4
Manganese as Mn	7.854	0.97
Mercury as Hg	0.642	0.024
Nickel as Ni	1.071	0.05
Potassium as K	3.57	1.6
Sodium as Na	16.064	4.0
Sulfate as SO_4	142.796	30.0
Tin as Sn	<7.139	<0.20
Zinc as Zn	7.854	1.19
Nitrogen		
Total Kjeldahl as N	249.9	Not Tested
Phosphate as P	22.8	51.37
% Moisture	84.6	
Boron as B (10^{-6} g/g)	<20	< 20
Chloride as Cl	13	7.6
Cobalt as Co (10^{-6} g/g)	70	<200

* Source: Report on Sewage Sludge and Solid Waste Disposal Waste, 1974 by Anderson-Nichols and Co., Inc.

TABLE 2. CHEMICAL ANALYSIS OF LAGOON SUPERNATANT

Parameter*	Concentration
Total solids	8,300 mg/l
Dissolved solids	1,400 mg/l
Suspended solids	6,900 mg/l
Settleable solids	$<$0.1 mg/l
BOD_5	590 mg O_2/l
COD	2,080 mg O_2/l
pH	11.1
Alkalinity as $CACO_3$	190 mg/l
Cl^-	430 mg/l
TKN	480 mg/l
P	3.9 mg/l
Na	72.4 mg/l
Ca	19.2 mg/l
Mg	51.7 mg/l
K	74.3 mg/l

* Qualitative survey of metals present in water other than those above: moderate amount of Al, small amount of Fe and Si, trace amounts of Cu, Ag, Sn, Ba, Ti, Cr, Mn, Ni, and Pb.

Liner Sampling and Evaluation

Samples Taken During the First Site Visit--

During the examination of the site on the first trip, several areas of the liner were bare and completely exposed to the weather; also, the liner had split open in several places along the southwest edge (Figure 2). Round boulders some about 31 cm (1 ft) in diameter, were apparent in several places on the southwest edge of the pond beneath the surface of the liner. In such cases, the liner was stretched tautly over them as a result of the loss of plasticizer and shrinkage that had occurred in the PVC compound. The exposed liner had become brittle; in fact, it fragmented when touched, even though the liner was in the sun and warm. Such brittleness is indicative of considerable degradation of the PVC as well as loss of plasticizer.

Several samples of this weathered sheeting were collected and returned to the laboratory for testing (including the brittle pieces). Some of these materials had been partially under cover and some had been pulled out from under the solid cover.

Test results for these and two small liner samples picked up on the lagoon berm are presented in Table 3. The latter two samples appeared to have been under soil protection until just before they were sampled. Test results show a considerable variation in properties; those portions of the liner that had been exposed to the weather showed a loss of plasticizer and a stiffening. The sample that was taken above the boulders had a very low elongation (extending only 8 percent) and a thickness of only 11.5 mils (compared with the probable 15 mils of the original material). The extractables were still relatively high and might contain low-molecular-weight degradation products of the PVC. These data indicated strongly that a PVC liner should be covered and probably should be thicker than 15 mils if there is a possibility that the cover might be removed.

Samples Taken During The Second Site Visit--

Liner Samples--Removal of the sludge from the lagoon to facilitate collection of liner samples was delayed by heavy rainfall. This delay ultimately restricted the sampling (which took place in June 1980) to the northeast corner of the upper part of the dike (Figure 2). Consequently, the recovered samples were not taken from beneath the maximum depth of the sludge where anaerobic conditions were assured.

Four samples were obtained near an area of the pond where sludge was being removed. Three of these had been covered with soil or with sludge, and the fourth sample was located on the east berm and had been removed recently from the area where the excavation was taking place.

These samples were returned to the laboratory and tested; the results are presented in Table 3. All of the samples were flexible, but to various degrees. Test results show that the only material that had lost considerable elongation was the sample that had been exposed to the weather

