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PERFORMANCE OF PLASTIC CANAL LININGS

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16. ABSTRACT

A study was conducted to determine the performance of buried plastic membrane linings, primarily 10-mil PVC, used for seepage control in Bureau irrigation canals. Samples from 10 canal installations ranging in service life from 1 to 19 years were evaluated. Results of this study indicate that buried plastic membrane linings are provinding satisfactory service for seepage control. These linings are viable alternatives in areas not suitable for concrete or compacted earth linings. To increase the service life and reduce installation problems of PVC linings, a 20-mil rather than 10-mil thickness is now being specified. The additional cost of the heavier gage material will be minimal. With a 100-percent increase in thickness of the membrane, the overall cost of construction will only increase by about 15 percent.

Laboratory studies and field observations indicate that some stiffening of the PVC lining has occurred with time. This stiffening or aging is caused by the loss of plasticizer, the agent used in the manufacturing of the lining to impart flexibility. With aging, there is generally a reduction in elongation, an increase in modulus at 100 percent elongation, and a decrease in resistance to impact damage at low temperatures. The rate of this aging is primarily dependent on three factors: (1) The linings originally manufactured with a high plasticizer content exhibited less aging, (2) Samples obtained from within the water prism exhibited less aging than those obtained outside the prism, and (3) Samples obtained from areas where the lining had been placed over a fairly smooth subgrade exhibited less aging than those installed over a coarser base. This report also presents design criteria, construction procedures, and updated construction and material specifications for PVC linings.

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Performance of Plastic Canal Linings

by

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January 1984

Applied Sciences Branch
Division of Research and Laboratory Services
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Division of Dam and Waterway Design
Engineering and Research Center
Denver, Colorado

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GLOSSARY OF ABBREVIATIONS

ASTM	American Society for Testing Materials
CPER	reinforced chlorinated polyethylene
DSC	differential scanning calorimeter
EPDM	ethylene propylene diene monomer
E&R	Engineering and Research
EVAC	ethylene vinyl acetate
FML	flexible membrane lining
GC/MS	gas chromatograph/mass spectrometry
HDPE	high density polyethylene
IR	infrared spectrometry
LCCL	Lower Cost Canal Lining
LLDPE	linear low density polyethylene
n	Manning's coefficient of roughness
NSF	National Sanitation Foundation
OCCS	Open and Closed Conduit Systems
O&M	operation and maintenance
OWR	Office of Water Research
PE	polyethylene
PRESS	Program Related Engineering and Scientific Studies
PVC	polyvinyl chloride
Q	flow rate
R&B	rehabilitation and betterment
RCSPE	reinforced chlorosulfonated polyethylene
r	hydraulic radius
s	slope
s:s	ratio of side slopes
TGA	thermo gravimetric analyses
TIC	total ionization current
v	velocity

INTRODUCTION

Under the LCCL (Lower Cost Canal Lining) Program which began in 1946, the Bureau of Reclamation conducted laboratory research and field experimentation with virtually every material thought to have value as a lining material to control seepage from canals. Development of new or improved construction methods and maintenance techniques were also part of the program. Bureau engineers, working in cooperation with contractors and manufacturers, have also developed economical reinforced and unreinforced concrete and compacted earth linings. These linings are now in service on more than 8050 km (5000 mi) of Bureau irrigation systems.

Beginning in 1967, because of the growing emphasis to place more water conveyance systems underground in pipelines, the Bureau terminated the LCCL Program and initiated the OCCS (Open and Closed Conduit Systems) Program, which includes the study of closed systems and continuing studies of lower cost canal linings. Work under both programs has produced plastic membrane linings for seepage control in irrigation canals. Much of the earlier work is summarized in the Water Resources Technical Publication "Investigations of Plastic Films for Canal Linings," published in 1969 [1].[1]

Plastic linings generally have been used in conjunction with the rehabilitation of old, unlined canals. However, plastic linings are now being specified for new construction on the Closed Basin Division, San Luis Project, Colorado; and the Garrison Unit, Pick-Sloan Missouri Basin Program, North Dakota. A list of Bureau canal installations using plastic linings is summarized in table 1.

This report presents design criteria and construction procedures for plastic canal linings. Updated construction and material specifications for PVC (polyvinyl chloride) lining are given in appendixes A and B, respectively. This report also contains performance data on linings from the following canal installations:

- Helena Valley Canal, Helena Valley Unit, Montana
- East Bench Canal, East Bench Unit, Montana
- Wyoming Canal, Riverton Unit, Wyoming
- Bugg Lateral, Tucumcari Project, New Mexico
- McCaskey Lateral, Tucumcari Project, New Mexico
- Lateral H, Sun River Project, Montana
- Amarillo Canal, Navajo Indian Irrigation Project, New Mexico
- Mirage Flats, Mirage Flats Irrigation District, Nebraska
- Farwell Unit, Nebraska

In addition, this report summarizes special laboratory studies conducted regarding the performance of plastic linings.

CONCLUSIONS

1. Results of this study indicate that buried plastic membrane linings are providing satisfactory service for seepage control. These linings are viable alternatives in areas not suitable for concrete or compacted earth linings. To increase the service life and reduce installation problems of PVC linings, a 20-mil rather than 10-mil thickness is now being specified. The additional cost of the heavier gage material will be minimal. With a 100-percent increase in thickness of the membrane, the overall cost of construction will only increase by about 15 percent.

2. Laboratory studies and field observations indicate that some stiffening of the PVC lining has occurred with time. This stiffening or aging is caused by the loss of plasticizer, the agent used in the manufacturing of the lining to impart flexibility. With aging, there is generally a reduction in elongation, an increase in modulus at 100 percent elongation, and a decrease in resistance to impact damage at low temperatures. The rate of this aging is primarily dependent upon the following factors:

- *Source of PVC lining.*–Linings originally manufactured with a high plasticizer content exhibited less aging.
- *Location in canal.*–Samples obtained from within the water prism exhibited less aging than those obtained outside the prism.
- *Condition of subgrade.*–Samples obtained from areas where the lining had been placed over a fairly smooth subgrade exhibited less aging than those installed over a coarser base.

3. Preliminary GC/MS (gas chromatograph/mass spectrometry) analyses of PVC linings indicate this method has merit for both quality control and determining more accurately the chemical changes that occur during aging of the PVC lining. Additional testing is needed to refine the test procedures and develop a data base for future aging studies.

4. To ensure a satisfactory buried membrane lining installation, frequent and competent field inspection is required, especially during earth cover placement.

[1] Numbers in brackets refer to references listed in bibliography.

Table 1.—*Bureau of Reclamation canal installations using plastic membrane linings*

Specifications No.	Canal	Date of installation (month/year)	Material (thickness)	Area lined m^2	Area lined yd^2
604C-72	Helena Valley Canal Helena Valley Unit, Montana	10/68 - 4/69	PVC (10 mil)	24 700	29 560
604C-77	East Bench Canal East Bench Unit, Montana	10/69 - 4/70	PVC (10 mil)	72 000	86 100
604C-81	Helena Valley Canal Helena Valley Unit, Montana	10/70 - 4/71	PVC (10 mil)	23 800	28 440
400C-432	Cottonwood Creek - Huntington Canal Emery County Project, Utah	10/70	PVC (10 mil)	20 800	24 850
604C-85	East Bench Canal East Bench Unit, Montana	10/71 - 10/72	PVC (10 mil)	23 300	27 850
604C-86	Helena Valley Canal Helena Valley Unit, Montana	10/71 - 10/72	PVC (10 mil)	34 000	40 660
617C-97	Pilot Canal Riverton Unit, Wyoming	10/75 - 4/76	PVC (10 mil)	6 190	7 400
617C-99	Wyoming and Pilot Canals Riverton Unit, Wyoming	10/75 - 4/76	PVC (10 mil)	36 780	44 000
617C-108	Pilot Canal Riverton Unit, Wyoming	10/76 - 4/77	PVC (10 mil)	43 640	52 200
63-C0002	Fivemile Lateral Riverton Unit, Wyoming	10/77 - 4/78	PVC (10 mil)	23 650	28 300
63-C0005	Wyoming Laterals Riverton Unit, Wyoming	10/77 - 4/78	PVC (10 mil)	26 250	31 400
63-C0006	Wyoming Canal Riverton Unit, Wyoming	10/79 - 4/80	PVC (10 mil)	64 810	77 520
63-C0007	Wyoming and Pilot Canals, Riverton Unit, Wyoming	10/77 - 4/78	PVC (10 mil)	26 840	32 100
63-C0008	Sand Butte Lateral Riverton Unit, Wyoming	10/77 - 4/78	PVC (10 mil)	19 730	23 600
DC-7248	Amarillo Canal NIIP, New Mexico	6/78 - 9/78	PVC (10 mil)	13 380	16 000
			PVC (20 mil)	1 590	1 900
			PE (10 mil)	14 690	17 575
63-C0018	Fivemile Lateral Riverton Unit, Wyoming	10/78 - 4/79	PVC (10 mil)	13 150	15 730

Table 1.—*Bureau of Reclamation canal installations using plastic membrane linings*—Continued

Specifications No.	Canal	Date of installation (month/year)	Material (thickness)	Area lined	
				m^2	yd^2
63-C0015	Pilot Canal Riverton Unit, Wyoming	10/79 - 4/80	PVC (10 mil)	66 550	79 600
63-C0028	Fivemile Lateral Riverton Unit, Wyoming	10/80 - 4/81	PVC (10 mil)	13 040	15 600
63-C0032	Pilot Canal Riverton Unit, Wyoming	10/80 - 4/81	PVC (10 mil)	46 400	55 500
63-C0031	Pilot Canal Riverton Unit, Wyoming	10/81 - 4/82	PVC (20 mil)	65 380	78 200
63-C0046	Fivemile Lateral Riverton Unit, Wyoming	10/81 - 4/82	PVC (20 mil)	1 420	1 700
63-C0042	Lost Wells Lateral Riverton Unit, Wyoming	10/82 - 4/83	PVC (20 mil)	39 710	47 500
63-C0051	Pilot Canal Riverton Unit, Wyoming	10/82 - 4/83	PVC (20 mil)	41 720	49 900
63-C0054	Wyoming Canal Riverton Unit, Wyoming	10/82 - 4/83	PVC (20 mil)	30 850	36 900
DC-7553	Conveyance Channel Reach A, Closed Basin Division, San Luis Project, Colorado	9/83 - 9/84	PVC (20 mil)	193 116	231 000
DC-7571	Conveyance Channel Reach B, Closed Basin Division, San Luis Project, Colorado	2/84 - 4/85	PVC (20 mil)	355 230	401 000
63-C0059	Pavillion Canal Riverton Unit, Wyoming	10/83 - 4/84	PVC (20 mil)	61 000	73 000
63-C0060	Lost Wells Lateral Riverton Unit, Wyoming	10/83 - 4/84	PVC (20 mil)	31 000	37 200
63-C0061	Pilot Canal Riverton Unit, Wyoming	10/83 - 4/84	PVC (20 mil)	33 270	39 800
63-C0062	Wyoming Canal Riverton Unit, Wyoming	10/83 - 4/84	PVC (20 mil)	60 280	72 100
10-002280	Kennewick Main Canal Yakima Project Kennewick Division, Washington	10/83 - 4/84	PVC (20 mil)	123 700	148 000

A training course is recommended for inspectors not familiar with buried membrane lining construction. This training should be held before the preconstruction conference.

5. Results of recent studies on the use of bottom-only membrane lining indicate this may be an effective low-cost method of reducing canal seepage in loessial soils. In these studies, conducted on the Farwell Unit in Nebraska, a reduction of 52 percent in seepage was obtained when 10-mil PVC lining was installed in the canal invert. Additional studies are needed to verify the results and develop guidelines for design and construction associated with this type of membrane lining application.

6. With the increased use of buried membrane linings in new construction, additional studies are needed to:

a. Obtain design data to establish a Manning's hydraulic coefficient of roughness (n) for buried membrane linings.

b. Reevaluate the criteria for determining protective earth cover depth.

c. Design drainage systems associated with buried membrane linings both during construction and operation of the canal.

d. Evaluate the use of geotextiles under flexible membrane linings.

e. Evaluate concrete/membrane lining systems.

f. Develop a data base for chemical analyses used for quality control. These analyses include GC/MS, TGA (thermo gravimetric analyses), and DSC (differential scanning calorimeter).

7. To minimize construction costs in the placement of the protective cover, it is essential that the cover material be taken from an approved site and not blended; blending increases the cost.

8. Studies conducted by the Northern Research Institute of Hydraulic Engineering and Reclamation in Leningrad on measurement of the dynamic shear modulus (G_o) of plastic films indicate that this modulus may be a good indicator of film aging.

DESIGN CRITERIA

General

Irrigation canals and laterals to be lined shall be designed to meet the general requirements of existing standards [2]. A buried membrane lining system consists of a plastic film covered with a protective layer of earth. Because of the earth cover, buried membrane linings are restricted to canals having a low-velocity flow. The maximum allowable velocity may range from 0.3 to 1.0 m/s (1 to 3 ft/s), depending on the type of soil cover. All facilities should be designed so that they will not fail structurally without a lining, because there is always the possibility of the lining being damaged. A lined canal shall have enough capacity to function as designed without danger of overtopping. Figure 1 shows details for a buried membrane lining system. These design procedures apply to both new construction and rehabilitation work.

Cross Section

The canal cross section shall be sized for sufficient capacity to carry the required flow under maximum retardance conditions. In new construction, the prism should reflect an economical shape based on hydraulic design using the Manning formula and tractive force studies to determine the hydraulic properties. The Manning formula is:

$$Q = \frac{1}{n} A r^{0.667} s^{0.5} \qquad (1)$$

where:

Q = flow rate in m³/s,
n = Manning's coefficient of roughness,
A = cross sectional area of flow in m²,
r = hydraulic radius in m (A/WP, WP = wetted perimeter), and
s = slope of energy gradient (dimensionless).

or,

$$Q = \frac{1.486}{n} A r^{2/3} s^{1/2} \qquad (2)$$

where:

Q is in ft³/s, A in ft², and r in ft.

A roughness coefficient n of 0.025 is usually used for canals with capacities less than 2.8 m³/s (100 ft³/s), and 0.025 to 0.0225 for larger capacities. The n value for a uniform canal section covered with sand and gravel can be determined from the Strickler equation:

$$n = 0.028\, d_{50}^{0.1667} \qquad (3)$$

where:

d_{50} is the size in meters for which

50 percent of the bed material by weight is finer, or

$$n = 0.0342\ d_{50}^{1/6} \qquad (4)$$

where:

d_{50} is the size in feet.

Tractive force limits should also be considered to determine the canal shape and slope. These limits are based on the gradation of the cover material to be used.

In rehabilitation work, sufficient overexcavation of the earthen structure to provide for covering the membrane must be considered in the canal design.

Canals with buried membrane lining must be constructed so that the side slopes will be stable. Slope requirements will vary with different types of earth cover, but shall not be steeper than 2 to 1. Figure 2 shows the bank height and freeboard requirements for buried membrane linings.

Cover Material

An earth cover must be provided to protect the membrane lining from exposure to the elements and from injury by turbulent water, stock, plant growth, and maintenance equipment. The depth of cover depends on cover material, size of canal, water velocity, and canal side slopes. The minimum recommended total cover depth is 250 mm (10 in) plus 25 mm (1 in) for each 0.3 m (1 ft) of water depth.

To minimize costs, approved excavated material should be used for one-half the cover requirement. The upper layer should be a sand and gravel cover material conforming to the gradation limits shown on figure 3. These limits were developed in a study conducted by C. W. Jones [3]. If possible, the sand and gravel material should be obtained from an approved borrow area. The requirement of a sand and gravel layer for erosion protection is a major cost item in buried membrane lining construction. Using material that requires no blending lowers this cost. Larger gravel is generally required at the beach belt in larger canals for protection against wave action.

Membrane Lining

The membrane lining shall be 20-mil PVC conforming to the material requirements listed in appendix B. Other lining materials, which have been used in the past on a limited basis, include PE (polyethylene) and EVAC (ethylene vinyl acetate). These materials will be discussed subsequently in this report.

CONSTRUCTION

General

As previously mentioned, most of the Bureau's plastic membrane lining work has been accomplished under R&B (rehabilitation and betterment) programs. Generally, this work is restricted to the nonirrigation season and often involves wintertime construction. The installation of plastic membrane linings both in R&B work and new construction involves four procedures: (1) excavation, (2) subgrade preparation, (3) installation of the plastic lining, and (4) placement of the earth cover material. These four construction procedures are described in the following paragraphs. Cost data for several recent PVC installations are summarized in tables 2 through 4.

Excavation

Overexcavation of the existing canal prism, a minimum of 300 mm (12 in), is required to allow for placement of the protective earth cover. The side slopes are made sufficiently flat to ensure that the cover material remains on the slopes under operating conditions. The proper side slopes will depend upon the type of earth cover material used; however, even under best conditions, the slopes should never be steeper than 2:1. Two different excavation methods are shown on figures 4 and 5.

Subgrade Preparation

After the rough excavation is completed, the subgrade is prepared to a firm, relatively smooth surface. Sharp rocks, roots, and other objects that might puncture the membrane are either removed or padded by covering with 75 to 100 mm (3 to 4 in) of sand or fine-textured soil.

Dragging the subgrade with a heavy machine-type chain or an old tractor track, as shown on figure 6, is a rapid and effective method for smoothing the canal subgrade. In earlier plastic lining construction, there was a specification requirement for rolling to obtain a smooth subgrade. This particular requirement was a carryover from work with the hot, spray-applied asphalt membrane material [4]. However, subsequent experience with plastic linings indicates that this procedure is generally not required.

As a result of an earth cover slippage on the Pilot Canal, Riverton Unit, Wyoming, in February of 1977 (figs. 7 and 8), the Contracting Officer now has the option of specifying a 50-mm (2-in) thick layer of sand on subgrade soils, which may slicken upon wetting, such as clays and shales. This option is intended to provide more frictional resistance between the PVC and the canal subgrade. Operating

Table 2.—*Cost of PVC lining for Pilot Canal, Riverton Unit, Wyoming. Specifications No. 63-C0051, June 1982*

Work description	Quantity and unit	Engineering estimate per unit	Bid per unit	Cost
Excavation	56 000 yd^3	1.90	1.25	$ 70,000
Preparing subgrade for membrane lining	49 900 yd^2	0.75	0.50	24,950
Furnishing and placing PVC (20 mils thick)	49 900 yd^2	1.75	1.50	74,850
Placing earth cover, 230 mm (9 in) thick	11 600 yd^3	1.80	1.25	14,500
Furnishing and placing sand and gravel cover, 230 mm (9 in) thick	11 100 yd^3	5.70	4.00	44,400
Refill	1 865 yd^3	2.00	1.00	1,865
Furnishing and placing riprap	8 yd^3	25.00	20.00	160
Total cost				$230,725
Unit cost				$4.62/$yd^2$

Hydraulic properties	Sta. 17+48 to 48+00	Sta. 535+00 to 556+30
Q, m^3/s (ft^3/s)	23.9 (844)	23.9 (844)
V, m/s (ft/s)	0.70 (2.29)	0.67 (2.21)
bottom width, m (ft)	9.1 (30)	12.2 (40)
water depth, m (ft)	2.50 (8.19)	2.22 (7.29)
cover depth, mm (in)	457 (18)	457 (18)
s:s	2:1	2:1
s	0.00015	0.00015

a tractor on the side slopes has also been used to roughen the subgrade and improve the frictional resistance.

If weed growth is considered to be a possible problem, an approved soil sterilant should be applied to the subgrade. Care should be taken not to apply sterilants outside the lined area if landscaping or grasses are to be established later.

Plastic Lining Installation

The PVC lining is supplied to the jobsite in large, shop-fabricated sheets wide enough to cover the canal prism and to any length practical for handling to minimize the amount of field joining required. For handling, contractors prefer to use lengths up to 91 m (300 ft) for 20-mil PVC and 183 m (600 ft) for 10-mil PVC. The lining is packaged accordion-folded in both directions and is simply unfolded and pulled into place, as shown on figures 9 through 12.

The PE plastic lining is available in seamless widths to 12 m (40 ft), and usually in custom roll lengths up to 61 m (200 ft). The liner is folded several times and then rolled on a cardboard core. When installing, the liner is unrolled into the bottom of the canal, unfolded, and placed into position.

Installation of plastic lining in a canal is usually started at the downstream end. When tied into concrete structures, the ends of the plastic lining are cemented to the concrete surface using a vinyl-to-concrete adhesive for PVC and an asphaltic mastic

Table 3.—*Cost of PVC lining for Wyoming Canal, Riverton Unit, Wyoming. Specifications No. 63-C0054, June 1982*

Work description	Quantity and unit	Engineering estimate per unit	Bid per unit	Cost
Excavation	30 000 yd^2	1.20	1.10	$ 33,000
Preparing subgrade for membrane lining	36 900 yd^2	0.45	0.25	9,225
Furnishing and placing PVC (20 mils thick)	36 900 yd^2	1.40	1.35	49,815
Placing earth cover, 230 mm (9 in) thick	9 700 yd^3	1.20	1.10	10,670
Furnishing and placing sand and gravel cover, 230 mm (9 in) thick	9 300 yd^2	3.75	3.89	36,177
Refill	1 160 yd^3	0.95	0.89	1,032
Total cost				$139,919
Unit cost				$3.79/$yd^2$

Hydraulic properties	Sta. 752+00 to 781+94
Q, m^3/s (ft^3/s)	48.8 (1722)
V, m/s (ft/s)	0.76 (2.50)
bottom width, m (ft)	13.7 (45)
water depth, m (ft)	3.26 (10.69)
cover depth, mm (in)	508 (20)
s:s	2:1
s	0.00012

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similar to roofing flashing compound for PE. Where not tied into structures, the ends of the plastic lining should be buried into 300-mm (12-in) deep transverse cutoff trenches. For most R&B work, sheets of PVC lining can be joined simply by lapping the downstream end of one sheet 0.9 m (3 ft) over the upstream end of the adjacent sheet. The PVC has a tendency of adhering to itself and, with the weight of the earth cover, a sufficiently bonded joint is obtained where 100 percent seepage control is not required. Where a more positive seal is required, the PVC should be overlapped a minimum of 300 mm, and a solvent cement (recommended by the manufacturer) applied to a minimum width of 50 mm (2 in). The seam is then hand-rolled as shown on figure 13. During field seaming, it is important that a good foundation be provided upon which to work a field seam. Quite often a hard, flat surface (the best for rolling and seaming) is not available in most canal installations, and contractors have used a portable board device under the lining as a satisfactory working surface. A rope can be attached to the board to move it as the seaming progresses.