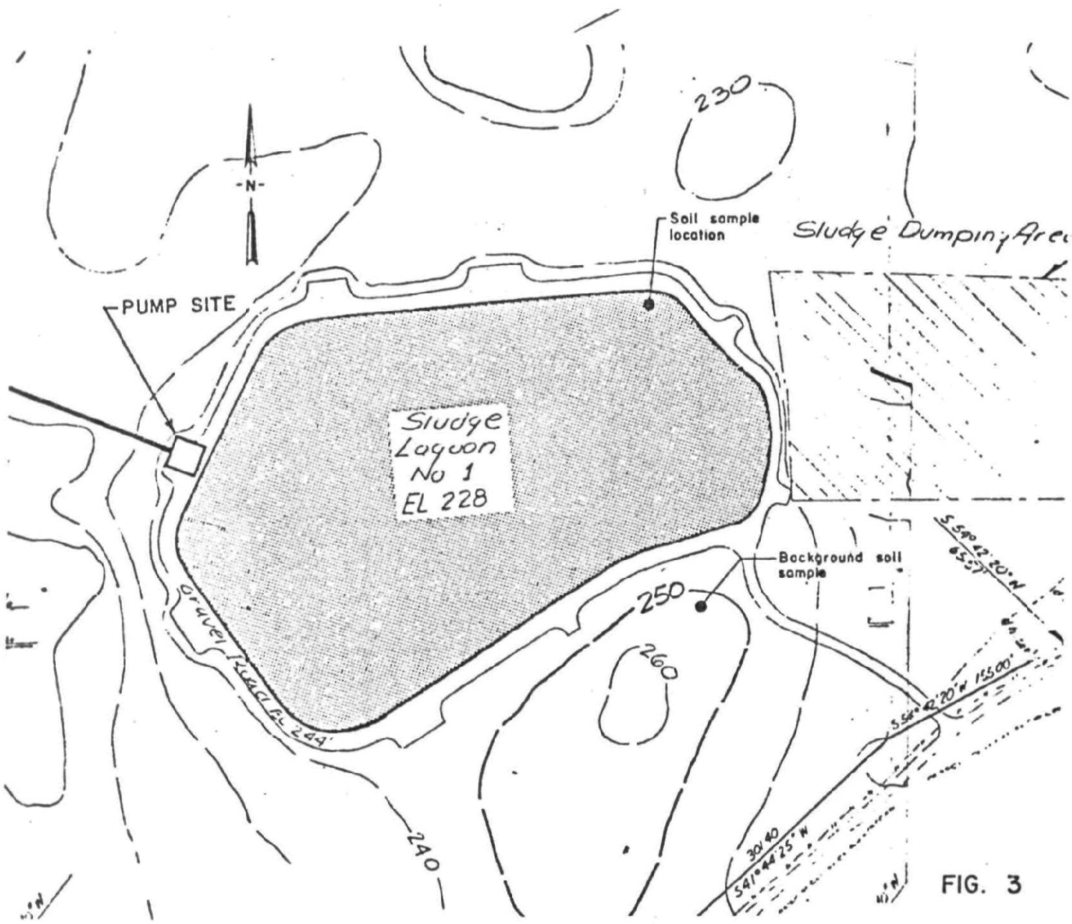

Figure 2. Site plan, New England sludge lagoon (SI)

TABLE 3. PROPERTIES OF 15-MIL PVC LINER SAMPLES FROM THE SLUDGE LAGOON (S1)

Property	Direction of test	Collected October 1979, southwest side				Collected June 1979 Berm		Collected June 9, 1980 Northeast corner			Collected June 9, 1980 East berm
		M1*	M2A	M2B	M3	M4A	M4B	1A	1B-2	1C	x*
Analyses:‡											
Volatiles (2 hr at 105°C), %	---	0.9-7.1	0.65	0.26	3.41	0.28	0.25	5.44	8.15	3.13	8.46
Ash, %	---	---	---	---	---	---	---	5.74	4.35	3.97	5.83
Specific gravity	---	---	---	---	---	---	---	1.27	1.31	1.25	1.32
Extractables, %	---	30.9-35.9	31.2	22.7	24.8	32.5	33.4	32.11	28.99	36.72	25.84
Physical properties											
Thickness, mils	---	12.4	14.7	14.8	11.6	15	15	16.5	15.0	16.0	16.0
Breaking factor, ppi	Machine	67.7	70.4	61.9	34.0	42.4	38.5	48.6	41.6	47.1	38.9
	Transverse	73.5	73.8	62.1	30.2	37.2	34.0	38.5	44.4	43.8	38.2
Elongation at break, %	Machine	335	275	310	8	310	300	290	225	350	170
	Transverse	295	285	325	5	300	300	270	225	400	175
Tensile set, %	Machine	86	127	110	2	92	87	83	86	86	101
	Transverse	63	180	127	1	97	95	54	114	109	91
S-100, ppi	Machine	36.2	60.0	40.9	---	28.4	25.5	29.7	33.8	22.9	36.1
	Transverse	43.9	58.0	39.7	---	25.9	22.7	26.0	35.5	19.1	34.9
S-200, ppi	Machine	45.2	68.3	50.4	---	34.1	32.1	38.6	41.4	32.1	---
	Transverse	53.4	65.8	49.7	---	31.2	27.7	33.8	42.3	26.4	---
Tear strength, Die C, lb	Machine	---	---	---	---	---	---	6.7	6.5	5.2	7.0
	Transverse	---	---	---	---	---	---	5.8	6.8	4.8	6.6
Hardness:											
Duro A:											
Instant reading	---	---	---	---	---	47.2	---	83	87	79	81
5-sec reading	---	---	---	---	---	36.8	---	81	86	75	81
Duro D:											
Instant reading	---	---	---	---	---	---	---	40	49	33	51
5-sec reading	---	---	---	---	---	---	---	33	44	27	46
Puncture strength:											
Thickness of specimen, mils	---	---	---	---	---	---	---	16.3	15.5	16.2	16.0
Stress, kg (lb)	---	---	---	---	---	---	---	13 (28.9)	12.9 (28.3)	12.8 (28.2)	9.6 (21.1)
Elongation, cm (in.)	---	---	----	----	---	---	---	1.9 (0.76)	1.3 (0.51)	2.3 (0.93)	0.89 (0.35)

* Sample number.

* Taken from excavation dike at the northeast corner of the lagoon.

‡ Solvent: $CH_3OH + CCl_4$.

and was obtained from the berm. Elongations and extractables of the samples varied considerably and indicated that plasticizers were lost during exposure to the sludge even when the liner had not been exposed to the weather.

The liner sample taken from the inside surface of the embankment and facing the sludge was distorted and torn in spite of the 16 cm (6 in.) sand base. Boulders either had worked their way out of the soil, or the sand had sloughed. The tear of the liner may have been the result of the sludge mass moving downward as it was being moved from the pond.

Also, an encrustation had developed at various places on the surface of the liner. When the liner samples were returned to the laboratory, dilute hydrochloric acid was applied to the encrustations. Fizzing resulted, which indicated that a calcium carbonate deposit was building up on the liner.

Soil Samples--A 38-cm (15-in.) column of soil was obtained from beneath the lagoon liner in a 7.5-cm (3-in.) diameter steel shelby tube and returned to the laboratory for examination and testing. A similar soil column was obtained in an area immediately adjacent to the lagoon. Samples were extruded, photographed, and subsampled for chemical analysis. Soils were analyzed for chemical constituents indicative of leachate that might have penetrated the liner.

Results of the chemical testing are presented in Table 4. Data from analysis of the background sample are shown for comparison. Although the results showed elevated concentrations of nearly all constituents beneath the liner when compared with background sample data, the evidence is not sufficiently conclusive without additional testing.

NEW YORK STATE LANDFILL (SII)

Site Condition

The New York State landfill (SII) is located on approximately 2.4 ha (6 acres) of rolling and wooded terrain in an area of predominantly clay and sandy soils with intermittent outcroppings of rocks. Precipitation averages 117 cm (46 in.) throughout the year. The area method of landfill is used to place wastes in 3.1 m (10 ft) lifts covered with soil. No liquid or hazardous wastes were accepted for disposal between 1976 (when landfilling commenced) and October 17, 1979, the date of the site visit.

Liner Sampling and Evaluation

During the site visit, a piece of the 30-mil PVC liner was collected from the surface near an exposed boulder. The PVC was gray and felt quite stiff after it had cooled to ambient temperature. Though the exposure could not be quantified, a series of tests was run and the results were compared with the specifications on the original sheeting. The results presented in Table 5 indicate that the sample had stiffened and probably lost plasticizer during its exposure to weather. The material was still extensible and had not become brittle, as is often the case with exposed PVC liner sheeting.

TABLE 4. CHEMICAL ANALYSIS OF SOILS AT SI

Constituent	Background sample 0-7.5 cm (0-3 in.)	Background sample 16-23 cm (6-9 in.)	Sample beneath liner 0-7.5 cm (0-3 in.)	Sample beneath liner 16-23 cm (6-9 in.)	Sample beneath liner 23-31 cm (9-12 in.)	Sample beneath liner 31-39 cm (12-15 in.)
Cadmium	0.002	0.002	0.003	0.002	--	--
Chloride	126.7	62.5	84.0	61.6	--	--
Iron	312	2125	1331	1211	3750	1815
Lead	0.16	0.01	0.52	0.32	0.01	0.01
Magnesium	47.0	126.3	78.6	55.4	115.0	56.3
Potassium	52.5	151.3	87.9	40.3	156.3	47.5
Sodium	18.7	15.0	27.9	21.7	22.0	24.0
Zinc	0.16	4.0	0.47	0.32	1.05	13.0
Mercury	--	0.0075	--	--	0.013	0.0065

TABLE 5. PROPERTIES OF WEATHERED PVC LINER AT SII OBTAINED ON OCTOBER 17, 1979

Property	Direction of test	Exposed sample	Supplier's specification
Analyses			
Volatiles, %	---	0.18	---
Ash dry basis, %	---	5.0	---
Specific gravity	---	1.264	1.2-1.3
Extractables, %	---	31.3	---
Physical properties			
Thickness, mils		29	30
Breaking factor, ppi	Machine	87.7	75 minimum
	Transverse	87.8	75 minimum
Elongation at break, %	Machine	260	300 minimum
	Transverse	300	300 minimum
Tensile set, %	Machine	91	---
	Transverse	111	---
S-100, ppi	Machine	66.4	30-48
	Transverse	58.7	30-48
S-200, ppi	Machine	77.9	---
	Transverse	71.1	---
Tear strength, lb	Machine	---	8.1 minimum
	Transverse	---	8.1 minimum
Hardness:			
Duro A:			
Instant reading	---	49	---
5-sec reading	---	42	---

* This sample consisted of a small piece of exposed liner that had covered an exposed rock. ASTM D412 was followed in testing tensile properties, using a dumbbell specimen 0.64 cm (0.25 in.) wide at restricted area.

Because no test data existed for the original liner material, no determination could be made of changes in properties that occurred during exposure. Suppliers specifications (Table 5) are generally minimum values and can be considerably lower than actual test values. No attempt was made to sample the subsoil or to obtain a sample of liner material exposed to the leachate.

BOONE COUNTY FIELD SITE (BCFS)

Site Conditions

The BCFS is an experimental landfill operated by EPA to determine landfill performance. This 4-ha (10-acre) tract sits on top of a ridge 5 miles west of the City of Walton in Northern Kentucky. This site contains a field-scale landfill and four smaller test cells. The study examines clay and synthetic liners from the field-scale landfill (TC-1) and from one of the smaller test cells (TC-2D).

TC-1

From TC-1, samples were taken of a clay liner, a chlorosulfonated polyethylene liner (CSPE), and a low-density polyethylene liner (LDPE). Figure 3 shows the relative positions of these liners in the test cell.

Clay Liner--

The clay liner between the refuse fill and the CSPE liner varied in thickness from 44 to 62 cm (17 to 24 in.). The liner was composed of a slightly sandy, moderately plastic clay containing limestone rock fragments up to 26 cm (10 in.) long. The clay was classified as a CL by the Unified Soil Classification System, with an average liquid limit of 42 and a plasticity index of 20. Rock fragments lay parallel to the liner surface. Average in-place dry density was 99 pcf, and average moisture content was 25 percent. Permeability ranged from 4 to 5 x 10^{-7} cm/sec for in-place tests; in laboratory tests, it was 2 x 10^{-8} cm/sec. These and other soil testing data are summarized in Table 6. The liner was light brown-gray to a depth of 31 to 36 cm (12 to 14 in.), where it abruptly changed to a more natural orange-tan for the remainder of its thickness. No visual signs of cracking, channeling, or unusual changes in texture or consistency were noted in any of the excavations. Chemical analyses of the clay liner in TC-1 (Figures 4 and 5) indicated that it provided effective leachate containment. Some leachate had collected below the clay liner. But this leakage resulted from a small perforation in the clay separating upper and lower drains, not from liner failure. The uniform contours of the perforation suggest accidental puncturing of the clay surface during cell preparation.

Synthetic Liners--

Three CSPE samples and one LDPE sample were collected from TC-1. The CSPE samples were taken from the unreinforced 0.75-mm (30-mil) sheeting that had been centered at the base of the cell to prevent leachate migration