When installing PE lining, adjacent sheets are overlapped a minimum of 300 mm (12 in) and joined using a polyethylene-backed adhesive tape with a minimum width of 100 mm (4 in). Since PE is a very inert material, it is very difficult to bond. The Soviet Union has developed heat seaming methods for PE lining in their canal lining work [5] (figs. 14 through 17). However, such methods have not been used in this country.

The upper edges of the plastic lining are buried in an anchor berm at the top of the slope at the time

Table 4.—*Cost of PVC lining for Lost Wells Lateral, Riverton Unit, Wyoming. Specifications No. 63-C0042, June 1982.*

Work description	Quantity and unit	Engineering estimate per unit	Bid per unit	Cost
Excavation	34 000 yd^2	1.50	1.19	$ 40,460
Preparing subgrade for membrane lining	47 500 yd^2	0.50	0.27	12,825
Furnishing and placing PVC (20 mils thick)	47 500 yd^2	1.50	1.47	69,825
Placing earth cover, 230 mm (9 in) thick	8 160 yd^3	1.50	1.19	9,710
Furnishing and placing sand and gravel cover, 230 mm (9 in) thick	7 600 yd^3	5.00	3.50	26,600
Refill	2 740 yd^3	1.50	0.90	2,466
Furnishing and placing riprap	45 yd^3	20.00	20.00	900
Total cost				$162,786
Unit cost				$3.43/$yd^2$

Hydraulic properties	Sta. 0+00 to 45+33	Sta. 45+48 to 91+29
Q, m^3/s (ft^3/s)	4.2 (148)	4.2 (148)
V, m/s (ft/s)	0.67 (2.21)	0.44 (1.44)
bottom width, m (ft)	4.3 (14)	6.1 (20)
water depth, m (ft)	1.04 (3.40)	1.20 (3.93)
cover depth, mm (in)	356 (14)	356 (14)
s:s	2:1	2:1
s	0.00045	0.00015

of installation, as shown on figures 1 and 18, to prevent removal of the lining by unexpected gusts of wind.

If at all posible, it is best to avoid windy weather when installing plastic lining (fig. 19); however, if special precautions are taken, plastic lining can be successfully installed during fairly high winds. These precautions are:

1. Place the lining, as nearly as possible, moving in the direction of the wind.

2. Sufficient personnel should be used to hold the lining tightly to the ground as it is unrolled or unfolded from the container.

3. As the lining is placed on subgrade, it should be weighted down immediately with temporary weights, such as sandbags. Discarded rubber tires can be conveniently used as temporary weights by rolling them off a moving truck following the lining placement crew (fig. 20).

4. As soon as possible, the berms anchoring the edges of the plastic should be filled and some cover material placed.

It is important that the plastic lining is placed in the canal in a slack condition, as shown on figure 21, so that the weight of the earth cover will not cause severe stressing.

Placement of Protective Earth Cover

The earth cover is placed soon after the plastic membrane is installed to eliminate possible wind or other damage. The earth cover is an essential part of a buried membrane lining system because its function is to protect the membrane from the elements, animal traffic, vandalism, and mechanical damage during canal cleaning operations.

Protective cover placement should begin as soon as the plastic lining is judged to be properly positioned, jointed, and repaired, if necessary. The cover material can be placed with draglines, conveyors, trucks, or by other means, preferably starting at the toe and working upslope. Various methods for placing the cover are shown on figures 22 and 23. During the initial stages, careful inspection should be made to ensure that the cover placement operations are not causing damage to the plastic lining. It is not necessary to compact the cover material by rolling; however, dragging is usually required to attain the required finished and uniform thickness. Figure 24 shows a typical section of a finished canal.

FIELD STUDIES

General

Under the PRESS (Program Related Engineering and Scientific Studies) Project, DR-302 and the OCCS program, a continuous study is being conducted to evaluate the performance of buried PVC membrane canal linings. The hydraulic properties of the canal installations evaluated to date are listed in table 5.

The study involves both field and laboratory evaluations. The field evaluation includes:

1. Obtaining samples of in-service linings for laboratory evaluation.

2. Making visual observations concerning the condition of the in-service linings and protective earth cover material.

Seepage tests have been conducted on the Helena Valley Canal, East Bench Canal, Lateral H, Farwell Main Canal, Fivemile Lateral, and the Amarillo Canal. The results of these tests are discussed under the appropriate sections.

The laboratory evaluation of the retrieved samples involves:

1. Visual examination.

2. Physical properties testing.

3. Conducting chemical extraction tests to determine plasticizer content of the PVC lining. The method used for this determination is discussed under "Laboratory Studies."

The canal installations are discussed on an individual basis in the following paragraphs; background information on each installation is also included.

Helena Valley Canal, Helena Valley Unit, Montana

In the fall and winter of 1968-69, a reach of the

Table 5.—*Typical hydraulic properties of plastic-lined canals and laterals*

Feature	Flow		Velocity		Slope	s:s	Bottom width		Normal water depth	
	m^3/s	ft^3/s	m/s	ft/s			m	ft	m	ft
Helena Valley Canal	4.25	150	0.64	2.10	0.00035	2:1	2.7	9.0	1.28	4.19
East Bench Canal	11.47	405	.59	1.95	.00013	2:1	6.1	20.0	1.96	6.44
Wyoming Canal	26.05	920	.94	3.09	.00020	2:1	18.3	60.0	2.87	9.41
Bugg Lateral	2.66	94	.57	1.86	.00035	2:1	2.4	8.0	1.04	3.40
Pilot Canal	14.29	505	.66	2.16	.00015	2:1	7.9	26.0	1.92	6.30
Fivemile Lateral	1.81	64	.68	2.22	.00082	2:1	3.0	10.0	0.66	2.15
Lateral GM 96 (H)	0.99	35	.47	1.54	.00050	2:1	3.0	10.0	0.55	1.80
Mirage Flats Canal	6.23	220	.62	2.05	.00038	1.5:1	5.5	18.0	1.37	4.50
Amarillo Canal										
Reach 4A (PE)	5.28	190	.46	1.51	.00010	2:1	3.2	10.5	1.74	5.72
Reach 5A (PVC)	4.81	170	.60	1.98	.00025	2:1	3.3	10.8	1.34	4.40
Farwell Main Canal	10.75	380	.65	2.12	.00017	2:1	6.1	20.0	1.74	5.70
Farwell Lower Main Canal	2.26	80	.48	1.58	.00025	2:1	2.7	8.8	1.00	3.30

Helena Valley Canal, 1930 m (6332 ft) in length, was lined with PVC plastic. This was the first PVC lining installation under a Bureau construction specifications (604C-72). After completion of the work, the Bureau office in Great Falls, Montana, prepared a comprehensive report on the installation [6].

Samples were obtained by field personnel in the spring of 1974 and submitted to the E&R Center for testing and evaluation [7]. Ponding tests were conducted in October 1973 and April 1974 to determine seepage losses. The results of the ponding tests were:

Location	Date	Water loss	
		$(L/m^2)/d$	$(ft^3/ft^2)/d$
Sta. 1321+93	Oct. 7-8, 1983	14.33	0.047
to 1377+58	April 25-26, 1974	16.76	0.055

Field personnel attribute the lower water losses in the fall to the higher ground-water table which occurs that time of the year.

In November 1977, an inspection was made on the Helena Valley and East Bench Canals [8]. On the Helena Valley Canal, a small area of the lining at station 1330+60 was uncovered for inspection and sampling. The lining appeared to be in good condition and a sample was obtained for laboratory evaluation (fig. 25). The subgrade was fairly smooth with no protruding aggregate and the sand/gravel cover appeared stable. The depth of cover was about 430 mm (17 in). The results of laboratory tests are summarized in tables 6 and 7.

During the 1977 inspection, the performance of the PVC lining was discussed with field personnel. It was their opinion that the plastic was performing satisfactorily. Growth of pond weeds and a recent infestation of Russian olive had created some minor maintenance problems. Also, at several locations, cattle had disturbed the sand/gravel cover and damaged the membrane. The most damage was at station 96+30 where heavy animal traffic had crossed the canal in a path 6 to 9 m (20 to 30 ft) wide.

Results of the physical properties tests indicate these materials have stiffened with time, as shown by the increase in modulus at 100 percent elongation and a reduction in ultimate elongation. Also, there has been a decrease in cold impact resistance. The changes in these physical properties are primarily due to partial loss of plasticizer (the agent used in PVC compounds to impart flexibility) through migration, volatilization, or chemical change.

Chemical extraction tests showed about a 34-percent loss in plasticizer for the 9-year-old field sample (B-6874). However, the rate of plasticizer loss has decreased with time.

Of the two samples (5.3 years of service) obtained from the same location, the one from within the water prism showed less aging. Presumably, this was primarily due to the fact that the lining in this area is subjected to fewer wetting and drying cycles and lower and more uniform temperature conditions.

All three samples appeared to have been taken from areas where the lining had been placed over a fairly smooth subgrade. However, some pinholes and a few small tears due to sharp aggregate edges were noted. For example, the visual examination of sample No. B-6874, about 760 by 760 mm (30 by 30 in) in size, revealed 17 pinholes and 2 small tears.

East Bench Canal, East Bench Unit, Montana

The lining evaluated from the East Bench Canal, near Dillon, Montana, was installed in the fall and winter 1969-70 under specifications No. 604C-77. After completion of work, a construction report was prepared by the Project Office in Great Falls [9].

As with the Helena Valley Canal, samples were obtained in 1974 and 1977. In addition, samples were submitted by field personnel in 1975 [10]. Ponding tests were conducted in October 1973 and April 1974, and the results were:

Loation	Date	Water loss	
		$(L/m^2)/d$	$(ft^3/ft^2)/d$
Station 878+00	Oct. 17-18, 1973	11.58	0.038
to 933+61	April 10-11, 1974	17.07	0.056

As with the Helena Valley Canal, lower water losses occurred in the fall of the year.

During the November 1977 visit, the canal at stations 1353+60 and 906+15 were uncovered and inspected. The lining at station 1353+60 appeared to be in good condition; however, it was very taut. The subgrade contained several large rocks, 75 to 100 mm (3 to 4 in) in size, which the lining had bridged. The sand and gravel cover material was stable and was about 350 to 380 mm (14 to 15 in) in depth. The lining at station 906+15 was also in good condition, but it appeared to be in a more relaxed state than that noted for the lining at station 1353+60. However, the process of sampling the lining revealed that it was quite brittle and fractured when cut (fig. 26). The subgrade at this site was much smoother than noted at the other location. The cover material was stable and ranged from 380 to 410 mm (15 to 16 in) in depth. Regional personnel

Table 6.—*Physical properties test results for PVC membrane linings on Helena Valley Canal. Specifications No. 604C-72, installed fall and winter 1968-69.*

Physical property	Specifications requirements	Sample No. B-5716 (original)	Sample No. B-6666 (5.3 years of service, BWL[2])	Sample No. B-6667 (5.3 years of service, AWL[1])	Sample No. B-6874 (9 years of service, BWL)
Thickness, mm (mils)	0.25 (10)	0.27 (10.76)	0.26 (10.12)	0.25 (9.78)	0.26 (10.17)
percent change	±10		−5.9	−9.1	−5.5
Tensile strength, N/mm (lbf/in)	3.0 (17)*	5.4 (30.6) L[4] 5.8 (33.3) T[3]	4.1 (23.5) L 4.5 (25.5) T	4.1 (24.8) L 4.0 (23.0) T	6.1 (34.6) L 5.0 (28.7) T
percent change			−23.2 L −23.4 T	−19.0 L −30.9 T	+13.1 L −13.8 T
Elongation percent	225*	353 L 348 T	190 L 326 T	179 L 201 T	180 L 225 T
percent change			−46.2 L −6.3 T	−49.3 L −42.2 T	−49.0 L −35.3 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	2.4 (13.9) L 2.2 (12,8) T	3.2 (18.5) L 2.4 (13.9) T	3.7 (20.9) L 3.2 (18.1) T	4.8 (27.2) L 3.7 (21.4) T
percent change			+33.1 L +8.6 T	+50.4 L +41.4 T	+95.7 L +67.2 T
Elmendorf Tear, grams	1500*	2590 L 2200 T	2750 L 3145 T	3000 L 3905 T	1825 L 3490 T
percent change			+6.2 L +42.9 T	+15.8 L +77.5 T	−29.5 L +58.6 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at −18 °C (0 °F)	10 tested 0 failures	5 tested 0 failures	5 tested 5 failures	Not determined
Bonded seam strength, percent of parent material	75	87	Not determined	Not determined	92
Plasticizer content, percent	Not required	37.5	31.8	26.8	24.6
percent change			−15.2	−28.5	−34.4

[1] AWL denotes above normal waterline
[2] BWL denotes below normal waterline
[3] T denotes transverse direction
[4] L denotes longitudinal direction
* Minimum, each direction

obtained samples of cover material from both locations and conducted gradation tests. The results, summarized in table 8, indicate that very little change has occurred after 8 years of service.

The overall performance of buried membrane linings on the East Bench Unit was discussed with Mr. Richard Kennedy, Manager, East Bench Irrigation District. Mr. Kennedy was involved in the original construction under 604C-77. He reported that the district has been quite pleased with the performance of the buried membrane linings. Occasional cover repair is required, especially in areas subjected to heavy cattle traffic. It is his contention that a mini-

Table 7.—*Results of visual examination of PVC membrane lining samples from Helena Valley Canal, Helena Valley Unit, Montana*

Laboratory sample No.	Service life (years)	Location in canal	Sample size (m^2)	Sample size (yd^2)	Remarks
B-6666	5.3	Sta. 1322+33, from within water prism	0.836	1.000	Sample obtained from an area where the lining had been placed over a fairly smooth subgrade
B-6667	5.3	Sta. 1322+33, from above high waterline	.836	1.000	Sample slightly stiffer than B-6666. Same type of subgrade condition as noted for B-6666.
B-6874	9.0	Sta. 1330+60, from within water prism	.562	0.673	Sample fairly flexible; contained 1 shovel tear, 7 aggregate tears, and 17 pinholes

Table 8.—*Gradation of cover material for PVC linings on East Bench Canal, East Bench Unit, Montana*

Screen size	Percent passing by mass: Station 1356+80 (original)	Station 1353+60 (8 years)	Specifications requirements 604C-77
75 mm (3 in)	98	98	90-100
38.1 mm (1.5 in)	80	77	80-100
19 mm (0.75 in)	69	62	65-100
9.5 mm (0.375 in)	51	49	45-95
4.75 mm (No. 4)	39	41	30-85
2.36 mm (No. 8)	32	29	20-70
1.18 mm (No. 16)	26	18	10-55
600 μm (No. 30)	20	9	5-35
300 μm (No. 50)	13	1	0-20
150 μm (No. 100)	7	0	0-10
75 μm (No. 200)	3	0	0-5

mum cover depth of about 410 mm (16 in) is necessary to protect the membrane from animal traffic and accidental damage during canal cleaning operations. Due to the rather short growing season and use of the sand and gravel cover, weed growth in the canal has not presented any major maintenance problems. Also, the water supplied from Clark Canyon Reservoir is quite clean and, consequently, the problems with silting are minimal.

Results of laboratory tests for the six samples from the East Bench Canal are summarized in tables 9 and 10. These results indicate that initially this PVC lining had aged at a faster rate than noted for the Helena Valley lining. However, chemical extraction tests indicated negligible plasticizer loss between 5 and 8 years of service. As with the Helena Valley lining, samples obtained within the water prism exhibited less aging than for those obtained from above high waterline.

Visual examination of the samples showed that all had sustained some physical damage from coarse aggregate contained in the subgrade below the lining, or from coarse aggregate in the cover material immediately above the lining. For example, examination of sample No. B-6872 revealed 27 pinholes and 7 tears from sharp aggregate. This sample was about 760 by 760 mm (30 by 30 in) in size.

Table 9.—*Physical properties test results for PVC membrane linings on East Bench Canal. Specifications No. 604C-77, installed fall and winter 1969-70.*

Physical property	Specifications requirements	Sample No. B-6007 (original)	Sample No. B-6668 (4.3 years of service, AWL[1])	Sample No. B-6669 (4.3 years of service, BWL[2])	Sample No. B-6752 (5 years of service, AWL)
Thickness, mm (mils)	0.25 (10)	0.26 (10.2)	0.24 (9.3)	0.24 (9.6)	0.24 (9.4)
percent change	±10		−8.8	−5.9	−7.8
Tensile strength, N/mm (lbf/in)	3.5 (20)*	5.6 (31.9) L[4] 4.9 (28.0) T[3]	5.2 (29.7) L 4.6 (26.4) T	4.6 (26.3) L 3.7 (21.1) T	5.2 (29.6) L 5.0 (28.7) T
percent change			−6.9 L −5.7 T	−17.6 L −24.6 T	−7.2 L +2.5 T
Elongation percent	250*	312 L 334 T	105 L 92 T	149 L 128 T	153 L 208 T
percent change			−66.3 L −72.5 T	−52.2 L −61.7 T	−51.0 L −37.7 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	2.8 (16.0) L 2.4 (13.9) T	5.1 (29.2) L Not determined	4.1 (23.6) L 3.4 (19.7) T	4.7 (26.7) L 4.2 (23.8) T
percent change			+82.5 L Not determined	+47.5 L +41.7 T	+66.9 L +71.2 T
Elmendorf Tear, grams	1600*	2622 L 3022 T	1265 L 2615 T	2450 L 4070 T	1440 L 1760 T
percent change			−51.8 L −13.5 T	−6.6 L +34.7 T	−45.1 L −41.8 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at −18 °C (0 °F)	10 tested 0 failures	5 tested 5 failures	5 tested 5 failures	5 tested 5 failures
Plasticizer content, percent	Not required	33.2	20.4	25.3	22.5
percent change			−38.6	23.8	−32.2

Riverton Unit, Wyoming

The lining installation on the Wyoming Canal was the first use of PVC on the Riverton Unit. It was installed in the fall and winter of 1975-76 under specifications No. 617C-99. Samples from the Wyoming Canal were obtained in November 1977 after 2 years of service [11] and again in December 1979 after 4 years [12].

Photographs taken during the 1979 inspection are shown on figures 27 through 30. The PVC lining and protective cover material were in good condition after 4 years of service.

Laboratory test results for the four samples evaluated are summarized in tables 11 and 12. All samples were in good condition, and appeared to have been taken from areas where the lining had been placed over a fairly smooth subgrade.

Results of the physical properties test indicate that the lining is continuing to stiffen. This was noted by both the continued increase in modulus at 100 percent elongation and decrease in ultimate elongation. Also, the impact resistance has decreased, as evidenced by the results of the Elmendorf tear and low temperature impact tests. In addition, there has been a decrease in the thickness of the lining since installation.

In November 1981, samples of 10-mil PVC were obtained from the bottom of the Pilot Canal (1 year of service) and the bottom of the Wyoming Canal (2

Table 9.—*Physical properties test results for PVC membrane linings on East Bench Canal. Specifications No. 604C-77, installed fall and winter 1969-70.*—Continued

Physical property	Specifications requirements	Sample No. B-6753 (5 years of service, BWL[2])	Sample No. B-6872 (8 years of service, BWL)	Sample No. B-6873 (8 years of service, BWL)
Thickness, mm (mils)	0.25 (10)	0.24 (9.6)	0.24 (9.5)	0.23 (9.2)
percent change	±10	−5.9	−6.9	−9.8
Tensile strength, N/mm (lbf/in)	3.5 (20)*	5.0 (28.8) L[4] 4.7 (27.1) T[3]	5.1 (29.3) L 4.9 (27.8) T	4.8 (27.7) L 4.7 (27.0) T
percent change		−9.7 L −3.2 T	−8.2 L −0.7 T	−13.2 L −3.6 T
Elongation percent	250*	156 L 193 T	148 L 180 T	109 L 175 T
percent change		−50.0 L −42.2 T	−52.6 L −46.1 T	−65.1 L −47.6 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	4.5 (2.58) L 4.0 (23.0) T	4.7 (26.9) L 4.1 (23.7) T	4.7 (27.1) L 4.2 (23.8) T
percent change		+61.2 L +65.5 T	+68.1 L +70.5 T	+69.4 L +71.2 T
Elmendorf Tear, grams	1600*	2225 L 3140 T	1200 L 2175 T	790 L 1060 T
percent change		−15.1 L −3.9 T	−54.2 L −28.0 T	−69.9 L −64.9 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at −18 °C (0 °F)	5 tested 5 failures	Not determined	Not determined
Plastizer content, percent	Not required	22.6	21.7	20.9
percent change		−31.9	−34.6	−37.0

[1] AWL denotes above normal waterline
[2] BWL denotes below normal waterline
[3] T denotes transverse direction
[4] L denotes longitudinal direction
* Minimum, each direction

years of service) to determine if any damage had occurred to the PVC as the result of the Contractor's method of placing earth cover in the canal invert as shown on figure 31. Results of laboratory tests, summarized in tables 12 through 15, indicated that the samples were in good condition with no apparent damage.

During October 1982, seepage tests were conducted under the FY83 OCCS Program on Fivemile Lateral between stations 200+00 and 207+00 [13]. This reach had been lined with 10-mil PVC in the fall of 1980 under specifications No. 63-C0028. The test was conducted for 100 hours, and the results indicated a seepage loss of 1.83 (L/m²)/d (0.006 (ft³/ft²)/d). In the fall of 1983, it is planned to conduct seepage tests on a reach of this lateral lined with 20-mil PVC. Presently, there are no seepage data available on this thickness of PVC.

Lateral H, Sun River Project, Montana

Under the UM Region LCCL Program in the spring of 1966, a test section was installed on Lateral H

Table 10.—*Results of visual examination of PVC membrane lining samples from East Bench Canal, East Bench Unit, Montana*

Laboratory sample No.	Service life (years)	Location in canal	Sample size (m^2)	Sample size (yd^2)	Remarks
B-6668	4.3	Sta. 900+80, from above high waterline	0.836	1.000	Both samples B-6668 and B-6669 were stiffer than those obtained from Helena Valley Canal. They also suffered more damage from subgrade aggregate
B-6669	4.3	Sta. 900+80, from within water prism	0.836	1.000	
B-6752	5.0	Sta. 904+30, from above high waterline	1.333	1.115	Sample contained 1 large tear from shovel during sampling and 25 small tears from contact with protruding subgrade aggregate
B-6753	5.0	Sta. 904+30, from within water prism	1.388	1.160	Sample slightly stiffer than B-6752. It appeared to have been taken from an area where the lining had been placed over a fairly smooth subgrade. Sample contained 7 tears and 2 pinholes
B-6872	8.0	Sta. 1353+60, from within water prism	0.562	0.673	Sample contained small tears from contact with protruding subgrade aggregate and 27 pinholes
B-6873	8.0	Sta. 906+15, from within water prism	0.562	0.673	Two diagonal tears occurred during sampling. Sample contained 28 pinholes

(Lateral GM 96), Greenfields Division, Sun River Project, Montana [14]. About 4390 m^2 (5250 yd^2) of 10-mil PVC was installed between stations 137+45.4 and 152+97. The PVC was supplied in three sheets, each 9 m (30 ft) wide by 160 m (525 ft) long. Placing the three sheets took less than 3 hours.