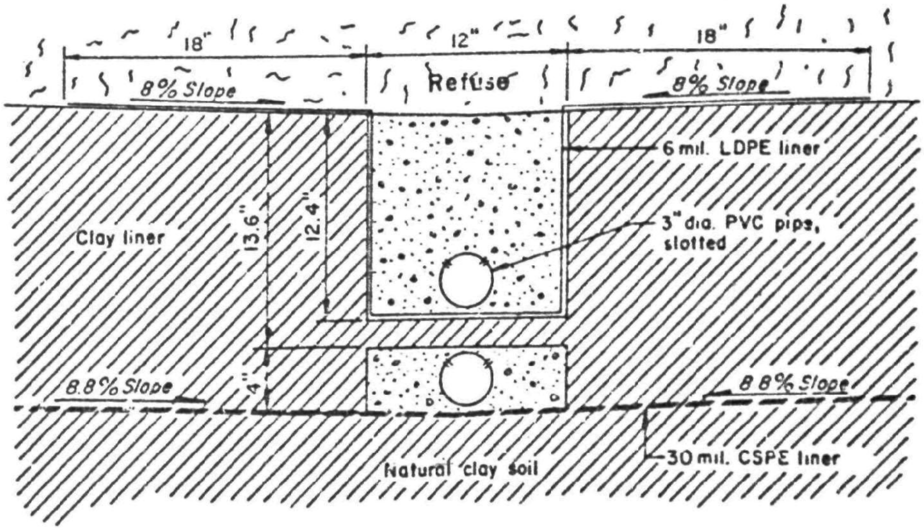

Figure 3. Cross Section of TC-1 at Observation Bulkhead

TABLE 6. SOIL TESTING DATA FOR CLAY LINER IN TC-1

Location	Sieve Analysis* Clay (%)	Sieve Analysis* Silt (%)	Sieve Analysis* Sand (%)	Liquid limit (%)	Plasticity index (%)	Unified Soil Classification	In-place Moisture content (%)	In-place Dry density (pcf)	Permeability In-place (cm/sec)	Permeability Laborat (cm/se
Background+	24	70	6	40	19	CL	-	-	-	-
Background‡	10	86	4	46	22	CL	-	-	-	-
B	34	54	12	45	23	CL	30	95	5×10^{-7}	2 x 10
E	0	88	12	44	21	CL	23	109	4×10^{-7}	2 x 10
G	30	62	8	36	16	CL	23	93	4×10^{-7}	2 x 10

* ASTM-ASCE grain size scale.

\+ Sample of clay retained at time of liner placement.

‡ Sample of clay from borrow area.

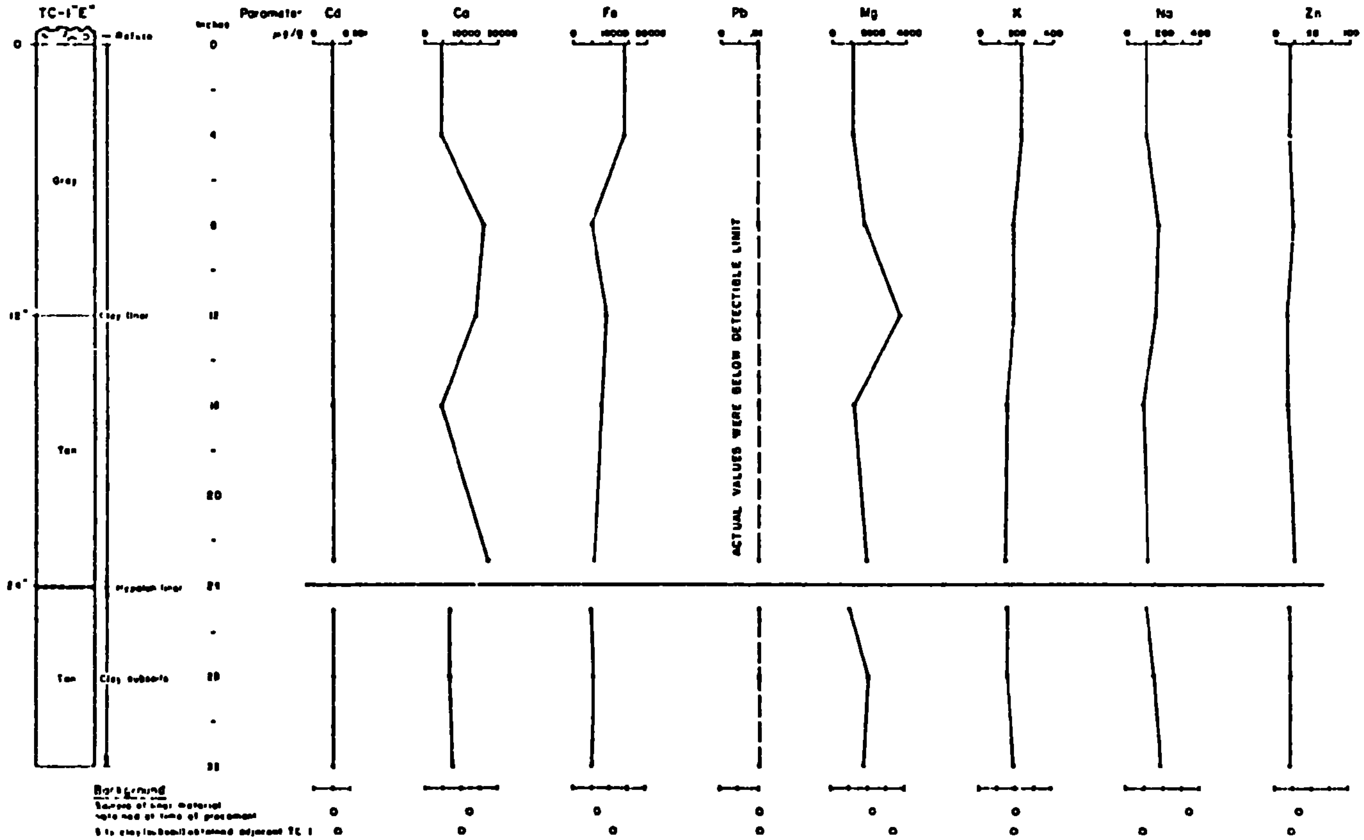

Figure 4 Chemical Analysis of Clay Liner - TC-1E.