The field test also involved the placement of three sections of different cover material combinations for experimental evaluation. These cover sections, starting at the upstream end, consisted of:

1. 150 mm (6 in) of earth from lateral overexcavation with 150 mm of imported gravel. The gravel source was about 5.6 km (3.5 mi) from the site.

2. 300 mm (12 in) of gravelly material from lateral overexcavation.

3. 300 mm of a homgeneous mixture of earth from lateral overexcavation and imported gravel.

Ponding tests were conducted in Lateral H before lining, immediately after lining, and again in the fall of 1970 [15]. Test results were:

Table 11.—*Physical properties test results for PVC membrane linings on Wyoming Canal. Specifications 617C-99, installed fall 1975.*

Physical property	Specifications requirements	Sample No. B-6762	Sample No. B-6870 (2 years of service, AWL[1])	Sample No. B-6871 (2 years of service, BWL[2])	Sample No. B-6991 (4 years of service, BWL[2])	Sample No. B-6992 (4 years of service, AWL[1])
Thickness, mm (mils)	0.25 (10)	0.26 (10.4)	0.25 (9.8)	0.26 (10.2)	0.24 (9.5)	0.23 (8.9)
percent change	±10		−5.8	−1.9	−8.6	−14.4
Tensile strength, N/mm (lbf/in)	3.5 (20)*	4.4 (25.4) L[3] 4.7 (26.7) T[4]	4.9 (28.1) L 4.5 (25.6) T	5.0 (28.4) L 4.4 (25.4) L	5.5 (31.6) L[3] 5.0 (28.8) T[4]	5.1 (29.3) L 5.6 (31.8) T
percent change			+10.6 L −4.1 T	+11.8 L −4.9 T	+24.4 L +7.9 T	+15.4 L +19.1 T
Elongation percent	250*	253 L 305 T	155 L 196 T	181 L 206 T	159 L 196 T	123 L 176 T
percent change			−38.7 L −35.7 T	−28.4 L −32.4 T	−37.2 L −35.7 T	−51.4 L −42.3 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	3.1 (17.6) L 2.6 (15.0) T	4.1 (23.5) L 3.5 (20.0) T	3.7 (21.0) L 3.1 (17.8) T	3.9 (22.4) L 4.3 (24.5) T	4.9 (27.9) L 4.9 (27.8) T
percent change			+33.5 L +33.3 T	+19.3 L +18.7 T	+27.3 L +63.3 T	+58.5 L +85.3 T
Elmendorf Tear, grams	1600*	2335 L 3390 T	2055 L 2065 T	2725 L 3600 T	1390 L 1730 T	1190 L 990 T
percent change			−12.0 L −39.2 T	+16.7 L +6.1 T	−40.5 L −48.9 T	−49.0 L −70.8 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at −18 °C (0 °F)	10 tested 0 failures	10 tested 5 failures	5 tested 0 failures	10 tested 10 failures	10 tested 10 failures
Plasticizer content, percent	Not required	31.4	27.2	28.9	23.7	21.1
percent change			−13.4	−8.0	−24.5	−32.3

[1] AWL denotes above normal waterline
[2] BWL denotes below normal waterline
[3] L denotes longitudinal direction
[4] T denotes transverse direction
* Minimum, each direction

Date	Water loss $(L/m^2)/d$	Water loss $(ft^3/ft^2)/d$
Sept. 10, 1965 (before lining)	152.5	0.50
Oct. 10, 1966 (after lining)	0.0	0.00
Sept. 29-30, 1970	3.1	0.01

During the ponding tests in 1970, an inspection of the lateral was made. The following is excerpted from the field report:

> "The lining appeared to be in good shape and was effectively preventing seepage. This lining had three different types of cover material, as explained in a report of a ponding test conducted in the fall of 1966. The upper 500 feet, which was lined with 6 inches of earth covered by 6 inches of clean gravel, showed slightly less bank erosion than the other reaches and had a firm bottom. The remainder of the reach had a very soft bottom. When wading across the lateral, one would sink through the cover material to the lining. This would make cleaning the lateral quite difficult, as the cover material furnishes little protection to the lining.
>
> "Aquatic weed growth was heavy throughout the lined reach. It was noticeably heavier through the lined reach than on the unlined

Table 12.—*Results of visual examination of PVC membrane lining samples from Wyoming Canal, Riverton Unit, Wyoming*

Laboratory sample No.	Service life (years)	Location in canal	Sample size (m^2)	Sample size (yd^2)	Remarks
B-6870	2	Sta. 482+50, from above high waterline	1.445	1.728	Sample in good condition with no apparent pinholes or tears
B-6871	2	Sta. 482+50, from within water prism	0.955	1.143	Sample in good condition with no apparent pinholes or tears; more flexible than B-6870
B-6991	4	Sta. 480+50, from within water prism	1.445	1.728	Sample in good condition, 13 pinholes noted
B-6992	4	Sta. 480+50, from above high waterline	1.000	1.203	Sample in good condition, 6 pinholes noted
B-7119	2	Sta. 739+00, centerline of canal bottom	0.768	0.918	Sample in good condition; 3 small tears, and one tear from shovel

reaches above or below the lined reach. The type of cover material did not affect the aquatic growth. The lined reach has a very flat grade, approximately 0.00025, and is almost ponded by the check structure at the lower end. This results in very slow and incomplete drainout of the reach when the water is shut off. The lining prevents the ponded water from draining out through the lateral bottom and sides. This provides a marshy type condition in the lateral which promotes excessive growth of aquatic plants."

A sample of the lining was obtained in May 1971 for laboratory evaluation. Another inspection was made in the fall of 1979, and two additional samples were obtained for laboratory evaluation [16]. Photographs taken during this inspection are shown on figures 32 through 36.

The field reported that the lining was still functioning very well. During sampling, it was noted that the lining was intact but appeared brittle. There was a good cover over the lining. After removing the lining, grass roots were observed on the subgrade (fig. 34) but there was no evidence that vegetation had penetrated the lining. Regarding vegetation, the field reported that Lateral H often experiences a high grass growth across the entire canal prism. This growth appears heavier in the lined section due to a higher retention of moisture. Consequently, this condition creates more maintenance activities (cleaning) and shortens the effectiveness of the lining due to uncovering by machinery.

Results of the laboratory tests are summarized in tables 16 and 17. Photographs of the samples obtained in 1979 are shown on figure 37. Laboratory test results indicate that the lining is stiffening, as indicated by an increase in modulus and a decrease in elongation. Tensile tests conducted on samples of factory seams indicate they are still functioning very well after 13.5 years of service. An average value of 4.0 N/mm (22.6 lbf/in) was obtained. This compares to 3.6 N/mm (20.7 lbf/in) for the original sample. Results of chemical extraction tests showed a plasticizer loss of 26.1 percent for the 13.5-year-old sample obtained below the normal waterline and 37.3 percent above the waterline.

Bugg Lateral, Tucumcari Project, New Mexico

In the spring of 1961, a small test section of 10-mil PVC was installed on Bugg Lateral under the LCCL Program [17]. The test section was about 228 m (750 ft) in length. It is the oldest test installation for which performance data are available for this material.

An inspection of the canal was made in 1965 and a sample retrieved for laboratory evaluation. Results of the inspection and laboratory tests are summarized in reference [1]. Samples were also obtained in 1970, 1975 [18], and 1980 [19] after 19 years of service. Photographs taken during the 1980 field inspection are shown on figures 38 through 43. Results of the inspection indicate the lining was intact below water level, but has suffered some damage from root penetration above the

Table 13.—*Physical properties test results for PVC membrane linings on Wyoming Canal. Specifications 63-C0006, installed fall and winter 1979-80.*

Physical property	Specifications requirements	Sample No. B-6972 (original)	Sample No. B-7119 (2 years of service, BWL[1])
Thickness, mm (mils)	0.25 (10)	0.24 (9.6)	0.26 (10.3)
percent change	±10		+7.3
Tensile strength, N/mm (lbf/in)	3.5 (20)*	5.4 (30.6) L[2] 4.6 (26.0) T[3]	5.4 (30.7) L 5.0 (28.8) T
percent change			+0.3 L +10.0 T
Elongation percent	250*	258 L 269 T	167 L 233 T
percent change			−35.3 L −13.4 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	3.1 (17.6) L 2.5 (14.4) T	4.3 (24.8) L 3.5 (19.9) T
percent change			+40.9 L +38.2 T
Elmendorf Tear, grams	1600*	2500 L 3400 T	2020 L 3920 T
percent change			−19.2 L +15.3 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at −18 °C (0 °F)	10 tested 0 failures	5 tested 1 failure
Bonded seam strength, percent of parent material	80	96	91
Plasticizer content, percent	Not required	31.5	29.0
percent change			−7.9

[1] BWL denotes below normal waterline
[2] L denotes longitudinal direction
[3] T denotes transverse direction
* Minimum, each direction

waterline. Photographs of the retrieved samples are shown on figures 44 and 45.

Results of the laboratory tests are summarized in tables 18 and 19. Chemical extraction tests indicated that this PVC lining was originally manufactured with a higher plasticizer content than that noted for the linings previously discussed. Also, the plasticizer used (phthalate ester) had a slightly higher molecular weight.

McCaskey Lateral, Tucumcari Project, New Mexico

In the spring of 1962, about 22 240 m² (26 600 yd²) of 10-mil PVC was installed on McCaskey Lateral [20]. An inspection of the lining was made in the spring of 1980 [19]. Photographs taken during the inspection are shown on figures 46 through 52. The earth cover material appeared stable and was about 430 to 460 mm (17 to 18 in)

Table 14.—*Physical properties test results for PVC membrane linings on Pilot Canal. Specifications 63-C0032, installed fall and winter 1980-81.*

Physical property	Specifications requirements	Sample No. B-7057 (original)	Sample No. B-7118 (1 year of service, BWL[1])
Thickness, mm (mils)	0.25 (10)	0.26 (10.3)	0.26 (10.2)
percent change	±10		−1
Tensile strength, N/mm (lbf/in)	3.5 (20)*	5.2 (29.5) L[2] 4.6 (26.3) T[3]	5.4 (30.7) L 5.0 (28.6) T
percent change			+4.1 L +8.7 T
Elongation percent	250*	247 L 260 T	221 L 242 T
percent change			−10.5 L −6.9 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	3.0 (17.4) L 2.6 (15.1) T	3.5 (20.2) L 3.2 (18.2) T
percent change			+16.1 L +20.5 T
Elmendorf Tear, grams	1600*	2025 L 3200 T	2025 L 3920 T
percent change			0 L Not determined
Impact resistance	Not more than 2 specimens out of 10 shall fail at −18 °C (0 °F)	10 tested 0 failures	5 tested 0 failures
Bonded seam strength, percent of parent material	80		Not determined
Plasticizer content, percent	Not required	32.7	30.8
percent change			−5.8

[1] BWL denotes below normal waterline
[2] L denotes longitudinal direction
[3] T denotes transverse direction
* Minimum, each direction

Table 15.—*Results of visual examination of PVC membrane lining sample from Pilot Canal, Riverton Unit, Wyoming*

Laboratory sample No.	Service life (years)	Location in canal	Sample size (m^2)	Sample size (yd^2)	Remarks
B-7118	1	Sta. 1283+40, centerline of canal bottom	0.813	0.972	Sample in good condition. Three pinholes noted.

Table 16.—*Physical properties test results for PVC membrane linings on Lateral GM96. Sun River Project, Montana, installed spring 1966.*

Physical property	Specifications requirements	Sample No. B-4604 (original)	Sample No. B-6355 (5 years of service)	Sample No. B-7008 (13.5 years of service, BWL[1])	Sample No. B-7009 (13.5 years of service, AWL[2])
Thickness, mm (mils)	0.25 (10)	0.27 (10.7)	0.26 (10.1)	0.24 (9.4)	0.24 (9.3)
percent change	±10		−5.6	−12.1	−13.1
Tensile strength, N/mm (lbf/in)	3.0 (17)*	4.7 (27.1) L[3] 4.2 (24.0) T[4]	4.8 (27.2) L 3.8 (21.9) T	5.7 (32.4) L 4.6 (26.5) T	6.4 (36.4) L 5.0 (28.8) T
percent change			+0.4 L −8.8 T	+19.6 L +10.4 T	+34.3 L +20.0 T
Elongation percent	225*	280 L 302 T	258 L 259 T	209 L 232 T	207 L 200 T
percent change			−7.9 L −14.2 T	−25.4 L −23.2 T	−26.1 L −33.8 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	2.5 (14.4) L 2.2 (12.6) T	2.8 (16.0) L 2.3 (13.0) T	4.0 (22.6) L 3.3 (18.9) T	4.9 (28.2) L 4.2 (23.8) T
percent change			+11.1 L +3.2 T	+56.9 L +50.0 T	+95.8 L +88.9 T
Elmendorf Tear, grams	1500*	2390 L 2120 T	2230 L 2875 T	1930 L 3200 T	790 L 1970 T
percent change			−6.7 L +35.6 T	+19.2 L Not determined	−66.9 L −7.1 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at −18 °C (0 °F)	10 tested 0 failures	10 tested 10 failures	5 tested 5 failures	5 tested 5 failures
Bonded seam strength, percent of parent material	75	86.2	93.6	84.9	79.2
Plasticizer content, percent	Not required	37.5	35.2	27.7	23.5
percent change			−6.1	−26.1	−37.3

[1] BWL denotes below normal waterline
[2] AWL denotes above normal waterline
[3] L denotes longitudinal direction
[4] T denotes transverse direction
* Minimum, each direction

in depth. The area uncovered indicated the lining was intact below water level, but had suffered some damage from root penetration and red ants above the waterline. Photographs of the retrieval samples are shown on figures 53 and 54.

Results of laboratory tests are summarized in tables 20 and 21. The results indicate that the lining is stiffening, as reflected by the increase in modulus and decrease in elongation. Chemical extraction test results showed a plasticizer loss of 35.5 percent for the 18-year-old sample obtained below the waterline, and 27.7 percent above the waterline. The same type and amount of plasticizer was determined as for the lining on Bugg Lateral. Tensile tests conducted on samples of the factory seams indicate

Table 17.—*Results of visual examination of PVC membrane lining samples from Lateral GM 96, Sun River Project, Montana*

Laboratory sample No.	Service life (years)	Location in canal	Sample size (m^2)	Sample size (yd^2)	Remarks
B-7008	13.5	Sta. 150+00, from within water prism	0.743	0.889	Sample somewhat flexible and contained 2 large tears, about 3 inches long; 11 small tears, 1 inch or less in length; and 4 pinholes. Some rust staining was noted. Sample contained a factory seam.
B-7009	13.5	Sta. 150+00 from within water prism	0.426	0.509	Sample slightly stiffer than B-7008. Sample contained two large tears, about 3 inches long. No pinholes were noted. Some rust staining. Sample contained a factory seam.

they are still functioning very well after 18 years of service.

Amarillo Canal, Navajo Indian Irrigation Project, New Mexico

As part of the joint U.S./U.S.S.R. studies on "Plastic Films and Soil Stabilizers for Hydrotechnical Construction," it was agreed that study sections would be constructed with plastic linings in an operating canal in each country, according to the technology of the respective country [21]. The Amarillo Canal, part of the Navajo Indian Irrigation Project, was chosen as the U.S. site for the joint study.

A major portion of this 18.3-km (11.4-mi) long canal was lined with concrete, but two study sections of PE and PVC were constructed:

1. Reach 4A, station 403+87 to station 436+00, 979 m (3213 ft) long, 10-mil PE.

2. Reach 5A, station 569+96 to station 604+50, 1052 m (3450 ft) long, 10-mil PVC.

A cross-sectional view of these two reaches, constructed in the summer of 1978, is shown on figure 55.

In each study section, a seepage monitoring station 30 m (100 ft) in length was constructed (fig. 56). A monitoring station was also constructed under the concrete lining, as shown on figure 57.

As part of the study, various earth cover materials were evaluated:

1. Reach 4A, station 403+97.47 to station 416+00; and reach 5A, station 569+96 to station 584+50. The cover material was placed in two layers. The base layer was excavated material from the canal prism placed to one-half the total depth called for on figure 55. The upper layer was sand and gravel placed to one-half the total depth. The gradation is shown on figure 58. This material was taken from the gravel pit and did not require blending.

2. Reach 4A, station 416+00 to station 426+00; and reach 5A, station 594+50 to station 594+50. The cover material was the same as in 1., except the sand and gravel cover was rolled.

3. Reach 4A, station 426+00 to station 436+00; and reach 5A, station 594+50 to station 604+50. The cover material was sand and gravel placed to a total depth as shown on figure 55.

To determine seepage losses, a Stevens type A71 water level recorder was installed in 1980 along with a small pump at each site. The first seepage measurements were taken by field personnel during August 1980 [22]. The following results were obtained:

Table 18.—*Physical properties test results for PVC membrane linings on Bugg Lateral. Tucumcari Project, New Mexico, installed spring 1961.*

Physical property	Specifications requirements	Sample No. B-3526 (typical original results)	Sample No. B-4343 (4 years of service, BWL)	Sample No. B-6094 (9 years of service, BWL[2])	Sample No. B-6763 (14 years of service, AWL[1]
Thickness, mm (mils)	0.25 (10)	0.28 (11.2)	0.26 (10.2)	0.25 (9.8)	0.24 (9.3)
percent change	±10		−8.9	−12.5	−17.0
Tensile strength, N/mm (lbf/in)	3.0 (17)*	4.5 (25.6) L[3] 4.0 (22.8) T[4]	4.8 (27.4) L 4.1 (23.7) T	4.4 (25.2) L 4.0 (22.6) T	4.6 (26.0) L 5.8 (33.3) T
percent change			+7.0 L +3.9 T	−1.6 L −0.9 T	+1.6 L +46.0 T
Elongation percent	225*	412 L 462 T	322 L 336 T	260 L 433 T	169 L 225 T
percent change			−21.8 L −27.3 T	−36.9 L −6.3 T	−59.0 L −51.3 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	2.0 (11.4) L 1.8 (10.3) T	2.3 (13.3) L 2.0 (11.7) T	2.8 (15.8) L 2.0 (11.7) T	3.9 (22.4) L 4.3 (24.8) T
percent change			+16.7 L +13.6 T	+38.6 L +13.6 T	+96.5 L +140.8 T
Elmendorf Tear, grams	1500*	1830 L 2290 T	2430 L	2900 L 2840 T	1660 L 2210 T
percent change			+32.8 L	+58.6 L +24.0 T	−9.3 L −3.5 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at −18 °C (0 °F)	10 tested 1 failure	10 tested 0 failures	10 tested 0 failures	5 tested 5 failures
Plasticizer content, percent	Not required	39.8	Not determined	35.2	23.1
percent change				−11.6	−42.0
Bonded seam strength, percent of parent material	65	100	97.9	94.4	Not determined

- Reach 4A, station 423+00, polyethylene lined:

  Canal data:

  b (base) = 10.50 ft, d (depth) = 5.72 ft, s:s = 2:1, and WP (wetted perimeter) = 36.08 ft.
  Length of seepage section = 102 ft.

  Average seepage rate for section is 24 gal/h.

  Seepage section has a wetted surface of (102)(36.08) = 3680.16 ft².

  Seepage rate for section $= \frac{(24\ \text{gal/h})\ (24\ \text{h})}{7.4806\ \text{gal/ft}^3}$

  $= 76.99\ \text{ft}^3/\text{d}$

  Established seepage rate $= \frac{76.99\ \text{ft}^3/\text{d}}{3680.16\ \text{ft}^2}$

  $= 0.021\ (\text{ft}^3/\text{ft}^2)/\text{d}$

- Reach 5, station 444+00, concrete lined:

Table 18.—*Physical properties test results for PVC membrane linings on Bugg Lateral. Tucumcari Project, New Mexico, installed spring 1961.*—Continued

Physical property	Specifications requirements	Sample No. B-6764 (14 years of service, BWL)	Sample No. B-7022 (19 years of service, BWL[2])	Sample No. B-7023 (19 years of service, AWL[1])
Thickness, mm (mils)	0.25 (10)	0.24 (9.6)	0.24 (9.6)	0.21 (8.2)
percent change	±10	−14.3	−14.3	−26.8
Tensile strength, N/mm (lbf/in)	3.0 (17)*	4.2 (24.2) L[3] 4.6 (26.1) T[4]	4.6 (26.4) L 5.2 (29.8) T	5.0 (28.6) L 4.7 (26.9) T
percent change		−5.5 L +14.5 T	+3.1 L +30.7 T	+11.7 L +18.0 T
Elongation percent	225*	268 L 274 T	211 L 188 T	151 L 188 T
percent change		−35.0 L −40.7 T	−48.9 L −59.3 T	−63.3 L −59.3 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	2.4 (13.8) L 2.4 (13.8) T	3.6 (20.5) L 4.2 (23.9) T	4.6 (26.0) L 4.2 (23.9) T
percent change		+21.1 L +34.0 T	+79.8 L +132.0 T	+128.1 L +132.0 T
Elmendorf Tear, grams	1500*	3000 L 2865 T	3000 L 2200 T	450 L 1300 T
percent change		+63.9 L +25.1 T	+63.9 L −3.9 T	−75.4 L −43.2 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at −18 °C (0 °F)	5 tested 5 failures	Not determined	Not determined
Plasticizer content, percent	Not required	34.1	27.0	21.6
percent change		−14.3	−32.2	−45.7
Bonded seam strength, percent of parent material	65	Not determined	Not determined	Not determined

[1] AWL denotes above normal waterline
[2] BWL denotes below normal waterline
[3] L denotes longitudinal direction
[4] T denotes transverse direction
* Minimum, each direction

Canal data:

b = 5.00 ft, d = 4.40 ft, s:s = 1.5:1, and WP = 20.86 ft.
Length = 104.25 ft.

Average seepage rate for section is 8.2 gal/d.

Seepage section has a wetted surface of (104)(20.86) = 2169 ft².

$$\text{Established seepage rate} = \frac{8.2 \text{ gal/d}}{(7.4806 \text{ gal/ft}^3)(2169 \text{ ft}^2)}$$

$$= 0.0005 \ (\text{ft}^3/\text{ft}^2)/\text{d}$$

- Reach 5A, station 599+00, PVC lined:

Canal data:

Table 19.—*Results of visual examination of PVC membrane lining samples from Bugg Lateral, Tucumcari Project, New Mexico*

Laboratory sample No.	Service life (years)	Location in canal	Sample size (m^2)	Sample size (yd^2)	Remarks
B-6763	14	Sta. 229+00, from above high waterline	0.836	1.000	Sample somewhat flexible; obtained from an area where the lining had been placed over a fairly smooth subgrade. Sample contained one large hole and one large tear. Numerous pinholes noted in two general areas.
B-6764	14	Sta. 229+00, from within water prism	0.836	1.000	Sample in good condition no defects noted; more flexible than B-6763.
B-7022	19	Sta. 232+50, from within water prism	1.016	1.215	Sample contained one large hole from protuding aggregate in subgrade, two tears, and nine pinholes.
B-7023	19	Sta. 232+50, from above high waterline	0.809	0.968	Sample not as flexible as B-7022; contained 98 pinholes and 8 tears.

b = 10.75 ft, d = 4.40 ft, s:s = 2:1, and WP = 30.43 ft.
Length = 104.25 ft.

The project reported the seepage well was pumped from August 8 through August 29, 1980, using a 5-horsepower gas engine diaphragm pump with a 3-inch discharge hose. During this time, the well could not be pumped dry due to the large volume of inflow.

To determine the reason for the high seepage noted for reach 5A, an inspection was made in March of 1981 [23]. The PVC lining was uncovered by hand labor, as shown on figure 59, and inspected at the following locations:

(a) Centerline of canal invert from station 599+50 to station 600+00.

(b) Right slope at station 599+10.

(c) Right slope at station 599+50. Before removing the earth cover, a piece of 10-mil PE sheeting was exposed about halfway up the slope.

(d) Right slope at station 600+00. Before removing the earth cover, a small area of the PVC lining was exposed at the toe of the slope.

For location (a), the PVC appeared taut and the cover material (sand/gravel) decreased in thickness from 510 mm (20 in) at station 599+50 to 178 mm (7 in) at station 600+00. The design cover depth in this reach was 380 mm (15 in). As shown on figure 60, the subgrade appeared to have heaved at this location, indicating possible seepage problems. A small area of the lining downstream at about station 600+05 was exposed.

The PVC lining at location (b) was in good condition, although taut. The cover material was stable and about 380 mm (15 in) in depth.

At location (c), a large triangular-shaped hole, about 0.26 m^2 (2.8 ft^2) in size, was found in the lining (fig. 61). This hole was probably made during the original installation, and the piece of 10-mil PE placed over it and covered in an attempt to patch the lining. Since this location is directly upslope from the outlet structure leading to the observation well, the hole was probably the primary reason for the high seepage noted in this test reach.

Table 20.—*Physical properties test results for PVC membrane linings on McCaskey Lateral. Tucumcari Project, New Mexico, installed spring 1962.*

Physical property	Specifications requirements	Sample No. B-3584 (original)	Sample No. B-7024 (18 years of service, BWL[2])	Sample No. B-7025 (18 years of service, AWL[1])
Thickness, mm (mils)	0.25 (10)	0.27 (10.6)	0.22 (8.7)	0.23 (9.0)
percent change	±10		−17.9	−15.1
Tensile strength, N/mm (lbf/in)	3.0 (17)*	4.4 (25.1) L[3] 4.1 (23.5) T[4]	5.1 (29.4) L 4.6 (26.0) T	4.5 (25.8) L 4.7 (26.9) T
percent change			+17.1 L +10.6 T	+2.8 L +14.5 T
Elongation percent	225*	330 L 365 T	185 L 180 T	163 L 214 T
percent change			−43.9 L −50.7 T	−50.6 L −41.4 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	1.9 (10.9) L 1.8 (10.0) T	4.3 (24.7) L 4.0 (22.6) T	4.0 (22.7) L 3.8 (21.5) T
percent change			+126.6 L +126.0 T	+108.3 L +115.0 T
Elmendorf Tear, grams	1500*	1830 L 2290 T	1600 L 3000 T	3000 L 2400 T
percent change			−12.6 L +31.0 T	+63.9 L +4.8 T
Impact resistance	Not more than 2 specimens out of 10 shall fail at −18 °C (0 °F)	10 tested 1 failure	Not determined	Not determined
Bonded seam strength, percent of parent material	75	Unknown	Not determined	75
Plasticizer content, percent	Not required	39.7	25.6	28.7
percent change			−35.5	−27.7

[1] AWL denotes above normal waterline
[2] BWL denotes below normal waterline
[3] L denotes longitudinal direction
[4] T denotes transverse direction
* Minimum, each direction

The lining at location (d) was taut and appeared brittle, which resulted in some shovel damage during removal of the cover material. The cover was about 200 mm (8 in) in depth. Also, slumping or deformation of the cover had occurred at the toe of the slope.

An inspection of the seepage monitoring station in Reach 4A was also made. A Grade-All (fig. 62) was used to uncover the PE lining at the following locations:

- Centerline of canal invert from station 422+05 to station 422+75.
- Centerline of canal invert from station 422+90 to station 423+10.
- Centerline of canal invert at stations 421+90 and 423+15.

Hand labor was used to uncover the right and left slopes at station 422+10.

Table 21.—*Results of visual examination of PVC membrane lining samples from McCaskey Lateral, Tucumcari Project, New Mexico*

Laboratory sample No.	Service life (years)	Location in canal	Sample size (m^2)	Sample size (yd^2)	Remarks
B-7024	18	4.9 m (16 ft) upstream of turnout 51R, from within water prism	0.790	0.945	Sample contained eight pinholes and two tears.
B-7025	18	4.9 m (16 ft) upstream of turnout 51R, from above high waterline	.70	.945	Sample contained 69 pinholes, 2 large holes, and 9 tears. Sample contained a factory seam.

Overall, the PE lining appeared to be in excellent condition. It was more elastic and did not exhibit the brittle property as noted with the PVC material. The longitudinal field seams inspected were in good condition. For the transverse field seams inspected at station 422+10, several loose areas were noted, but there was no evidence of major seepage through them, primarily due to the 0.9-m (3-ft) overlap.

The cover material on the side slopes within the monitoring station was stable and in good condition. The cover depth on the side slopes was about 760 mm (30 in) normal to the slope, which was greater than the design cover of 410 mm (16 in) for the slopes and canal invert in this reach.

Silting appears to be the major contributor to the thick cover material noted in the canal invert. The cover depth was about 1170 mm (46 in) from station 422+00 to station 423+00 and about 610 mm (24 in) both upstream and downstream from the monitoring section. Based on this condition, it appears that reach 4A is operating as a silting basin behind the check structure at station 436+00.

The plastic linings were repaired with a polyethylene/rubberized asphalt membrane material, and seepage measurements were repeated in August 1981 [24]. The results were:

Reach 4A

Over a period of 8 days of pumping and recording, the project established an average rate of 2.85 gal/min for the section.

Seepage rate for section

$$= \frac{(2.8 \text{ gal/min})(60 \text{ min})(24 \text{ h})}{7.4806 \text{ gal/ft}^3}$$

$$= 548.6 \text{ ft}^3/\text{d}$$

Wetted surface for section = 3680.16 ft^2

$$\text{Established seepage rate} = \frac{548.6 \text{ ft}^3/\text{d}}{3680.16 \text{ ft}^2}$$

$$= 0.15 \ (\text{ft}^3/\text{ft}^2)/\text{d}$$

Rate (1980) = 0.021 $(ft^3/ft^2)/d$.

Rate (1981) = 0.149 $(ft^3/ft^2)/d$.

The rate of increase could be due to damage to the lining caused during the inspection of the lining in March, which was not noted.

Reach 5A

The project reported the seepage well was pumped August 11-21, 1981, using a 65-horsepower diesel pump with a 4-inch discharge hose. Using this large pump, they established an average seepage rate of 28.8 gal/min.

Canal data:

b = 10.75 ft, d = 4.40 ft, s:s = 2:1, WP = 30.43 ft, and length = 104.25 ft.

Total wetted surface = (30.43)(104.25)

$$= 3{,}172.33 \text{ ft}^2.$$

Seepage rate for section

$$= \frac{(28.8 \text{ gal/min})(60 \text{ min})(24 \text{ h})}{7.4806 \text{ gal/ft}^3}$$

$$= 5543.9 \text{ ft}^3/\text{d}$$

$$\text{Established seepage rate} = \frac{5543.9 \text{ ft}^3/\text{d}}{3172.33 \text{ ft}^2}$$

$$= 1.75 \ (\text{ft}^3/\text{ft}^2)/\text{d}$$

This seepage rate indicates that major damage to the lining still exists and has not been observed to date.

In addition to 1981, inspections of the Amarillo Canal were made in 1979 [25] and 1980 [26], and samples were obtained for laboratory evaluation. The results of the laboratory tests, summarized in tables 22 through 25, indicate that the PE has exhibited essentially no change in its physical properties while the PVC has stiffened due to stressing and plasticizer loss.

Mirage Flats Canal, Mirage Flats Irrigation District, Nebraska

In the spring of 1968, a small test section of a newly developed polyethylene copolymer film, EVAC (ethylene vinyl acetate copolymer), was installed on the Mirage Flats Canal near Hay Springs, Nebraska [27]. The test section, about 335 m (1100 ft) in length, was installed in a sandy soil that had a history of high seepage. Laboratory tests previously conducted on the EVAC film indicated that it had physical properties between PVC and PE [1].

For this installation, the manufacturer provided 36 rolls of 10-mil EVAC, 4.9 m (16 ft) by 30 m (100 ft) long; 30 rolls of PE tape; and 95 L (25 gal) of adhesive. A plastic sheeting width of 14 m (46 ft) was required to line the canal, therefore it was necessary to splice together three 4.9-m widths of the 30-m roll.

Although this particular plastic lining is no longer being manufactured, a sample was obtained in September 1982 to determine its condition after 14 years of service [28]. The sample was obtained from the bottom of the canal at station 136. The earth cover, 350 mm (14 in) in depth, consisted primarily of a sandy material. The field reported that the performance of the lining has been very good [29]. The only problem has been in keeping the cover on the outside curves. The placement of 25-mm (1-in) size aggregate has minimized this problem. There has been no evidence of damage from deer and antelope traffic.

Laboratory test results for the retrieved sample are summarized in tables 26 and 27. Except for some discoloration, the sample appeared to be in good condition.

Farwell Unit, Middle Loup Division, Nebraska

In the spring of 1982, the Nebraska-Kansas Projects Office initiated a study in cooperation with the Loup Basin Reclamation District to determine the most cost-effective method of using plastic membrane lining for seepage control. This is one of several methods being considered for meeting increased water demands on the Farwell Unit. The plastic lining study consists of a two-phase program:

Phase 1: Full Prism Lining.–About 11 290 m² (13 500 yd²) of 20-mil PVC was installed in the Farwell Lower Main Canal between stations 26+30 and 52+60. The plastic membrane was covered with 350 mm (14 in) of excavated material (loess). No sand/gravel material was placed for erosion protection. This phase will provide data on the performance of loess as a cover material, and the effect of the plastic lining on the subsurface drainage requirements adjacent to the canal. High ground-water conditions were severely limiting corn crop production for about 76 to 91 m (250 to 300 ft) east of this reach of the canal prior to lining.

Phase 2: Bottom Lining.–About 6440 m² (7700 yd²) of 10-mil PVC was installed in the invert of the Farwell Main Canal between stations 1027+10 and 1053+40, as shown on figure 63. Excavation of the invert is shown on figure 64. The excavated material was placed on the canal berm for future use as the lining cover. There was some difficulty in getting the required depth of cut at the toe of the side slopes. The difficulty was that the side slopes had to be cut back vertically to allow the lining to be placed and covered in order to be secured into the bank.

It was planned to excavate enough material out of the bottom of the canal to allow a minimum of 410 mm (16 in) of earth cover over the lining at design grade. However, heavy and continuing spring rains prevented proper placement of the loess cover material. The cover was placed by backhoe and dragline into the canal, which had some standing water. The cover material was not spread uniformly or compacted. Random checks of the cover depth ranged from 183 mm (7.2 in) to 396 mm (15.6 in). Additional cover material will be placed before the next irrigation season.

A report was prepared by the Bureau's Nebraska-Kansas Projects Office in cooperation with the Loup Basin Reclamation District on the two installations and the results after one irrigation season [30].

For the full prism lining, the loess material performed satisfactorily as a cover material. The test reach was located in a straight section of the canal; gravel protection would be required on curves. With regard to the effect of the lining on subsurface drainage requirements, corn was again planted on the adjacent field. The crop was again affected; however, the effect was only about 15 to 23 m (50 to 75 ft) east of the canal. Possibly, with good "onfarm"

Table 22.—*Physical properties test results for PVC membrane linings on Amarillo Canal. Specifications DC-7248, installed summer 1978.*

Physical property	Specifications requirements	Typical original results	Sample No. B-6951 (0.6 year of service, BWL[2])	Sample No. B-7013 (1.8 years of service, BWL[2])	Sample No. B-7014 (1.8 years of service, AWL[1])	Sample No. B-7075 (2.7 years of service, AWL)
Thickness, mm (mils)	0.25 (10)	0.26 (10.1)	0.25 (9.7)	0.25 (9.7)	0.25 (9.8)	0.22 (8.5)
percent change	±10		−4.0	−4.0	−3.0	−15.8
Tensile strength, N/mm (lbf/in)	(24)*	5.3 (30.2) L[3]	4.5 (25.9) L	5.4 (31.1) L[3]	5.1 (29.4) L	4.1 (23.5) L
		4.6 (26.2 T[4]	3.9 (22.4) T	4.6 (26.2) T[4]	5.2 (29.6) T	4.4 (25.2) T
percent change			−14.2 L	+3.0 L	−2.6 L	−22.2 L
			−14.5 T	0 T	+1.5 T	−3.8 T
Elongation percent	250*	254 L	163 L	195 L	202 L	87 L
		270 T	165 T	220 T	206 T	57 T
percent change			−35.8 L	−23.2 L	−20.5 L	−65.7 L
			−38.9 T	−18.5 T	−23.7 T	−78.9 T
Modulus at 100 percent elongation, N/mm (lbf/in)	Not required	3.1 (17.7) L	3.7 (21.2) L	4.1 (23.2) L	3.8 (21.8) L	4.4 (25.0) L**
		2.5 (14.2) T	3.3 (18.6) T	3.3 (18.9) T	4.1 (23.4) T	4.9 (28.0) T**
percent change			+19.8 L	+31.0 L	+23.1 L	+41.2 L
			+30.9 T	+33.1 T	+64.7 T	+97.2 T
Graves Tear, N (lbf)	Not required	14.2 (3.2) L	Not determined	17.8 (4.0) L	19.1 (4.3) L	Not determined
		16.0 (3.6) T	Not determined	18.2 (4.1) T	20.0 (4.5) T	Not determined
percent change				+25.0 L	+34.3 L	
				+13.9 T	+25.0 T	
Plasticizer content, percent	Not required	30.4	27.8	26.6	24.8	23.2
percent change			−8.6	−12.5	−18.4	−23.7

[1] AWL denotes above normal waterline
[2] BWL denotes below normal waterline
[3] L denotes longitudinal direction
[4] T denotes transverse direction
* Minimum, each direction
** Estimated

Table 23.—*Physical properties test results for PE membrane linings on Amarillo Canal. Specifications No. DC-7248, installed summer 1978.*

Physical property	Specifications requirements	Typical original results	Sample No. B-7015 (1.8 years of service, BWL)	Sample No. B-7016 (1.8 years of service, AWL[1])	Sample No. B-7076 (2.7 years of service, BWL[2])
Thickness, mm (mils),	0.25 (10)	0.32 (12.6)	0.33 (12.8)	0.30 (11.9)	0.35 (13.7)
percent change			+1.6	−5.6	+8.7
Tensile strength,	3.0 (17) L	5.3 (30.2) L	4.2 (23.9) L	4.5 (25.5) L	4.2 (24.3) L
N/mm (lbf/in)	2.1 (12) T	4.5 (25.5) T	4.4 (25.1) T	3.8 (21.9) T	4.8 (27.7) T
percent change			−20.9 L	−15.6 L	−19.5 L
			−1.6 T	−14.1 T	+8.6 T
Elongation percent	225 L	510 L	340 L	485 L	410 L
	350 T	580 T	625 T	455 T	522 T
percent change			−33.3 L	−4.9 L	−19.6 L
			+7.8 T	−21.6 T	−10.0 T
Graves Tear, N (lbf)	Not required	23.1 (5.2) L	28.0 (6.3) L	27.6 (6.2) L	36.0 (8.1) L
		24.9 (5.6) T	29.8 (6.7) T	27.1 (6.1) T	30.2 (6.8) T
percent change			+21.1 L	+19.2 L	+55.8 L
			+19.6 T	+8.9 T	+21.4 T

[1] AWL denotes above normal waterline
[2] BWL denotes below normal waterline

Table 24.—*Results of visual examination of PVC membrane lining samples from Amarillo Canal, Navajo Indian Irrigation Project, New Mexico*

Laboratory sample No.	Service life (years)	Location in canal	Sample size (m^2)	Sample size (yd^2)	Remarks
B-6951	0.6	Sta. 599+00, right side below waterline	0.093	0.111	Sample contained 25 pinholes due to crushed gravel subgrade.
B-7013	1.8	Sta. 603+00, left side below waterline	.219	.262	Sample contained 3 small tears, 21 pinholes, and a factory seam.
B-7014	1.8	Sta. 603+10, left side above waterline	.186	.222	Sample contained two small tears and six pinholes.
B-7075	2.7	Sta. 600+00, right side above waterline	.097	.116	Sample somewhat stiff, and contained 45 pinholes.

Table 25.—*Results of visual examination of PE membrane lining samples from Amarillo Canal, Navajo Indian Irrigation Project, New Mexico*

Laboratory sample No.	Service life (years)	Location in canal	Sample size (m^2)	Sample size (yd^2)	Remarks
B-7105	1.8	Sta. 421+50, below waterline	0.129	0.154	Sample in good condition. No imperfections noted.
B-7016	1.8	Sta. 421+40, left side above waterline	.181	.216	Sample in good condition, one small tear, two pinholes, and two tears from shovel damage noted.
B-7076	2.7	Sta. 422+10, right side below waterline	.187	.223	Sample in good condition; three pinholes and one tear from shovel damage noted.

efficiency in irrigation, the water table adjacent to the canal may decline further.

This test reach had a total of seven observation wells that were monitored before the lining was installed, and they indicated a high water table condition all around the canal. Similarly, the water table after the lining was installed remained fairly high. However, the fluctuations of the water level in several wells followed the irrigation pattern of the adjacent field. This indicated that the local water table is controlled more by deep percolation from field irrigation than by seepage from the canal. The high 1981 water table is probably a result of the combined canal seepage and deep percolation from irrigation. Precipitation recorded at St. Paul, Nebraska, from January 1 to September 1, 1981, was 109 mm (4.29 in) below normal. For the same period in 1982, the precipitation was 54 mm (2.13 in) above normal. Despite the greater amount of precipitation, the 1982 water table shows slightly lower levels. This decline in the water table can be attributed to the reduction of seepage in the canal.

For the bottom lining phase, the primary purpose was to determine the reduction in seepage. Ponding tests were conducted before and after the lining was installed in the canal invert. The seepage was reduced from 1.98×10^{-6} to $9.5 \times 10^{-5}(m^3/m^2)/s$ [0.56 to 0.27 $(ft^3/ft^2)/d$], a reduction of 52 percent. The Project Office was encouraged by these results but believe that additional studies are needed to verify them.

SUMMARY OF FIELD STUDIES

Results of the field studies indicate that buried plastic membrane linings generally are providing satisfactory service for seepage control. Minor problems have been encountered with animal traffic damaging the protective earth cover, necessitating some repair work.

Several projects reported some problems with weed growths, which create more maintenance activities (cleaning). It appears that the linings, in combination with the earth cover, provide a receptive environment for establishing and maintaining vegetation. Damage to the linings from root penetration has been minimal. When damage has occurred, as noted on the Tucumcari Project, New Mexico, it has been in areas primarily above the waterline.

To protect the linings from animal traffic and cleaning operations, a minimum cover depth of 410 mm (16 in) is recommended. Regarding cleaning operations, several recent specifications have included a requirement for the installation of markers (steel pins) for future use in locating the lining. This should be beneficial to equipment operators involved in canal maintenance activities.

Laboratory studies and field observations indicate that some stiffening of the PVC lining has occurred with time. This stiffening or aging of PVC is caused by the loss of plasticizer, the agent used in the manufacturing of PVC to impart flexibility. With aging, there is generally a reduction in elongation, an increase in modulus at 100-percent elongation, and a decrease in resistance to impact damage at low temperatures. In regard to the latter, PVC linings are now being used more in cold climates, and often must be installed in the wintertime. Consequently, good low temperature properties are important to ensure that the lining is not damaged when unfolding and installing, and also during the placement of the protective earth cover. After the lining has been installed and in service, the requirement for good

Table 26.—*Physical properties test results for EVAC membrane linings on Mirage Flats Canal. Mirage Flats Irrigation District, Nebraska, installed spring 1968.*

Physical property	Typical original results	Sample No. B-7152 (14.3 years of service, BWL[1])
Thickness, mm (mils)	0.23 (9.2)	0.27 (10.5)
Tensile strength, N/mm (lbf/in)	4.6 (26.4) L[2] 3.8 (21.9) T[3]	3.4 (19.6) L 3.4 (19.5) T
percent change		−25.8 L −11.0 T
Elongation percent	678 L 660 T	467 L 418 T
percent change		−31.1 L −36.7 T
Modulus at 100 percent elongation, N/mm (lbf/in)	1.8 (10) L 1.6 (9) T	2.3 (13.3) L 2.4 (13.9) T
percent change		+33.0 L +54.4 T
Elmendorf Tear, grams	1670 L 1680 T	1900 L 1600 T
percent change		+13.8 L −4.8 T
Impact resistance at −18 °C (0 °F)	10 tested 0 failures	5 tested 0 failures

[1] BWL denotes below normal waterline
[2] L denotes longitudinal direction
[3] T denotes transverse direction

resistance to impact damage at low temperatures is not as critical.

The rate of aging on PVC lining is primarily dependent upon the following factors:

- *Source of PVC lining.*–Linings originally manufactured with a high plasticizer content exhibited less aging.
- *Location in canal.*–Samples obtained from within the water prism exhibited less aging than those obtained outside the prism. This is probably because the lining within the water prism is subjected to fewer wetting and drying cycles and more uniform temperature conditions.
- *Condition of subgrade.*–Samples obtained from areas where the lining had been placed over a fairly smoothy subgrade exhibited less aging than those installed over a coarser base.

Results of field studies on polyolefin-type linings such as polyethylene and ethylene vinyl acetate copolymers indicate they have excellent aging characteristics. However, additional work is needed with these materials to develop better field seaming techniques. Because of their inertness, they are very difficult to seam. If suitable methods can be developed, such materials would be good candidates for the bottom-only lining studies being conducted by the Bureau's Grand Island, Nebraska office.

LABORATORY STUDIES

General

Since plasticizer stability is very important regarding the performance of PVC linings, several laboratory studies were conducted on stability. The studies included chemical analyses to identify plasticizer content and composition, and long-term volatility tests.