Note: Acid extraction process used for soil testing

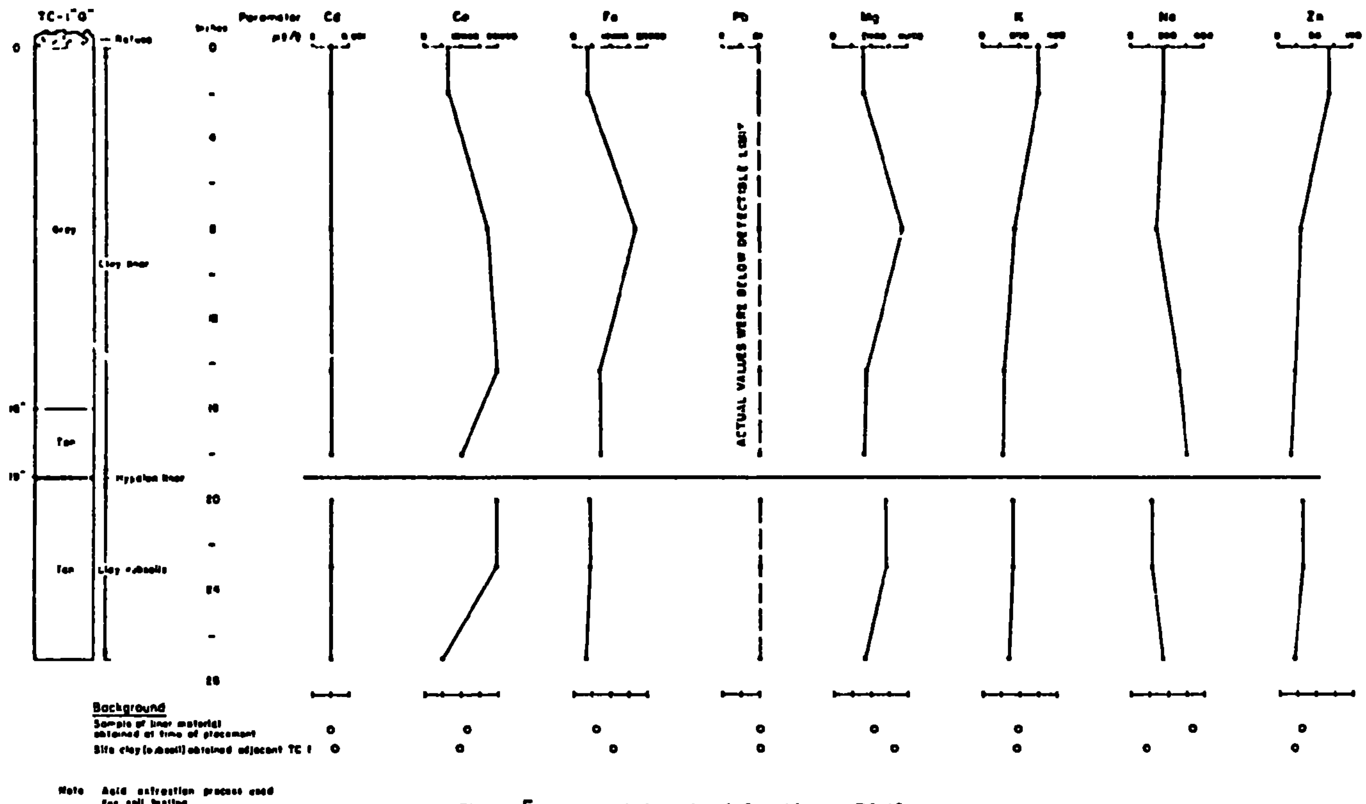

Figure 5 Chemical Analysis of Clay Liner - TC-1G.

below the cell (See Figure 3). A slotted collection pipe surrounded by gravel was placed directly above the CSPE liner in the clay liner beneath the refuse.

The LDPE sample was taken from the liner of a trench that had been installed in the top 32 cm (12.4 in.) of the clay liner (Figure 4). This trench was lined with .15 mm (6 mil), unpigmented LDPE and contained a second pipe to prevent the short circuiting of the leachate to the lower pipe. The space around both of the pipes was filled with clean silica gravel. Thus the effectiveness of the clay liner could be assessed by measuring the flow of leachate into the lower pipe.

Tests showed that the amount of leachate that had permeated the clay liner was only a fraction of the actual quantity generated in the cell during the 9-year study period. Nonetheless, the CSPE liner had been in contact with this small amount of dilute leachate for the full 9 years, and the LDPE liner had been in contact with full-strength leachate for the same period.

The leachate-exposed samples were sealed in polyethylene bags and kept damp until tested. Test results for all liner samples from TC-1 are summarized in Table 7.

CSPE Results--The CSPE samples exposed to leachate had imprints of gravel and were swollen and soft. They had a small-scale rough appearance similar to that of a nervy compound after calendering. (Nerve in uncrosslinked polymer compounds is the unrelieved stress that was introduced during manufacture of the sheeting either by calendering or by extrusion). Calender roll markings were not visible to indicate grain direction. Seams had blisters filled with fluid that appeared to be essentially water.

Substantial amounts of the dilute leachate were absorbed by the CSPE samples: Weights increased by 23.9 to 28.4 percent, and volumes increased by 57 percent, based on the original composition.

The ash values of the relatively high specific gravities reported in Table 7 indicate a high inorganic filler content. The extractables (after the volatiles were removed) were relatively low, indicating either a relatively low plasticizer content in the unexposed sheeting or a loss of plasticizer during exposure.

The physical properties of the CSPE samples all appeared to be approximately the same. Recovered samples were substantially thicker than were the original materials. Part of this increased thickness is due to the swelling, and part is probably a result of the relaxing of the compound and the puckering of the liner material (which occurred because of the residual nerve in the sheeting). The values all appear to be relatively normal for a CSPE material.

No significant differences were noted in the data among the different samples. This result indicates that the location of the sample in the cell did not affect the results, and that the materials all came from the same lot.

TABLE 7. PROPERTIES OF LEACHATE-EXPOSED CSPE AND LDPE SAMPLES TAKEN FROM TC-1

Parameter	Direction of test	30-mil CSPE Trench "E" #12	Trench "B" #14B	Trench "G" #16	6-mil LDPE Median, #14A
Analyses:					
Volatiles, %	---	28.2	28.4	22.9	---
Ash (db)*, %	---	21.98	21.88	23.32	0.15
Specific gravity (db)	---	1.457	1.440	1.442	---
Extractables of specimens ≠ after devolatilization, % +	---	2.97	3.77	3.07	1.10
Physical properties:					
Thickness, as received	---	45.0	43.5	43.0	7.0
Thickness, after devolatilizing	---	45.9	46.6	44.6	6.6
Tensile at yield, ppi	Machine	---	---	---	9.9
	Transverse	---	---	---	9.9
Breaking factor, ppi	Machine	53.2	59.2	59.2	11.0
	Transverse	48.8	48.8	46.0	10.2
Elongation at break, %	Machine	300	300	310	345
	Transverse	350	320	370	225
Set after break, %	Machine	111	100	110	245
	Transverse	140	116	146	119
S-100, ppi	Machine	26.3	22.8	24.6	9.6
	Transverse	14.0	14.7	12.4	9.6
S-200, ppi	Machine	42.8	39.1	40.0	9.7
	Transverse	24.8	17.0	21.2	9.6
Tear strength, lb	Machine	6.5	6.6	6.8	2.9
	Transverse	6.7	6.1	6.5	2.8
Hardness:					
Duro A.					
Instant reading	---	58	66	59	---
5-sec reading	---	54	60	56	---
Puncture strength:					
Stress, lb	---	33.3	35.3	33.9	7.0
Elongation, in.	---	0.90	0.91	0.86	0.27
Thickness of specimen, mils	---	45.5	44.0	42.0	7.0

* Volatiles equal the accumulated weight loss on drying for 7 days in air at room temperature, 5 days in oven at 50° C, and 2 hrs in air oven at 105° C.
\+ After devolatilization.
≠ Solvent is n-heptane

Changes in properties that occurred during exposure cannot be measured since a sample of the CSPE sheeting was not retained, and no baseline data are available on the original unexposed sheeting. However, two small samples of unreinforced CSPE sheeting manufacturered in 1971 or 1972 were tested to obtain data on a comparable material. Test results are compared in Table 8 with those for three CSPE samples recovered from the test cell. Note, however, the CSPE liner compounds tend to crosslink with age and change their properties. Since the data show a relatively great divergence in properties, it is not possible to present retention data. However, values for the leachate-exposed samples are between those for the two unexposed samples.

LDPE Results--The LDPE film was clear after the surface stain was washed off, and it appeared to be unaffected by its 9 years of exposure to the unattenuated leachate. The sample showed little swelling, and its properties (Table 7) were normal for a 6- to 7-mil LDPE. No puncture or tears of the material were observed during sample removal.

Subsoils--

An excavation was made into a thin clay mantle overlying limestone bedrock in TC-1. When the cell had originally been excavated in 1970, fractured limestone was encountered in scattered locations. Wherever limestone was exposed at that time, 18.5 cm (7.2 in.) of clay from the site was placed and compacted to a wet density of 126 pcf at 24 percent moisture (dry weight basis).

Clay subsoils were exposed at locations B, E, G beneath the CSPE liner. The clay immediately below this liner was a brown-gray for several millimeters, grading to a natural orange-tan. This clay was similar in consistency to the clay liner in TC-1, with an average liquid limit of 40 and a plasticity index of 18. Soil testing data are summarized in Table 9, and a chemical analysis of the subsoils and their relationship to the overlying clay liner are presented in Figures 4 and 5.

TC-2D

From TC-2D, six samples were taken of a 30-mil, unreinforced, chlorinated polyethylene (CPE) liner. Four of the samples were taken from the bottom of the cell, and two were collected above ground at the top of the cell (and had thus been exposed to the weather). Figure 5 shows the position of the CPE liner in relation to the other construction details of TC-2D.

Leachate-Exposed Samples--

The four samples from the bottom of the cell had been exposed to all the unattenuated leachate generated within the cell during the 9 years of operation. Chemical analyses of the layers of sand above and below the CPE liner indicated that it had contained the leachate within the cell. Properties of the leachate-exposed samples are presented in Table 10.

TABLE 8. COMPARISON OF PROPERTIES OF LEACHATE-EXPOSED CSPE FROM TC-1 WITH TWO UNSUPPORTED CSPE SHEETINGS

Parameter	Direction of test	Average value for leachate exposed CSPE samples	Value for Manufacturer A, 30-mil liner: Unexposed	Value for Manufacturer A, 30-mil liner: Aged in lab 8 years	Value for Manufacturer B, 30-mil liner, Aged in lab 3 years
Analyses					
Volatiles, %*	---	26.5	0.84	0.5+	0.3+
Ash (db)‡, %	---	22.4	37.5	39.9+	3.6+
Specific gravity	---	1.446(db)‡	1.433(AR)‡	1.429(AR)	1.376(AR)
Extractables of specimens after devolatilization, %	---	3.27	1.49	---	---
Solvent	---	n-heptane	acetone	---	---
Physical properties					
Thickness, as received	---	43.8	31	31	31.2
Thickness, after devolatilizing	---	45.7	---	---	---
Breaking factor, ppi	Machine	57.2	51.2	79.0	58.9
	Transverse	47.9	44.4	73.0	50.5
Elongation at break, %	Machine	305	575	500	300
	Transverse	345	645	525	310
Set after break, %	Machine	107	367	199	142
	Transverse	134	375	202	148
S-100, ppi	Machine	24.6	20.8	23.3	33.9
	Transverse	13.7	16.0	17.9	26.3
S-200, ppi	Machine	40.6	26.4	26.9	56.5
	Transverse	24.3	19.2	19.5	46.0
Tear strength, lb	Machine	6.6	8.8	9.8	9.7
	Transverse	6.4	8.3	8.0	9.4
Hardness: Duro A					
Instant reading	---	61	86	83	86
5-sec reading	---	57	83	83	85
Puncture strength:					
Stress, lb	---	34.2	25.4	40.8	42.2
Elongation, in.	---	0.89	1.15	1.00	0.68
Thickness of specimen, mils		44	31	31.0	31.5

* Volatiles equal the weight loss after 2 hrs at 105° C.

+ Value obtained using thermogravimetric analysis.

‡ db = After devolatilization; AR = as received.

TABLE 9. SOIL TESTING FOR SUBSOILS FROM TC-1

Trench	Sieve Analysis* Clay (%)	Sieve Analysis* Silt (%)	Sieve Analysis* Sand (%)	Liquid limit (%)	Plasticity index (%)	Unified Soil Classification	In-place Moisture content (%)	In-place Dry density (pcf)	Permeability In-place (cm/sec)	Permeability Laboratory (cm/sec)
B	0	92	8	31	11	CL	27	94	3×10^{-7}	1×10^{-7}
G	3	94	3	41	17	CL	22	101	6×10^{-7}	3×10^{-8}
E	0	93	7	48	26	CL	28	97	4×10^{-7}	5×10^{-8}

* ASTM-ASCE grain-size scale.