Table 27.—*Results of visual examination of EVAC membrane lining sample from Mirage Flats Canal, Mirage Flats Irrigation District, Nebraska*

Laboratory sample No.	Service life (years)	Location in canal	Sample size (m^2)	Sample size (yd^2)	Remarks
B-7153	14	Sta. 136, canal bottom	0.905	1.083	Sample contained 18 pinholes and 7 tears (2 from shoveling). Some discoloration (rust stains) on bottom side.

The Bureau also recently automated and improved its hydrostatic test facility for pressure testing flexible membrane linings over various subgrades and under different operating conditions [31, 32]. This equipment was designed and built in house. Limited hydrostatic testing was conducted on samples of 20-, 30-, and 45-mil PVC from the same manufacturer to determine their puncture resistance over several different subgrade conditions.

Chemical Analyses

To determine the extractable (plasticizer) content of the retained (original) and in-service PVC membrane lining samples, the following procedure was used:

1. A preweighed sample of about 5 grams is extracted with 200 cm^3 of ethyl ether (soxhlet extraction refluxing for 18 to 20 hours).

2. The ether containing the extract is then placed in a teared beaker, and the ether is allowed to evaporate to concentrate the extractables. (Note: All of the ethyl ether is driven off during this step.) By reweighing the beaker, the percent extractables are determined.

Test results are summarized in tables 6, 9, 11, 13, 14, 16, 18, 20, and 22.

An IR (infrared spectrometry) and GC (gas chromatographic) analysis were conducted on a limited basis to identify the plasticizer. The IR analysis is used in the quality program for paints because it is a fast and relatively inexpensive technique. However, for identifying plasiticizers, the IR analysis is limited in that it only identifies what functional groups are present.

In 1981, the Bureau installed a computerized, high-resolution mass spectrometer system. This instrument was funded through the Lower Colorado Region, E&R Center, and OWR (Office of Water Research).

The operation of the mass spectrometer involves placing a sample into the instrument's ionization chamber. Once inside this chamber, the sample molecules are bombarded by electrons of a given energy and population. The collisions between the molecules and electrons result in the physical decomposition of the molecules. The decomposition products are a series of neutral, positive, and negative charged ions. These ions are called fragmentation ions, and each ion possesses a specific mass and a specific charge. The distribution or graphical representation of the fragment ions is called a fragmentation pattern or mass spectrum. The identification of an organic compound is done by examining the fragmentation pattern. This pattern is a unique fingerprint of a specific organic compound, and is dependent upon the special arrangement of the elements which form the structure of the molecule. With few exceptions, no two organic compounds have an identical fragmentation pattern.

A mass spectral analysis was conducted in 1982 on three 20-mil PVC lining samples (B-7142, B-7151, and B-7154) submitted for approval for use on the Riverton Unit in Wyoming. As discussed in the next section, 56-day volatility tests were also conducted on the three samples.

The analytical methodology used for the mass spectral analysis was:

Finely divided 1- to 4-gram samples of PVC were placed in a 250 mL screwcap centrifuge bottle and extracted overnight with 200 mL of carbon tetrachloride/methanol (2:1). This solvent system is approved by ASTM. The ASTM extraction procedures call for a soxhlet extraction technique; however, this technique was not used for the following reasons:

(1) The method used reduces the extraction time to 1 day as compared to 2 days for the soxhlet extraction.

(2) Contamination of the sample by the extraction thimble has been detected through the method blanks. The method used eliminates these contaminates.

(3) A comparison of the results between the soxhlet extraction and the bottle extraction demonstrated no difference in the amount and type of material extracted.

(4) Both methods give the same results within 1 percent.

After extraction, the extraction solvent is decanted into a K-D concentration apparatus. The solvent is then boiled away leaving behind the extractable material. This material is then weighed to determine the percent of extractable material.

After the percent extractable material has been determined, a 10-mg sample of the extract is diluted with an appropriate solvent to 10 mL. From this dilute solution, a 0.5 to 1.0-μL sample and a standard is injected into the GC/MS. The results from the GC/MS analysis indicate the type and quantity of material extracted. Table 28 lists the compounds which have been detected and identified, and the percent of the total detected.

The reconstructed gas chromatographics, hereafter referred to as the TIC (total ionization current), for the original sample B-7142 is shown on figure 65. The TIC for the aged sample of B-7142 is shown on figure 66. There were two compounds detected in each sample by the GC/MS. The peaks labeled 391 (fig. 65) and 386 (fig. 66) represent the standard which is coinjected along with the sample. The peak labeled 970 (mass spectrum, fig. 67) has been identified as diisooctyl phthalate. The peak labeled 1031 (mass spectrum, fig. 68) is an unknown at this time. This unknown component is not a typical alkylester of phthalic acid, but it is detected at the same time that dioctyl phthalate would be detected. Figure 69 is the TIC and the standard of dioctyl phthalate. Figure 70 is the mass spectrum of dioctyl phthalate and figure 71 is the mass spectrum of the diisooctyl phthalate standard and is included for comparison purposes. A comparison of the mass spectrum of the unknown (fig. 67) and the mass spectrum of dioctyl phthalate (fig. 70) indicates that the unknown in the sample is not dioctyl phthalate even though it is detected at the same time that would be expected for dioctyl phthalate. This is an excellent example of the limitations of strictly a gas chromatographic method.

The quantitation from the GC/MS is achieved by establishing the area under the various peaks and comparing these areas with the area of the standard which is coinjected. This procedure will establish how much material or the percent of total material which is detected in the sample. From the data in table 28 and a comparison of the TIC's (figs. 65 and 66), it is evident that there has been a change in the composition of the PVC material. The peak corresponding to diisooctyl phthalate in the aged material has decreased drastically in intensity when compared with the same peak in the original sample. The data indicate that the plasticizer content has decreased from 31.0 percent in the original to 10.9 percent in the aged. This weight change corresponds closely to that obtained in the volatility tests discussed in the next section.

Additional studies will be conducted to develop a data base for the mass spectral analyses which will be useful for both quality control and evaluating the aging characteristics of PVC membrane linings.

Volatility Tests

In 1979, accelerated aging tests were conducted under the joint U.S./U.S.S.R. study on "Plastic Films and Soil Stabilizers" [21] on samples of 10- and 20-mil PVC. To accomplish this aging, samples 178 by 178 mm (7 by 7 in) were placed individually on a 25-mm (1-in) layer of activated carbon in a container 356 mm (14 in) in diameter by 50 mm (2 in) high. The samples were then covered with a 25-mm thick layer of activated carbon. The containers, with lids, were then placed in a 70 °C (158 °F) oven to effect aging.

Table 28.—*Results of mass spectral chemical analysis on 20-mill PVC lining samples*

Laboratory sample No.	Plasticizer	Percent extractables (plasticizer)
B-7142 (original)	Diisooctyl phthalate Unknown	31.0
B-7142 (aged[1])	Diisooctyl phthalate Unknown	10.9
B-7151	Dioctyl phthalate	30.7
B-7154	Alphanyl phthalate	32.8

[1] 56-day volatility test

Samples were removed after 1, 7, 14, and 28 days of aging and the following data were obtained:

- Dimensional changes (length, width, thickness)
- Weight loss
- Modulus stress at 100 percent elongation (triplicate specimens)

Test results are summarized in table 29. As part of the joint studies, samples of the original and aged materials were sent to the Northern Scientific Research Institute of Hydraulic Engineering and Reclamation in Leningrad so that the dynamic shear modulus G_0 could be determined. Studies conducted by this institute indicate that the measurement of the dynamic shear modulus is a good indicator of film aging [33]. Test results, summarized in table 30, indicate the 10-mil PVC aged much faster in comparison to the 20-mil PVC.

In 1982 volatility tests, ASTM designation: D 1203, method A, "Loss of Plasticizer from Plastics (Activated Carbon Methods)," were conducted on three 20-mil PVC samples previously discussed under "Chemical Analysis."

Test results, summarized in table 31, indicate the 20-mil PVC containing the diisooctyl phthalate plasticizer, B-7142, exhibited the greatest plasticizer loss, 67.4 percent; while the PVC, B-7151, containing dioctyl phthalate as its plasticizer showed the lowest loss, 31.8 percent.

Table 29.—*Results of accelerated laboratory aging tests to determine percent change in physical properties on 10- and 20-mil PVC linings*

Days of aging	Percent weight loss		Average percent change in dimensions		Percent change in thickness		Percent increase in modulus at 100 percent elongation	
	10 mil	20 mil	10 mil	20 mil	10 mil	20 mil	10 mil	20 mil
1	1.2	1.3	−1.4	−1.0	0	0	8.7	9.8
7	4.4	3.0	−2.7	−1.8	0	0	12.0	11.2
14	11.0	6.2	−5.5	−3.3	−2.0	−1.0	30.0	24.0
28	14.6	12.2	−6.4	−5.6	−5.0	−8.3	37.2	74.9

Table 30.—*Results of accelerated laboratory aging tests to determine dynamic shear modulus for 10- and 20-mil PVC linings*

Days of aging	Thickness		G_O		Aging index[1]
	mm	(mils)	MPa	(lbf/in^2)	
0	0.23	(10)	13.8	(2 000)	1.00
1	.23	(10)	21.0	(3 040)	1.52
7	.23	(10)	52.2	(7 570)	3.78
14	.22	(10)	464.4	(67 360)	33.68
28	.21	(10)	1357.3	(196 850)	98.40
0	.49	(20)	11.0	(1 590)	1.00
1	.49	(20)	10.6	(1 540)	0.96
7	.48	(20)	13.3	(1 930)	1.21
14	.47	(20)	31.4	(4 560)	2.99
28	.47	(20)	98.3	(14 260)	8.97

[1] Aging index $= \frac{G_O \text{ (aged)}}{G_O \text{ (original)}}$, where G_O = dynamic shear modulus

The low temperature impact test, ASTM designation: D 1790, was also conducted on the three PVC samples. The current Bureau specifications requirement for this test is that no more than 5 of 10 specimens shall fail when tested at −26.1 °C (−15 °F). Samples B-7151 and B-7154 met the requirement while B-7142 did not.

Hydrostatic Testing

The equipment used for hydrostatic testing is shown on figures 72 and 73. The vessels are 610 mm (24 in) in diameter and are capable of testing lining materials over any subgrade and under variable hydrostatic or hydrodynamic loading conditions.

Samples of 20-, 30-, and 45-mil PVC were tested over the following three simulated subgrades:

1. Four plexiglass pyramids as shown on figures 74 and 75. These pyramids have equilateral bases of 100 mm (4 in) on a side, and heights of 70 mm (2.75 in). The pyramids are surrounded with sand which is varied to give different pyramid heights. For this test, a height of 25 mm (1 in) was used.

2. Five plastic pipes of varying diameters simulating interstitial voids. These pipes, 25 mm (1 in), 38 mm (1.5 in), 50 mm (2 in), 60 mm (2.38 in), and 75 mm (3 in), are shown on figure 76.

3. Gravel ranging in size from 10 mm (3/8 in) to 19 mm (3/4 in), as shown in figure 77.

The tests were performed using air over water and incrementally raising the test air pressure 6.9 kPa (1 lb/in^2) every 30 minutes. The water was maintained between 21.1 °C (70 °F) and 23.3 °C

Table 31.—*Results of volatility tests on 20-mil PVC linings. (ASTM: D 1203, method A)*

Sample No. B-7142, 31.0 percent[1]			Sample No. B-7151, 30.7 percent			Sample No. B-7154, 32.8 percent		
Days	Total weight loss, percent	Plasticizer weight loss, percent	Days	Total weight loss, percent	Plasticizer weight loss, percent	Days	Total weight loss, percent	Plasticizer weight loss, percent
1	0.37	1.19	1	0.66	2.15	1	1.02	3.11
3	1.27	4.10	3	1.01	3.29	3	1.89	5.76
7	2.78	8.97	7	1.54	5.02	7	2.65	8.08
14	4.43	14.29	14	2.10	6.84	14	4.19	12.77
28	16.09	51.90	28	4.66	15.18	28	9.96	30.37
56	20.91	67.45	56	9.76	31.79	56	14.87	45.33

[1] Plasticizer content, percent by weight

(74 °F). The test was conducted until failure of the PVC lining or to maximum line pressure if no failure occurred.

Test results are summarized in table 32. Of the three subgrades used, the one representing the void condition was the most severe. Typical failure of the PVC under this condition is shown on figure 78. For the pyramids, the PVC conformed to them as shown on figure 79, but did not fail. This conformable property of PVC has also been observed in the field, as shown on figure 80. Results of these tests indicate that newly manufactured PVC has excellent puncture-resistant properties. Additional testing is needed on aged samples to determine what changes occur to the puncture-resistant property with time.

FUTURE WORK

General

With the increased use of buried membrane linings in new construction, additional studies are needed to obtain design data associated with this work. Studies are needed to develop a data base for chemical analyses used for both quality control and evaluating the aging characteristics of flexible membrane linings. Also, studies are needed to determine the thermal behavior of polymers used in manufacturing membrane linings. In addition, studies are required to evaluate special lining applications such as exposed membrane linings, bottom-only linings, and concrete/plastic lining systems.

Design Data

Additional studies are needed to:

1. Obtain design data to establish a Manning's hydraulic roughness factor (n) for buried membrane linings.

2. Reevaluate the criteria for determining the protective earth cover depth. This depth should be based on data gathered on canal velocity, canal wetted perimeter, water surface top width, canal depth, tractive force, and capacity. Studies are needed to obtain these data from existing operating canals.

3. Research work is needed on methods to provide underdrains to protect the membrane from high ground water and provide dewatering during construction. Data are needed to determine how effective a geotextile placed over a plastic corrugated pipe would be instead of a gravel filter. Geotextiles would provide a cost savings. The location of the drains under the lining rather than on the operating road would also be a cost savings if an effective drain could be developed.

Thermal Analyses

The performance of all polymers used in the manufacturing of flexible membrane linings is influenced to some extent by temperature. For some materials (thermoplastics such as PVC), this influence can be severe. Knowledge of the thermal behavior of polymers is, therefore, essential to their proper engineering use. This is important not only in relation to end use, but in some cases may indicate the source of problems that are process related as a result of improper thermal treatment.

Although there are many methods of determining the effect of temperature, two methods of thermal analysis have become increasingly useful with the development of modern instrumentation. These two

Table 32.—*Puncture resistance test results on PVC linings*

PVC thickness, mm (mils)	Test subgrade[1]	Time to failure, min	Maximum pressure kPa	(lb/in²)	Remarks
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	1,189	286.1	(41.5)	Failed on 75-mm cylinder
0.51 (20)	Pyramids	–	503.3	(73.0)	No failure at max. line pressure
0.76 (30)	Pyramids	–	875.6	(127.0)	No failure at max. setting on pressure booster
1.14 (45)	Pyramids	–	875.6	(127.0)	No failure at max. setting on pressure booster
0.51 (20)	Gravel	–	503.3	(73.0)	No failure at max. line pressure
0.76 (30)	Gravel	2,710	675.7	(98.0)	One pinhole
1.14 (45)	Gravel	–	834.3	(121.0)	No failure at max. setting on pressure booster

[1] Test subgrades:

Cylinders: 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 heights of 25 mm (1 in).

Gravel: 9- to 19-mm (0.375- to 0.75-in) size aggregate.

NOTE: Water temperature for all tests was maintained between 21.1 °C (70 °F) to 23.3 °C (74 °F).

methods are the DSC (differential scanning calorimeter) and the TGA (thermo gravimetric analyses).

The DSC technique measures heat flow to a sample as it is heated at a controlled rate. By obtaining a continuous record over a wide temperature range of the caloric input rate required to maintain a constant rate of temperature increase, one can learn useful information about polymers from their melting temperatures and their glass transition (brittle or "freezing") temperatures. Limited studies conducted by Soviet and American investigators have shown a relationship between the glass transition temperature and plasticizer content of PVC material [34].

In addition, the DSC technique can help characterize polymers with regard to thermal stability, decomposition kinetics, effectiveness of plasticizers and

stabilizers, as well as determining composition of blends, degree of cure, and effectiveness of catalysts. Bureau use, to date, has been primarily to characterize end use limitations of elastomeric coatings as related to brittle temperature changes during accelerated aging. Preliminary studies indicate that a similar approach may provide useful information in regard to plasticized flexible membrane linings. It is also planned to use the DSC in the identification of PE density purity versus blends and in combination with other tests as a means of rapid identification for quality control of polymeric construction materials.

The basic use of TGA is for the thermal separation and characterization of components in a heterogenous product. Measurement of weight losses under different heating rates and different gaseous atmospheres can aid in the identification of the individual components of membrane linings and polymer products.

In combination with the information gained from the DSC analysis, the knowledge of oxidizability and thermal stability of components such as the basic polymer, low molecular weight polymer additives, plasticizers, and oil extenders should be useful in selecting proper materials for a given use, expediting quality control, and solving problems which may occur in use.

Exposed Flexible Membrane Linings

In FY 1982, a study was initiated to evaluate the possible use of exposed flexible membranes as alternates to concrete and buried plastic linings in the Bureau's irrigation canal lining work. Potential lining candidates include RCSPE (reinforced chlorosulfunated polyethylene), CPER (reinforced chlorinated polyethylene), EPDM (ethylene propylene diene monomer), butyl, and HDPE (high density polyethylene).

The potential advantages of using exposed membrane linings particularly in comparison to buried plastic linings include:

- Canal side slopes can be increased to 1.5:1 or even 1:1 with subsequent cost savings in reduced excavation and right-of-way.
- Elimination of the need for protective earth cover on the canal side slopes.
- Undetected damage to a membrane lining is minimized.
- Replacement of lining, if required, is easier.

Disadvantages and potential problem areas are always present with any new system and should be studied thoroughly. Exposed membrane linings (side slopes only) can be subjected to the following adverse conditions:

- Wind and water forces
- Possibility of vandalism
- Possibility of animal damage
- Minor ultraviolet surface degradation over time
- Abrasion

Three field sites representing different climatic conditions have been selected for the initial studies:

Imperial Valley Irrigation District, California

Four different lining materials (36-mil RCSPE, 36-mil CPER, 36-mil EPDM, and 30-mil HDPE alloy) were installed in Whisteria Lateral 6 in August 1982 [35]. The linings were installed for the dual purpose of studying the shading effects on Hydrilla weed control [36] and to study the concept of using exposed flexible membrane linings in the hot southwestern part of the United States. Mechanical and physical property tests have been completed on samples of the lining installed for future reference as to longevity and subsequent property changes.

Courtland Unit, Bostwick Division, Kansas

In May 1983, a 244-m (800-ft) long test section of 30-mil HDPE was installed in the Whiterock Extension Canal near Mankato, Kansas (figs. 81, 82, and 83) [37]. This canal is unlined and has experienced some embankment failures near milepost 12.5, which is in sandy soil. Equipment and labor were furnished by the Bostwick Irrigation District. As with the Imperial Valley installation, lining materials were furnished without cost from the manufacturers.

Uncompahgre Project, Colorado

Plans are proceeding for an extensive canal and lateral lining program on the Uncompahgre Project near Montrose, Colorado. The Uncompahgre Valley Water Users Association agreed to provide labor and equipment for a test installation in the fall of 1983. The proposed study section is on the M&D Canal and would involve installing a 152-m- (500-ft-) long test section of 36-mil EPDM furnished at no cost by the manufacturer.

The three study sites will be monitored for several irrigation seasons to determine any unusual problems encountered in the operation and maintenance of the canals. A report will be prepared at the completion of the monitoring period.

Bottom Lining

Additional studies will be conducted to verify initial test results obtained on the Farwell Unit, Nebraska, and to:

1. Establish guidelines for amount of seepage reducion that can be expected using this lining method including a cost/benefit ratio.

2. Establish a Manning's hydraulic roughness factor (n) for bottom-only linings.

3. Determine the best method for keying the membrane into the canal banks for optimum seepage reduction.

4. Develop methods for installing the membrane and placing the earth cover in one operation.

5. Develop methods of monitoring seepage appropriate to this type of system.

6. Determine performance of noncohesive soil as a bottom-only cover.

7. Evaluate the possible use of less costly plastic materials such as PE or LLDPE (linear low density polyethylene) which could result in additional cost savings.

Three test sites have been identified by the Nebraska-Kansas Project office in Grand Island, Nebraska, for additional testing [38]. The three selected sites in order of priority are:

1. Franklin Canal on the Nebraska-Bostwick Project, 6.5 m^3/s (230 ft^3/s), 4.3-m (14-ft) base width, sandy soils.

2. Upper Meeker Canal on the Frenchman-Cambridge Division, 8.0 m^3/s (284 ft^3/s), 4.9-m (16-ft) base width, sandy soils.

3. Sargent Canal or Farwell Main Canal, Loup Basin Reclamation Districts, both silty soils.

The Sargent Canal is being considered as the third site to test the effectiveness of bottom lining on smaller canals. This canal has a capacity of 3.7 m^3/s (130 ft^3/s) and a base width of 3.4 m (11 ft). The proposed site on the Farwell Main Canal is adjacent to the first test site, and would provide a means of verifying the initial results.

Installation of the 10-mil PVC bottom lining was scheduled for late 1983. Ponding tests will be conducted before and after installation to determine the amount of seepage reduction.

Concrete/Membrane System

A joint meeting was held January 29, 1980, with the U.S./U.S.S.R. Construction Methodology Team to discuss the placement of a concrete/membrane system [39]. The discussions indicated interest by both teams. An important result from the discussions was that the R. A. Hansen Co. is developing machinery for placement and related technology. The two teams developed the following advantages and disadvantages of a concrete/membrane system:

Advantages

1. The method of placing concrete over plastic would avoid overexcavation in expansive shales or clays, gypsiferous soils, and loessial soils.

2. For contact with high-sulfate soils, a concrete/membrane system provides protection instead of using expensive type V cement.

3. The system can be used when positive seepage control is required such as in drains that carry water with a high salinity.

4. If this technology is developed now, future crash programs can be avoided.

5. A concrete/membrane system would eliminate the use of PVC joints that are now a requirement when using an unreinforced concrete lining.

6. This system would avoid the need of sealing extensive random cracks in unreinforced concrete linings.

7. The concrete/membrane system could have applications to other related technology, e.g., soil/membrane linings.

Disadvantages and Problems

1. The concrete/membrane system may not be economically feasible.

2. The system's short-term use in the United States may be limited.

3. Long-term life performance is needed.

4. The system should have good material membrane specifications for long-term use.

5. Condensation under the membrane lining may cause slippage.

6. In the past, it was noted that stability of concrete on plastic during construction is poor.

7. An installation method is needed to reduce or eliminate back pressure during canal drawdown.

8. A procedure to install underdrains is required.

The Construction Methodology Team studies on the "U.S./U.S.S.R. Joint Working Group on Construction of Large Canals" involved a concrete/membrane system which is now in the preliminary stages.