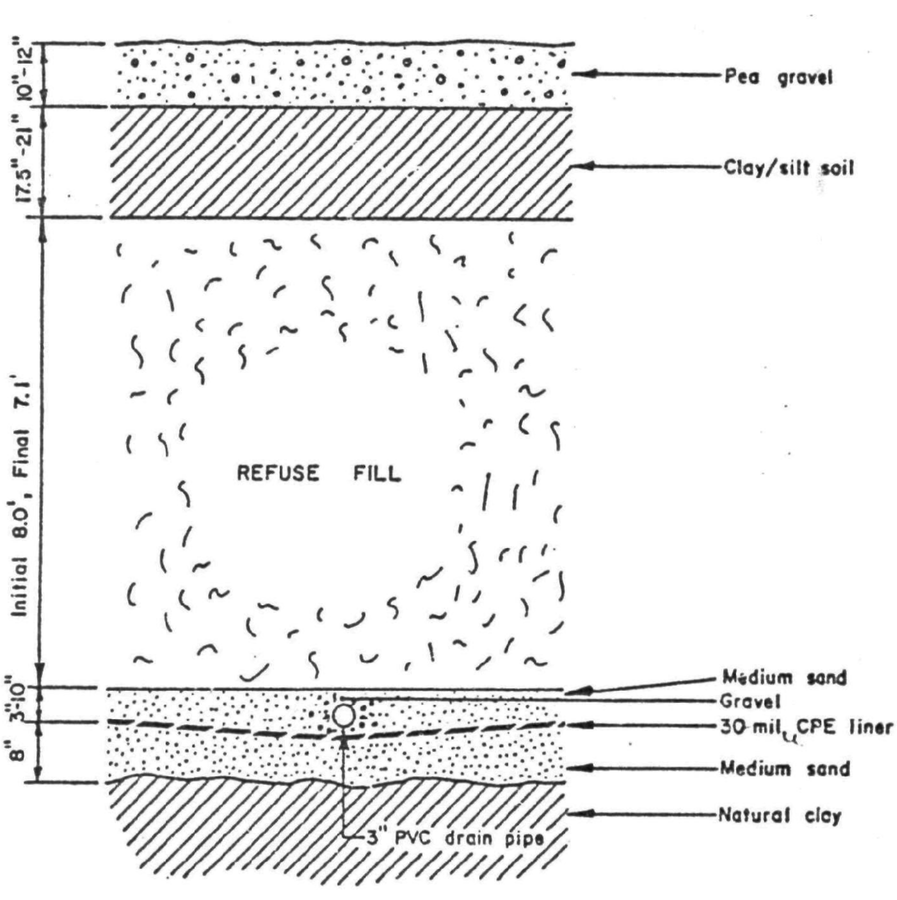

Figure 6. Test Cell Construction Details for TC-2D.

TABLE 12. PROPERTIES OF LEACHATE-EXPOSED AND WEATHERED CPE FROM TC-2D

Parameter	Excavation trench and sample number					
	TC-2DA No. 11	TC-2DC No. 13	TC-2DB No.15A	TC-2DB No.15B	TC-2DWA No. 20	TC-2DWB No. 21
Chemical analyses						
Volatiles, %[a]	18.8	18.3	17.6	16.7	6.63	7.25
Ash (db), %[b]	13.36	13.31	13.02	13.03	13.21	15.20
Specific gravity (db)[a]	1.372	1.376	1.368	1.361	1.34	1.34
Extractables, %[c]	4.81	4.42	4.43	5.15	4.42	3.81
Physical properties						
Thickness, as received	41.5	40.0	37.0	39.0	34	34
Thickness, devolatilized	39.2	39.4	35.1	38.9	...	...
Breaking factor, ppi						
machine	55.6	58.8	52.8	54.0	73.0	78.4
transverse	44.0	46.8	39.6	42.4	55.6	60.3
Elongation at break, %						
machine	240	220	270	260	275	295
transverse	320	310	335	350	335	335
Tensile set, %						
machine	134	117	147	131	178	187
transverse	125	115	136	123	168	157
Stress at 100%, ppi						
machine	36.1	41.6	30.5	33.6	49.5	54.7
transverse	17.7	18.3	14.6	14.1	24.9	32.1
Stress at 200%, ppi						
machine	51.2	57.6	43.6	46.8	62.2	66.0
transverse	28.3	30.2	23.9	22.9	36.0	42.5
Tear strength, lb						
machine	8.7	7.7	7.0	7.8	8.1	9.5
transverse	6.0	6.4	6.4	6.9	6.3	7.0
Hardness (Duro A)						
instant reading	79	78	65	69	77	72
5-sec reading	67	69	60	59	71	69
Puncture strength						
stress, lb	36.6	41.2	36.4	37.8	46.6	48.8
elongation, in	0.78	0.77	0.80	0.83	0.68	0.79
thickness, mil	39.0	40.0	37.0	40.5	34	34
Seam strength						
shear, lb	...	...	...	...	26.8	42.9
locus of failure[d]					AD	BRK/SE
peel - max/avg, lb	...	...	...	...	4.1/3.5	4.4/4.0
locus of failure[d]					AD	AD

[a]Data obtained on the CPE exposed to weather in field. No leachate exposure.

[b]db = after devolatilization.

[c]Extractables of specimens after devolatilization. Solvent is n-heptane.

[d]Locus of failure codes: AD = failure in adhesion; BRK = break of liner material outside seam area; SE = failure at seam edge.

The samples were stiff and leathery. The fine parallel line pattern introduced during calendering was visible on the surface and could be used to indicate grain direction. Also visible was a fine diamond-shaped pattern on the reverse side of the sheeting.

Though the exposed CPE samples showed significant absorption of leachate, their properties were relatively good. Volatile contents ranged from 16.7 to 18.8 percent. The latter value is equal to an increase of 23 percent by weight (based on the original), or a 31.7-percent increase by volume.

The data on the volatiles and on the devolatilized samples indicate that two different compositions were involved. The A and C samples are one composition, and the B samples are another. The two B samples have somewhat lower ash contents, volatiles, and extractables. Differences are also apparent in the results of the physical property tests.