Other Studies

Alberta Environment, an agency of the Alberta Government, is presently involved in an extensive irrigation canal rehabilitation program near Lethbridge. One of the major components of this rehabilitation program is the control of seepage losses from the canal system. To date, a detailed assessment of the various methods of seepage control available has led them to the conclusion that for their specific performance requirements, the installation of a buried membrane liner is generally the most feasible method of controlling seepage. As a result, the agency plans to install about 2 million square meters (2.4 million square yards) of linings within the next few years. For the initial work, 20-mil PVC is being specified.

Because of the climatic conditions to be encountered, Alberta Environment is conducting a significant amount of research in assessing the cold temperature performance characteristics of PVC materials. For this research work, a DSC will be used.

The Bureau plans to monitor both the construction and research activities being conducted by Alberta Environment because of their possible application to Bureau membrane lining work.

The Bureau has been working with the National Sanitation Foundation since 1978 on developing material standards for flexible membrane linings used in various containment systems including irrigation canals. If approved, the standards will be published in late 1983 or early 1984. The Bureau plans to incorporate these standards into its seepage control work.

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[34] *Change in Structural Properties of Polyvinyl Chloride with Combined Introduction of a Filler and a Plasticizer*, U.S.S.R. Report, Jelgava, Latvia S.S.R., translated from the Russian, Bureau of Reclamation translation book No. 7087 (G-21), 1980.

[35] Frobel, R. K., "Technical Assistance for Special Test Section Installation of a Flexible Membrane Liner for Hydrilla Weed Control," Imperial Valley Irrigation District, California, Travel Report, Bureau of Reclamation, Denver, Colo., Sept. 1, 1982.

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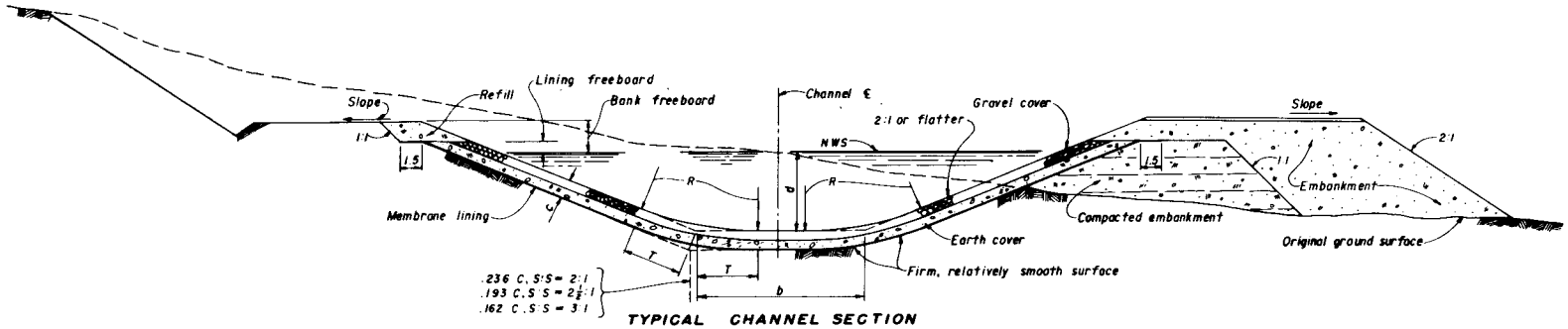
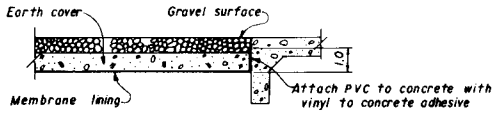
[38] "Transmittal of Lining Research – Proposal – Bottom Vinyl Lining," memorandum dated Apr. 25, 1983, from Project Manager, Grand Island, Nebr., to Regional Director, Denver, Colo.

[39] Reckner, F. V., L. O. Timblin, Jr., et al., "U.S./U.S.S.R.Joint Studies on Plastic Films and Soil Stabilizers," Interim Report, vol. 1, *Executive Summary*, Dec. 18, 1982.

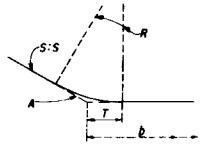


TYPICAL CHANNEL SECTION

$C = 10'' \pm \frac{d}{12}$, where C is in inches and d the water depth is in inches.



DETAIL OF MEMBRANE BONDING TO CONCRETE



b	T	S:S = 2:1, R = 4.23608 T, ΔWP = .00880 R, A = .00425 R²			S:S = 2½:1, R = 5.19259 T, ΔWP = .00466 R, A = .00233 R²			S:S = 3:1, R = 6.16226 T, ΔWP = .00290 R, A = .00140 R²		
		R	2ΔWP	2A	R	2ΔWP	2A	R	2ΔWP	2A
2	1.0	4.24	.07	.15	5.19	.05	.13	6.16	.03	.11
3	1.0	4.24	.07	.15	5.19	.05	.13	6.16	.03	.11
4	1.0	4.24	.07	.15	5.19	.05	.13	6.16	.03	.11
5	1.5	6.35	.11	.34	7.79	.07	.28	9.24	.05	.24
6	2.0	8.47	.14	.61	10.39	.10	.50	12.32	.07	.42
8	2.8	11.86	.20	1.20	14.54	.14	.99	17.25	.10	.83
10	3.5	14.83	.25	1.87	18.17	.17	1.54	21.57	.12	1.30
12	4.3	18.22	.31	2.82	22.33	.21	2.32	26.50	.15	1.97
14	5.0	21.18	.36	3.81	25.96	.24	3.14	30.81	.17	2.66
16	5.5	23.30	.40	4.61	28.56	.27	3.80	33.89	.19	3.22
18	6.0	25.42	.43	5.49	31.16	.29	4.52	36.97	.21	3.83
20	6.5	27.53	.47	6.44	33.75	.31	5.31	40.05	.22	4.49
22	7.0	29.65	.50	7.47	36.35	.34	6.16	43.14	.24	5.21
24	7.5	31.77	.54	8.58	38.94	.36	7.07	46.22	.26	5.98
26	7.9	33.47	.57	9.52	41.02	.38	7.84	48.68	.27	6.64
28	8.3	35.16	.60	10.51	43.10	.40	8.66	51.15	.29	7.33
30	8.7	36.85	.63	11.54	45.18	.42	9.51	53.61	.30	8.05
35	9.5	40.24	.68	13.76	49.33	.46	11.34	58.54	.33	9.60
40	10.5	44.48	.76	16.82	54.52	.51	13.85	64.70	.36	11.72
45	11.2	47.44	.81	19.13	58.16	.54	15.76	69.02	.39	13.34
50	12.0	50.83	.86	21.96	62.31	.58	18.09	73.95	.41	15.31

DETAILS OF BURIED MEMBRANE LININGS

NOTES

The gradation, type and thickness of the cover material is dependent on tractive forces and velocities in the section, and the type of material available in the area.

Δ Wp is the difference between 2T and the arc length. To obtain the wetted perimeter for a section, subtract 2ΔWp from the wetted perimeter for a trapezoidal section of width b.

A is the area of the fillet. To obtain the area for a section, subtract 2A from the area of a trapezoidal section of width b.

Figure 1.–Typical buried membrane lining section.

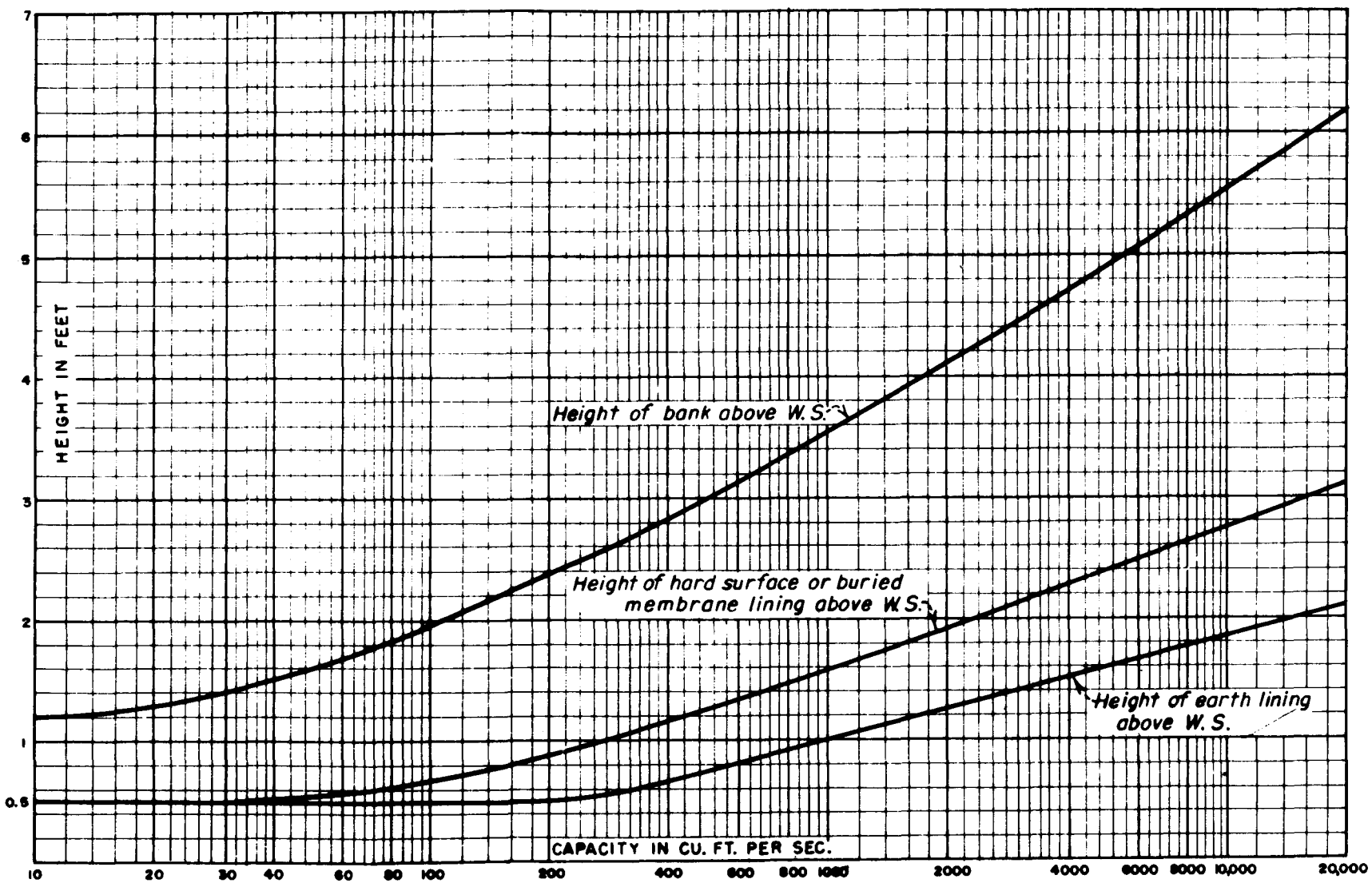
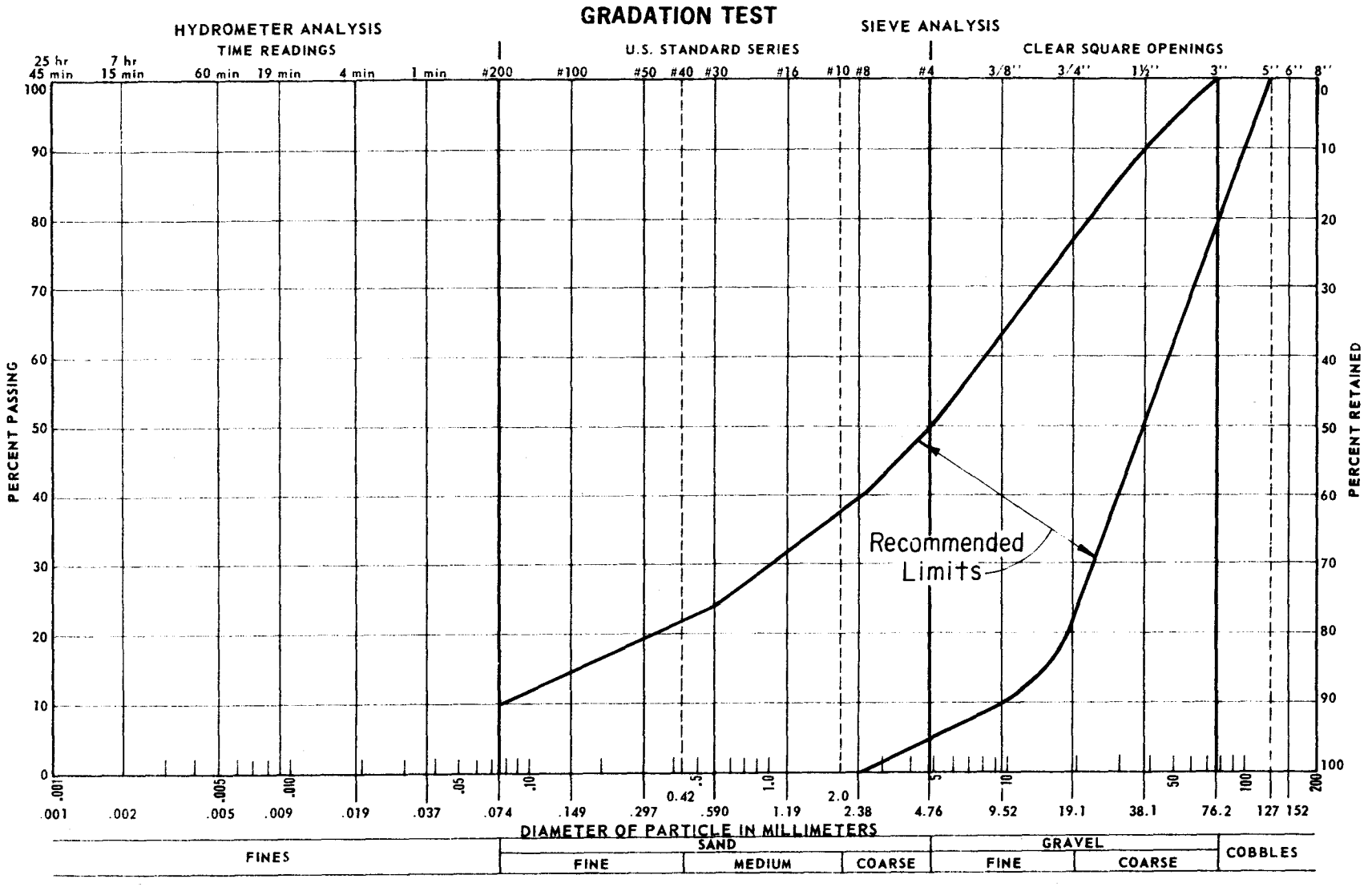


Figure 2.–Bank heights for canals; and freeboard for hard surface, buried membrane, and earth linings.



CLASSIFICATION SYMBOL _____

Gravel _____ %

Sand _____ %

Fines _____ %

ATTERBERG LIMITS

Liquid Limit _____ %

Plasticity Index _____ %

Shrinkage Limit _____ %

SPECIFIC GRAVITY

Minus No. 4 _____

Plus No. 4

Bulk _____ Apparent _____

NOTES _____

SAMPLE NO. _____ HOLE NO. _____ DEPTH _____ ft (_____ m)

Figure 3.–Sand and gravel cover gradation.

Figure 4.–Backhoe excavation on Pilot Canal, Riverton Unit, Wyoming. Contractor had to remove 0.9m (3 ft) of silt during excavation. Photo P801-D-80391

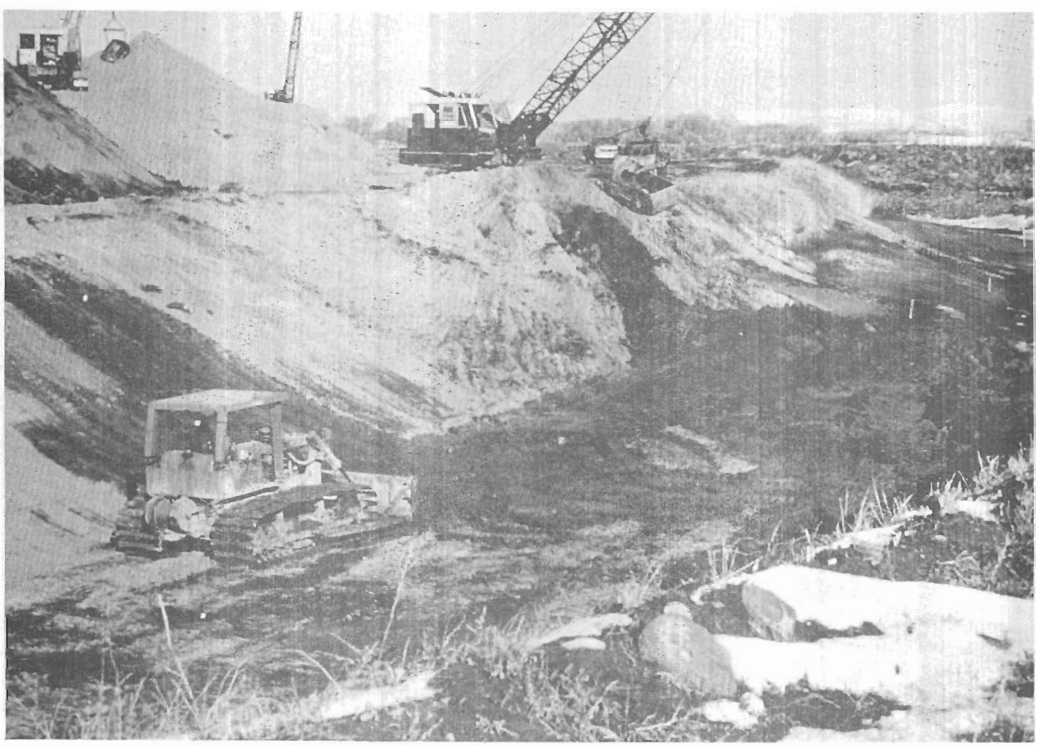


Figure 5.–Dragline excavation on Wyoming Canal, Riverton Unit, Wyoming. Photo P801-D-80392

Figure 6.–Dragging canal subgrade with chain from tractor-track in preparation for PVC lining on Lower Main Canal, Farwell Unit, Nebraska. Photo P801-D-80393

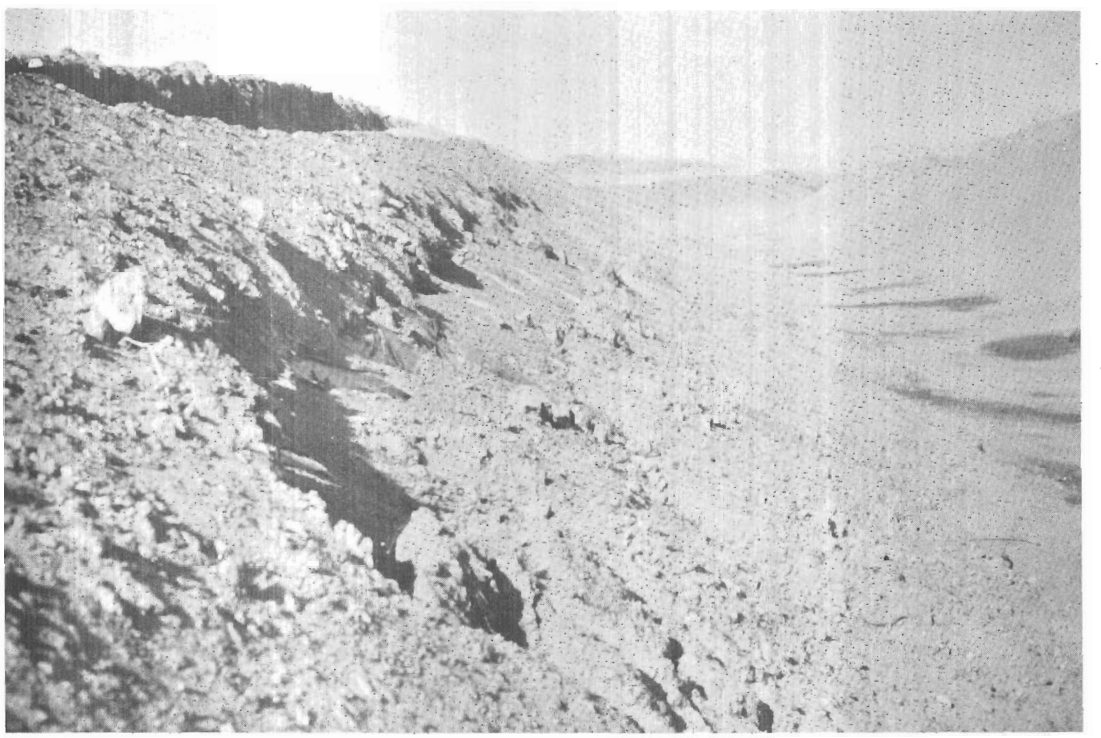


Figure 7.–Slippage of PVC membrane lining on Pilot Canal. Station 610+00 to station 612+00, February 1977. Photo P801-D-79547

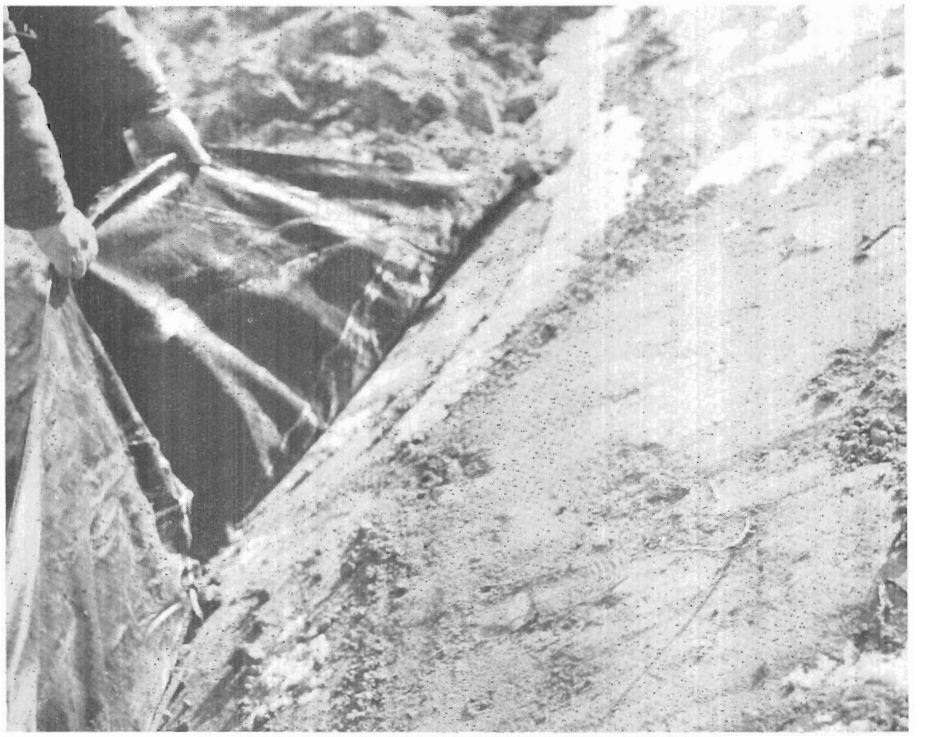


Figure 8.–Closeup view of cover slippage on Pilot Canal. Note frost accumulation under PVC lining. Photo P801-D-80394

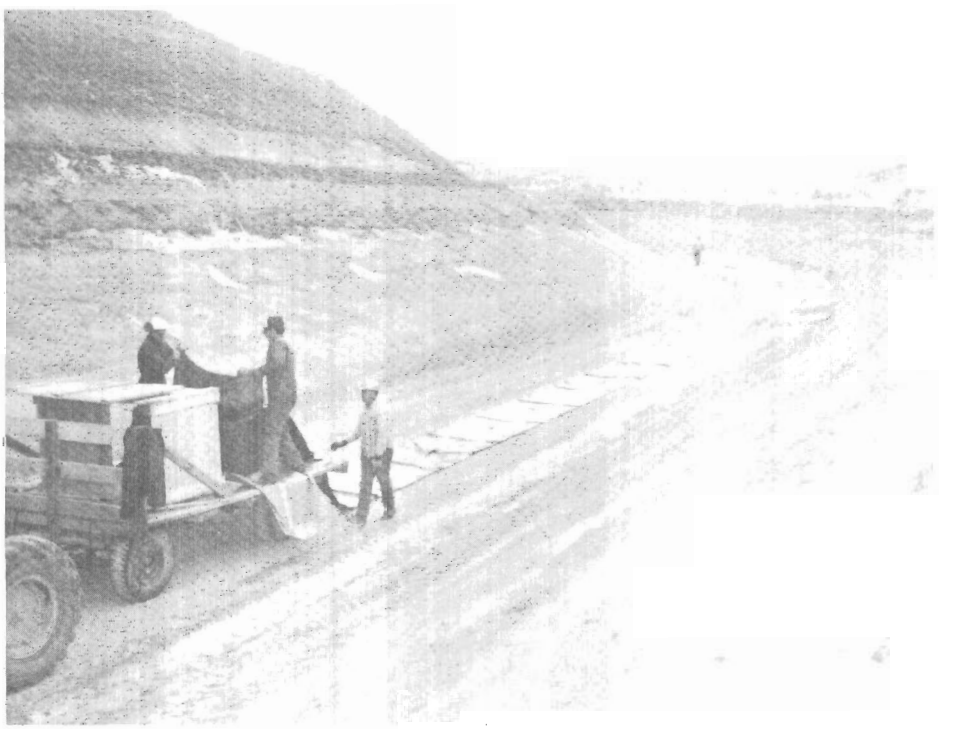


Figure 9.–View of PVC lining as delivered to job site. Lining is packaged accordion-folded in both directions, and is then simply unfolded and pulled into place. Photo P801-D-80395

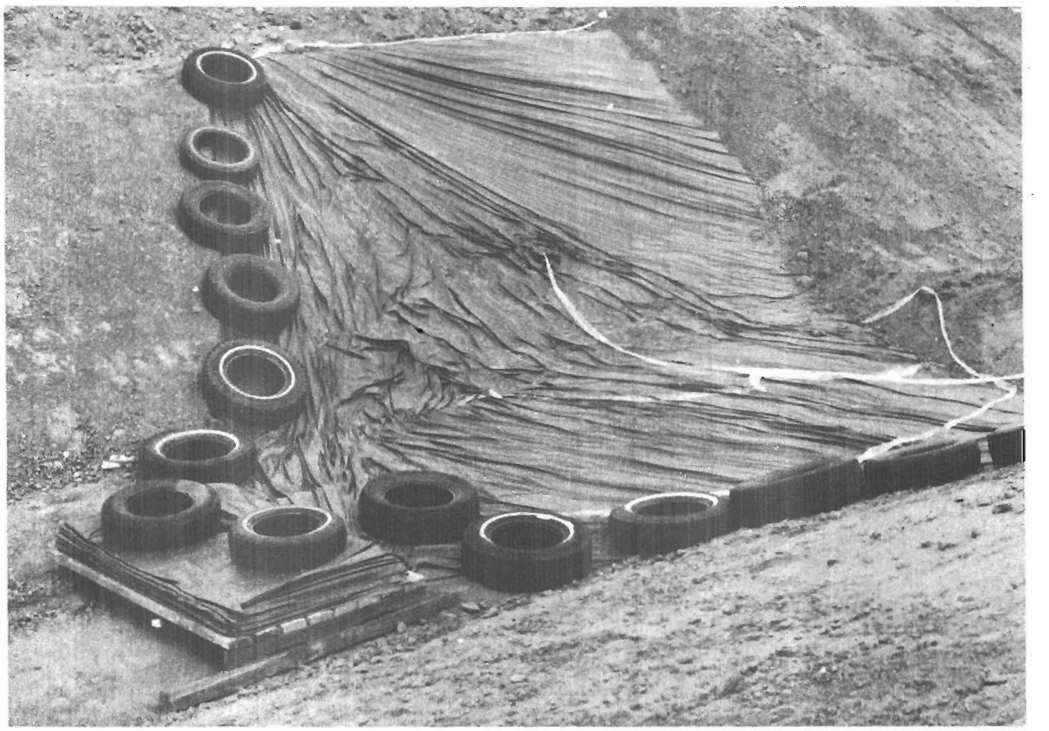


Figure 10.–View of Contractor's method of installing 10-mil PVC on Amarillo Canal, Navajo Indian Irrigation Project, New Mexico. Lining was delivered to jobsite accordion-folded and on pallets. The rubber tires are used to temporarily anchor the lining until earth cover is placed. Photo P801-D-80396

Figure 11.–Unfolding PVC lining. Photo P801-D-80397

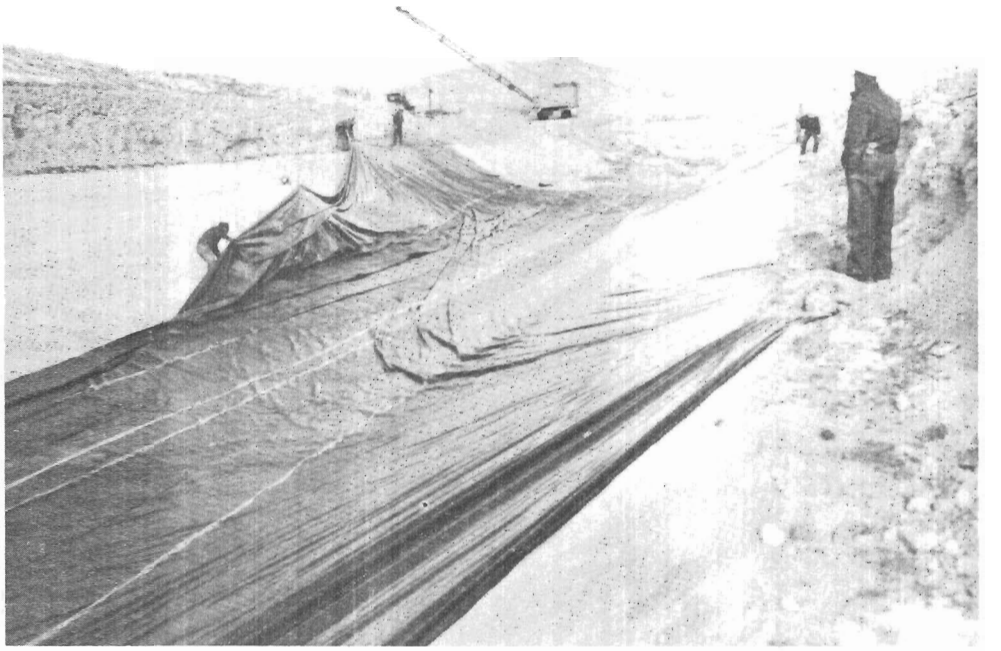


Figure 12.–Pulling PVC lining into place on side slopes. Photo P801-D-80398

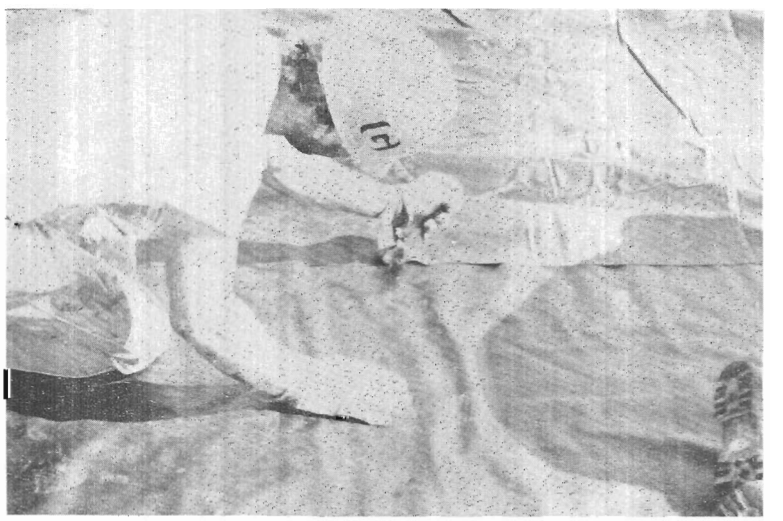


Figure 13.–Hand rolling seam on lining after application of solvent adhesive. Rolling progressing from left to right in photograph. Photo P801-D-79745

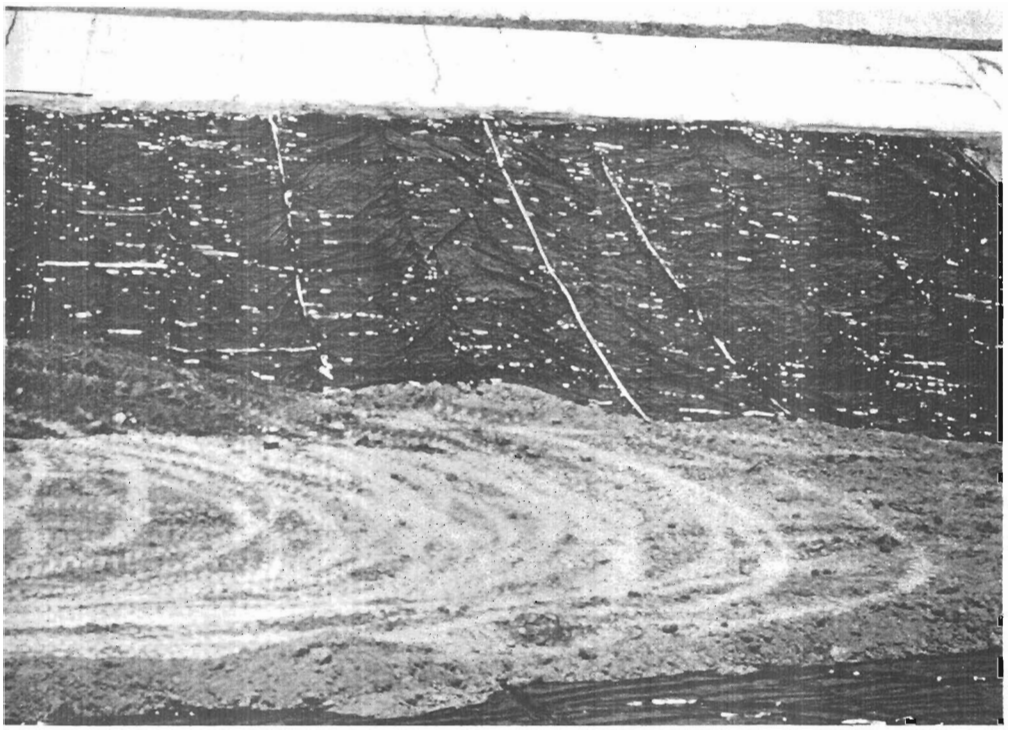


Figure 14.–View of Kakhovka Canal, Kakhovka Project, Ukraine (S.S.R.). View shows 0.9 m (3 ft) of soil being placed over two 8-mil sheets of PE lining. The plastic sheets, about 8 m (25 ft) wide, were installed transversely. Note concrete slabs placed at waterline for wave protection. Photo P801-D-80399

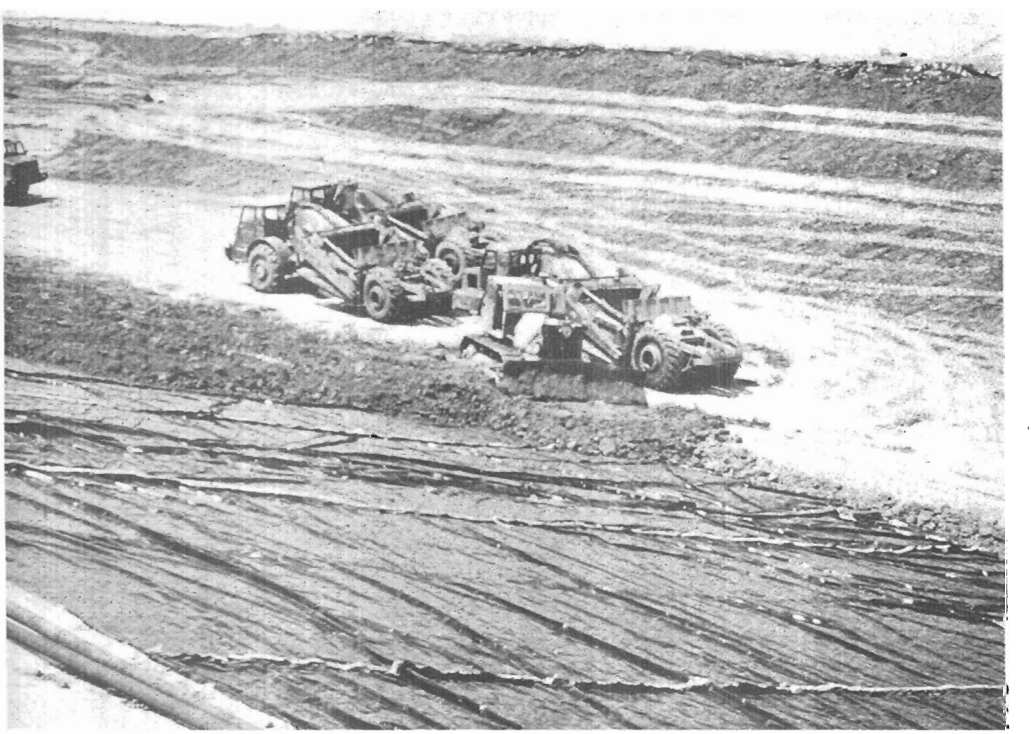


Figure 15.–Equipment placing soil cover in Kakhovka Canal. Note heat-sealed joints on PE lining. Photo P801-D-80400

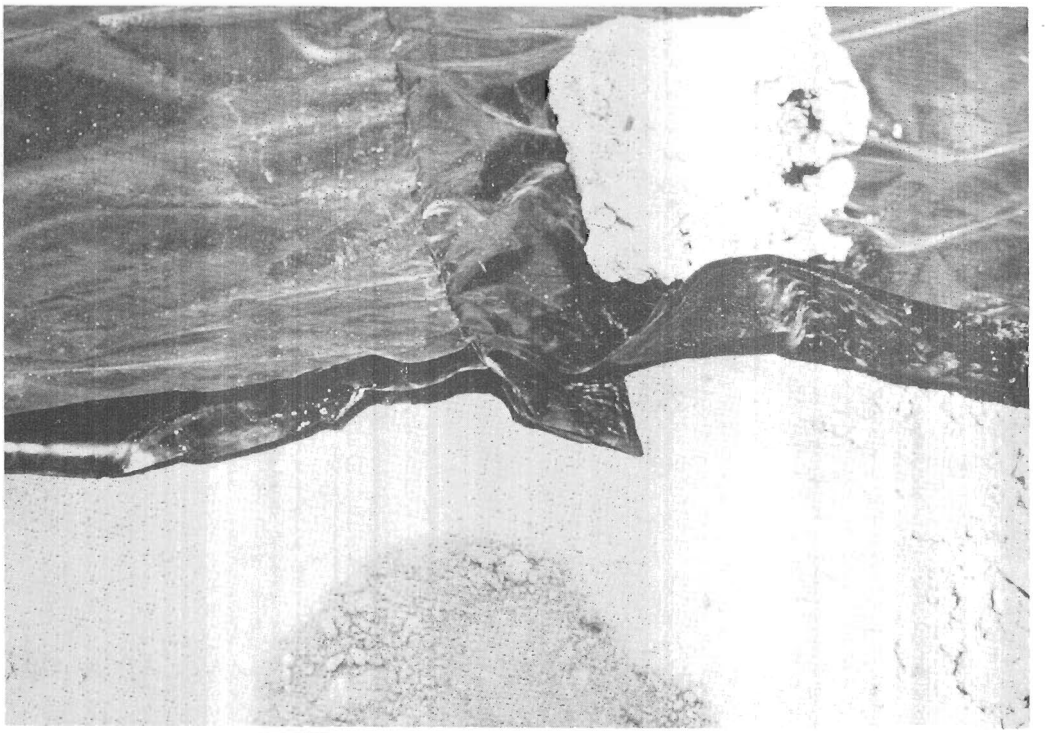


Figure 16.–Close-up view of heat-sealed joint on PE lining. Note the two 8-mil sheets. Photo P801-D-80401

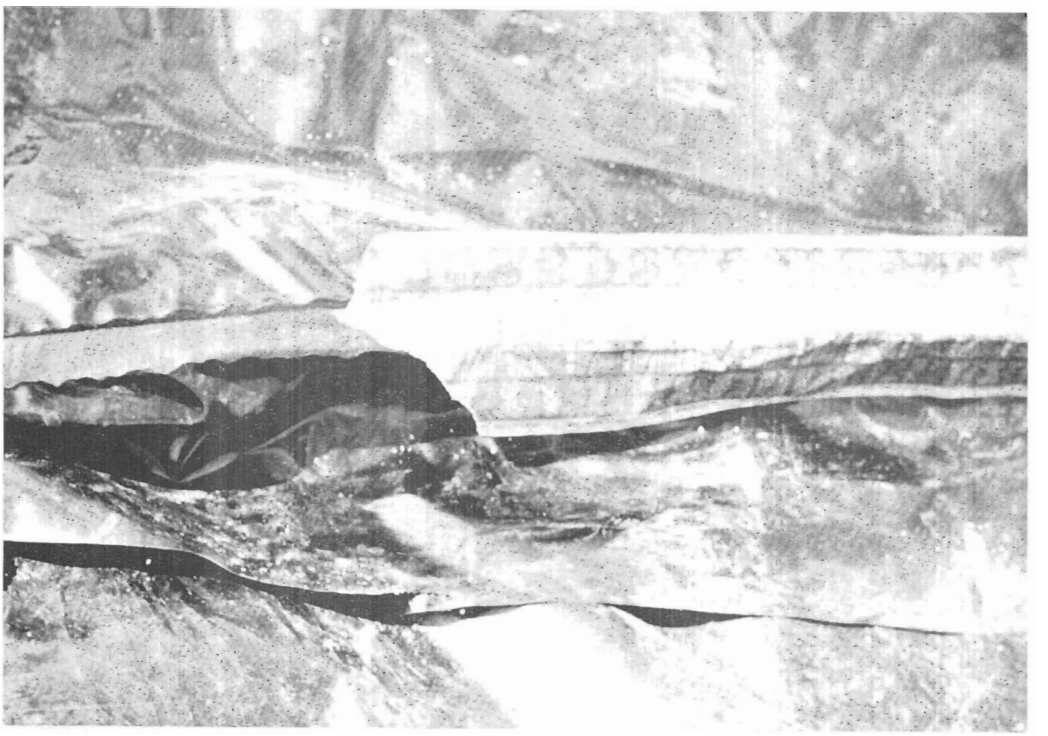


Figure 17.–View of waxed paper used to protect PE lining during heat-sealing operation. Paper prevents heat-sealing iron from sticking to plastic. Photo P801-D-80402

Figure 18.–View of 460-mm (18-in) wide anchor berm for securing PVC lining at top of slope. The horizontal berm is backfilled to hold lining in place. Photo P801-D-80403

Figure 19.–View of wind picking up lightweight PVC lining. Photo P801-D-80404

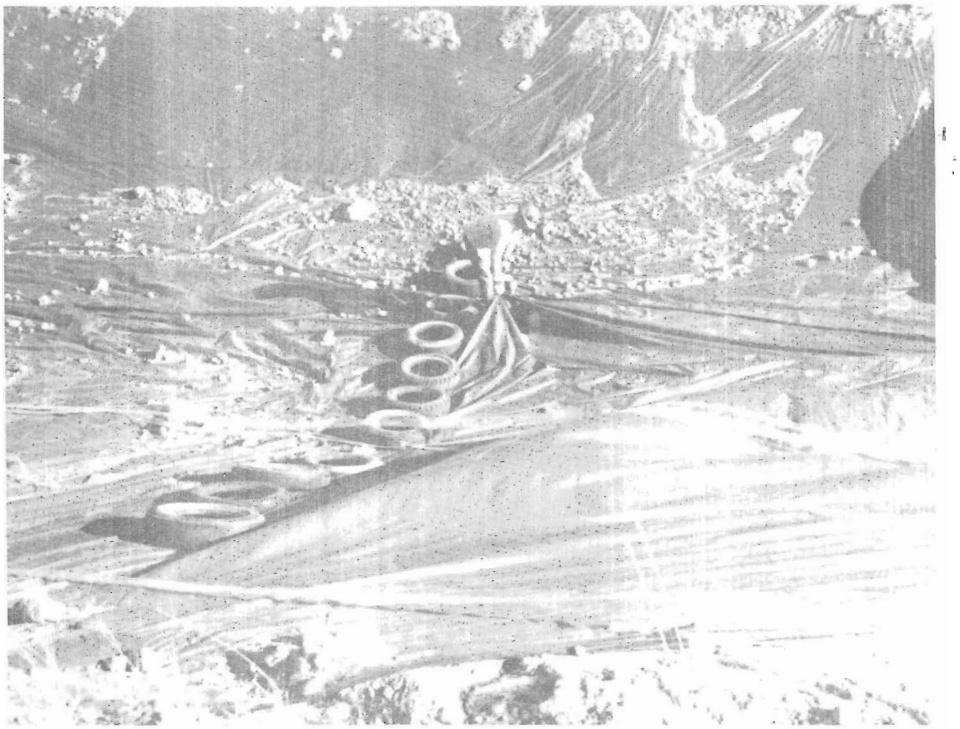


Figure 20.–Use of rubber tires to temporarily anchor lining until earth cover material is placed. Photo P801-D-80405