Weathered Samples--

The two samples of CPE liner that had been collected above the ground, where the liner extended beyond the cell, had been exposed only the the weather during the 9-year period and not to leachate. These samples were significantly higher in tensile strength, moduli, and puncture resistance compared with the leachate-exposed samples (Table 11). The lower values for the latter probably reflect the swelling by leachate, but crosslinking during exposure may contribute to the higher values of the weathered samples.

Comparison of CPE Samples with Similar Liners not Exposed to Leachate or to Weather--

As in the case of the CSPE and LDPE liners, no comparisons could be made with the orignal sheetings because no material samples or data were available for them. However, a CPE material of the same style had been used in earlier EPA liner studies, and the original data for this liner (Matrecon Liner #12) could be used as a baseline. Average data for the CPE samples from TC-2D are therefore compared with the original Matrecon data in Table 12.

Subsoils--

An excavation was made into a orange-tan clay underlying TC-2D. An excavation was made into a layer of sand and a section of clay underlying the CPE liner in TC-2D (see Figure 6). The sand, which was immediately beneath the CPE liner, was a light tan except for a 1.3- to 1.9-cm (1/2-to 3/4-in.) gray zone at the point of contact with the liner. Exploratory trenches had found the CPE liner to be under an upward hydrostatic pressure from fluids in the underlying sand. Analysis of fluid samples indicated, however, that the water did not contain leachate. Beneath the sand was a thick, natural clay section of moderate to high plasticity classified as CL-CH by the Unified Soil Classification System. The upper 2.5 to 5.1 cm (1 to 2 in.) were a mottled gray-green, with the remainder of the exposed clay a natural orange-tan. Soil test data are summarized in Table 13.

TABLE 11. COMPARISON OF THE LEACHATE-EXPOSED AND WEATHERED CPE SAMPLES FROM TC-20

Parameter	Direction of test	Average value for weathered samples	Average value for leachate exposed sample	
Analyses:				
Volatiles, %	---	6.94	17.9	
Ash (db)*, %	---	14.21	13.18	
Specific gravity+	---	1.34(AR)	1.369(db)	
Extractables, %‡	---	4.12	4.70	
Physical properties				
Actual thickness, as recieved, mils	---	34	39	(+5)
Breaking factor, ppi	Machine	75.7	55.3	(73)
	Transverse	58.0	43.2	(74)
Elongation at break, %	Machine	285	250	(88)
	Transverse	335	330	(99)
Tensile set, %	Machine	183	132	(72)
	Transverse	163	125	(76)
S-100, ppi	Machine	52.1	35.5	(68)
	Transverse	28.5	16.2	(57)
S-200, ppi	Machine	64.1	49.8	(78)
	Transverse	39.3	26.3	(67)
Tear Strength, Die C, lb	Machine	8.8	7.8	(89)
	Transverse	6.7	6.4	(96)
Hardness:				
Duro A				
instant reading	---	75	73	(-2)
5-sec reading	---	70	64	(-6)
Puncture resistance:				
Thickness, mils	---	34	39	(+5)
Stress, lb	---	47.6	38.0	(80)
Elongation, in.	---	0.74	0.80	(108)

* After devolatilization.

+AR = as received; db after devolatilization.

‡ Solvent is n-heptane. Figures indicate the average value for the leachate-exposed samples divided by the average value for the weathered samples multiplied by one hundred, except in the case of the hardness and thickness values, where they are the change in scale.

TABLE 12. COMPARISON OF CPE LINER SAMPLES IN TC-20 WITH MATRECON LINER #12

Parameter	Direction of test	Matrecon liner #12*	Average value for weathered samples in TC-2D	Average value for leachate-exposed samples in TC-2D
Analyses				
Volatiles, %	---	0.10	6.94	17.9
Ash (db)⁺, %	---	14.40	14.21	13.18
Specific gravity‡	---	1.360(AR)	1.34(AR)	1.369(db)
Extractables, %	---	7.47	4.12	4.70
Physical properties:				
Actual thickness, as received, mils	---	31	(+3)‡	(+8)‡
Breaking factor, ppi	Machine	77.6	(98)	(71)
	Transverse	65.6	(88)	(66)
Elongation at break, %	Machine	305	(93)	(82)
	Transverse	515	(65)	(64)
Tensile set, %	Machine	199	(92)	(66)
	Transverse	231	(71)	(54)
S-100, ppi	Machine	38.4	(136)	(92)
	Transverse	[illegible].4	(174)	(99)
S-200, ppi	Machine	57.[illegible]	(112)	(87)
	Transverse	26.4	(149)	(10[illegible]
Tear strength, Die C, lb	Machine	8.[illegible]	(105)	(93)
	Transverse	7.3	(92)	(88)
Hardness:				
Duro A				
Instant reading	---	35	(-10)	(-12)
5-sec reading	---	[illegible]	(-7)	(-13)
Puncture resistance:				
Thickness, mils	---	32	(+2)	(+7)
Stress, lb	---	47.0	(101)	(81)
Elongation, in.	---	104.0	(71)	(77)

* Haxo, H. E., R. M. White. Second Interim Report, Evaluation of Liner Materials Exposed to Leachate, EPA-600/2-76-255, U.S. Environmental Protection Agency, Cincinnati, Ohio. September 1976

⁺ After devolatilization. Solvent is n-heptane. AR = as received; db = after devolatilization.

‡ Numbers in parentheses are percent retentions calculated using the values reported for Matrecon Liner #12 as 100% except in the case of hardness and thickness where the numbers in parentheses are the change in scale.

TABLE 13. SOIL TESTING DATA FOR SUBSOILS IN TC-2D

Cell	Sieve Analysis* Clay (%)	Silt (%)	Sand (%)	Liquid limit (%)	Plasticity index (%)	Unified Soil Classification	In-place Moisture content (%)	Dry density (pcf)	Permeability In-place (cm/sec)	Laboratory (cm/sec)
A	49	43	8	41	19	SC-CL	36	82	1×10^{-7}	2×10^{-8}
B	44	37	19	51	27	SC-CH	37	87	4×10^{-7}	2×10^{-8}
C	46	48	6	55	29	SC-CH	32	88	5×10^{-7}	6×10^{-8}

* ASTM-ASCE grain size analysis.