Figure 21.–View showing placement of plastic lining in a slack condition in the canal. The weight of the earth cover will not cause severe stressing in the lining when using this method. Photo P801-D-80406

Figure 22.–Placement of earth cover material using dragline. The material should not be dropped from heights greater than 0.9 m (3 ft). Photo P801-D-80407

Figure 23.–Spreading cover material on side slopes. Contractor has welded steel plate to bucket. Photo P801-D-80408

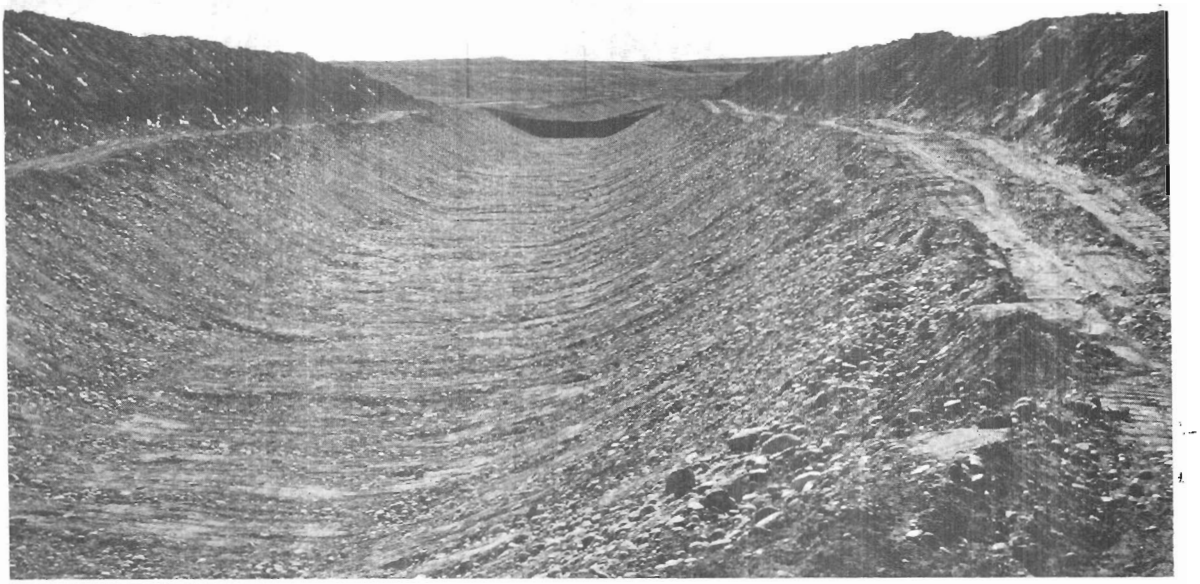


Figure 24.–View of completed canal section with buried membrane lining. Photo P801-D-80409

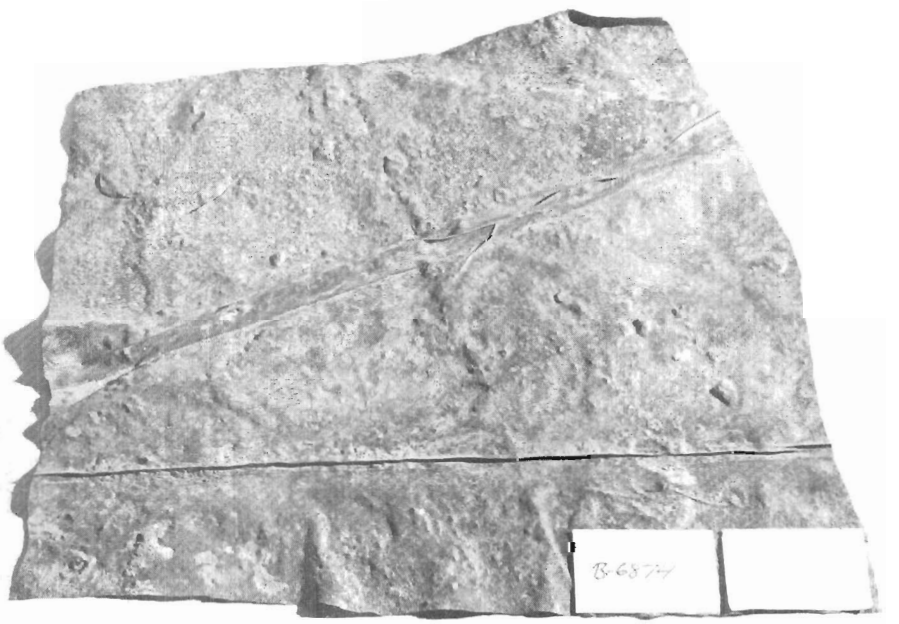


Figure 25.–View of PVC lining sample from Helena Valley Canal. The lining, from station 1330+60 and about 9 years old, was installed in the fall and winter 1968-69, under specifications 604C-72. A light test conducted on the sample, which is about 760 by 760 mm (30 by 30 in), revealed 17 pinholes. There also were two small tears from contact with protruding subgrade aggregate. Photo P801-D-80410

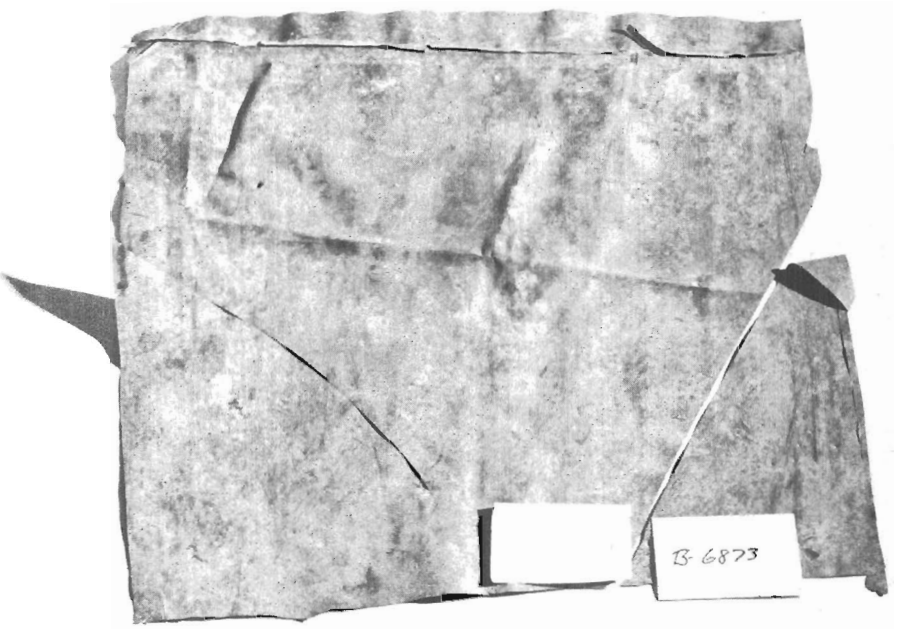


Figure 26.–View of PVC lining sample from East Bench Canal. The lining, from station 906+15 and about 8 years old, was installed in the fall and winter 1969-70, under specifications 604C-77. The two diagonal tears occurred during sampling. A light test conducted on the sample, about 760 by 760 mm (30 by 30 in), revealed 28 pinholes. Photo P801-D-80411

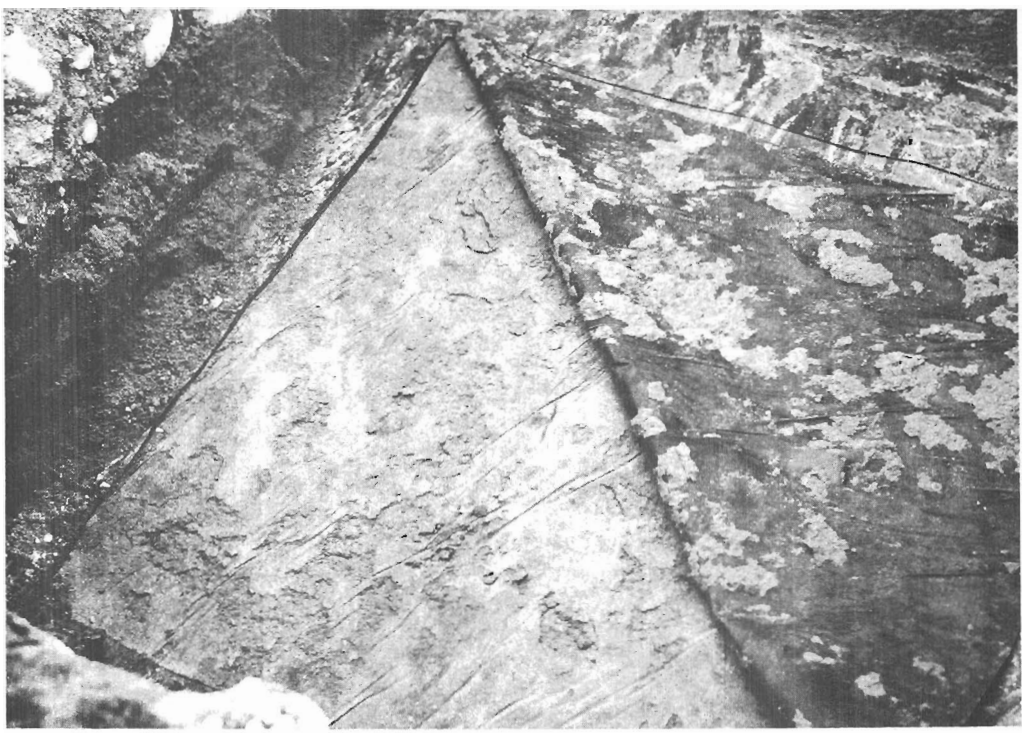


Figure 27.–View showing condition of subgrade and PVC lining on slope below waterline. Station 482+50, Wyoming Canal, Riverton Unit, Wyoming. Photo P801-D-80412

Figure 28.–View of PVC lining on slope above waterline. Depth of cover at this location, station 482+50, was 300 mm (12 in) of earth material and 330 mm (13 in) of sand and gravel, Wyoming Canal, Riverton Unit, Wyoming. Photo P801-D-80413

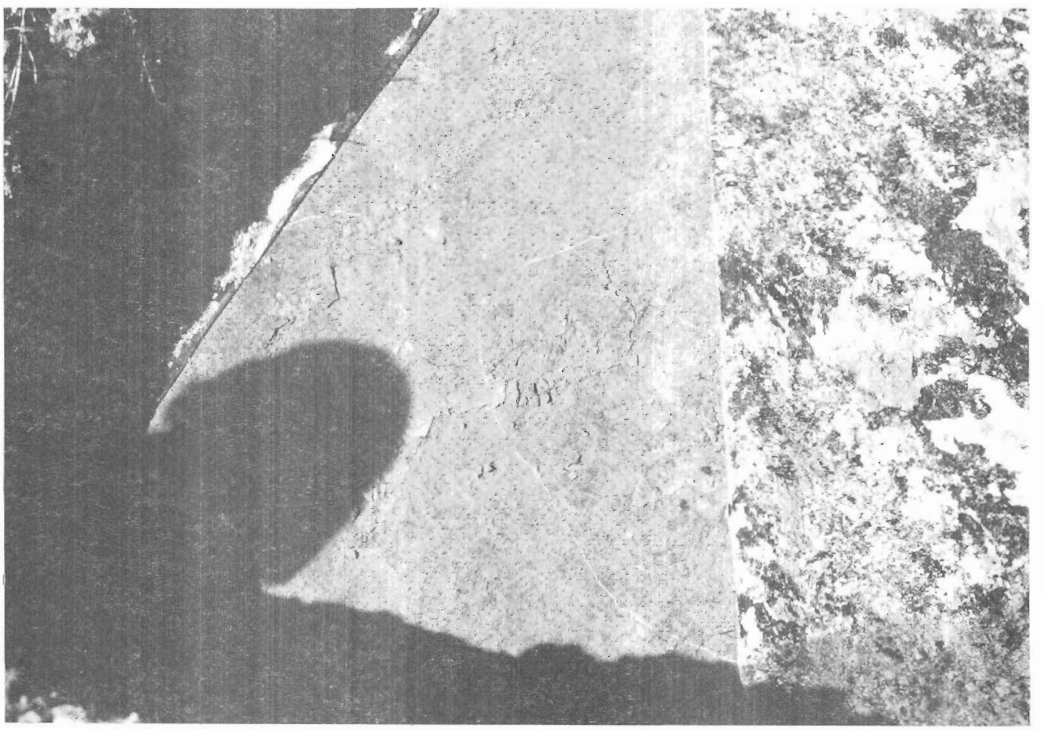
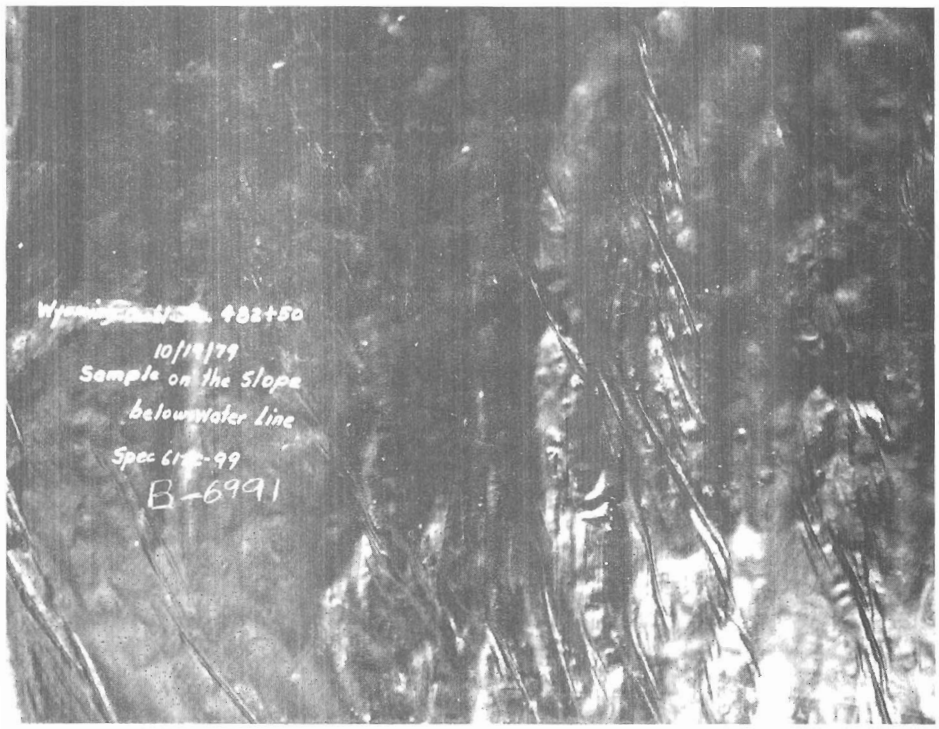
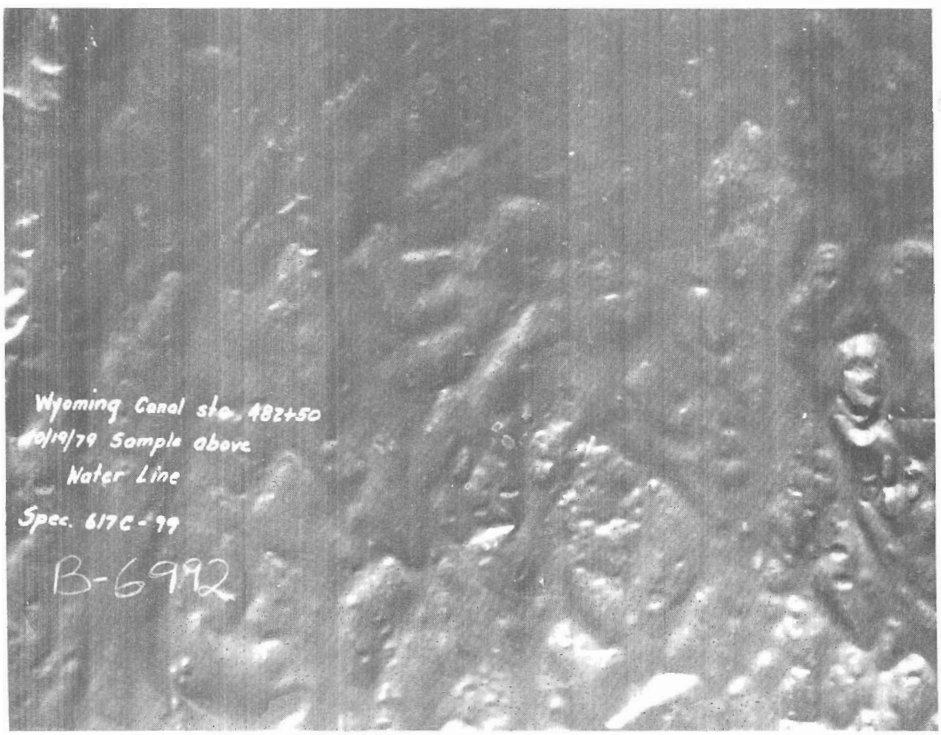


Figure 29.–View showing condition of subgrade and PVC lining on slope above waterline. Station 482+50, Wyoming Canal, Riverton Unit, Wyoming. Photo P801-D-80414



a. Sample B-6991. Photo P801-D-80415



b. Sample B-6992. Photo P801-D-80416

Figure 30.–Condition of 4-year old PVC samples from Wyoming Canal, Riverton Unit, Wyoming.

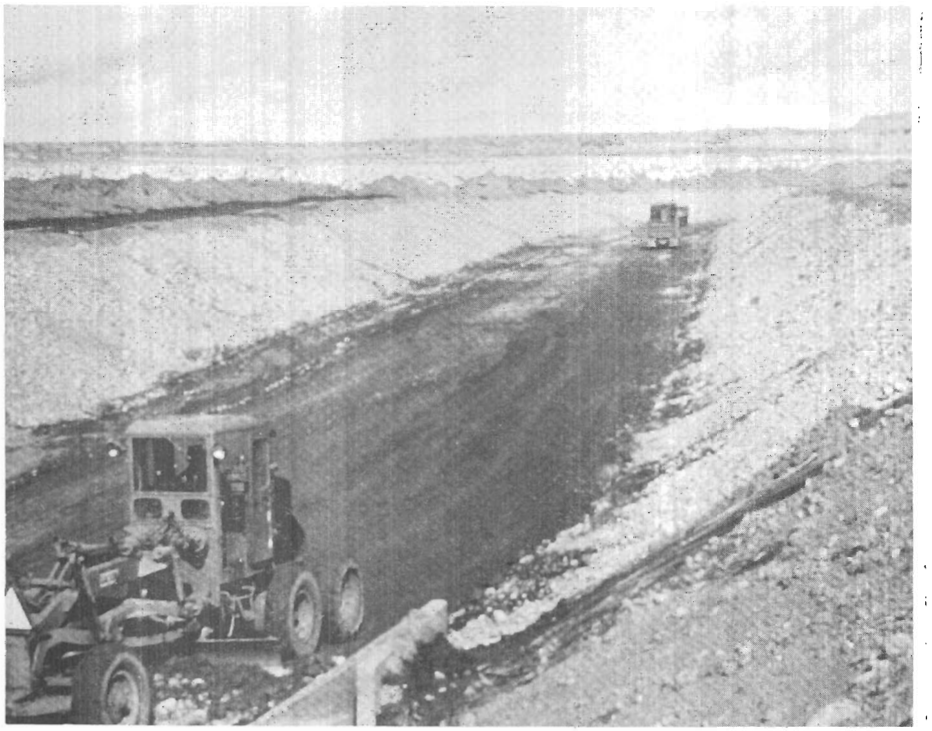


Figure 31.–Placement of cover material in bottom of Wyoming Canal, Riverton Unit, Wyoming. Photo P801-D-80417

Figure 32.–View of PVC lining on slope above waterline, Lateral GM96, station 150+00, Sun River Project, Montana. Photo P801-D-80418

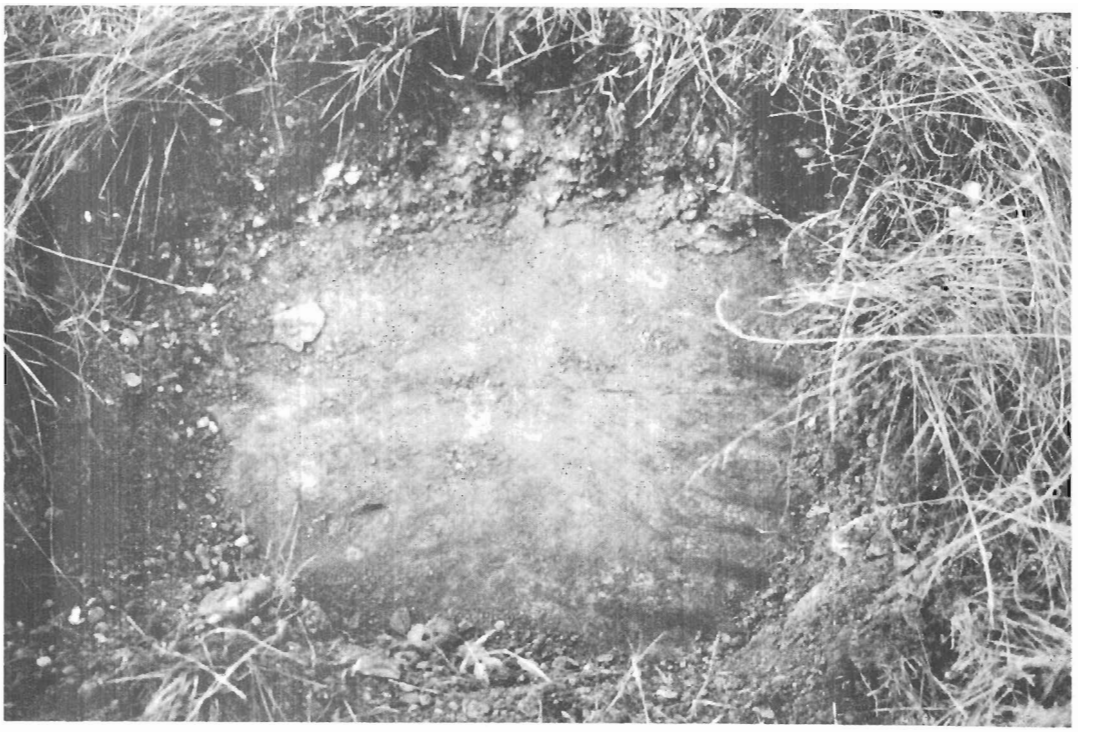


Figure 33.–Closeup view of PVC lining on slope above waterline, Lateral GM96, station 150+00, Sun River Project, Montana. Photo P801-D-80419

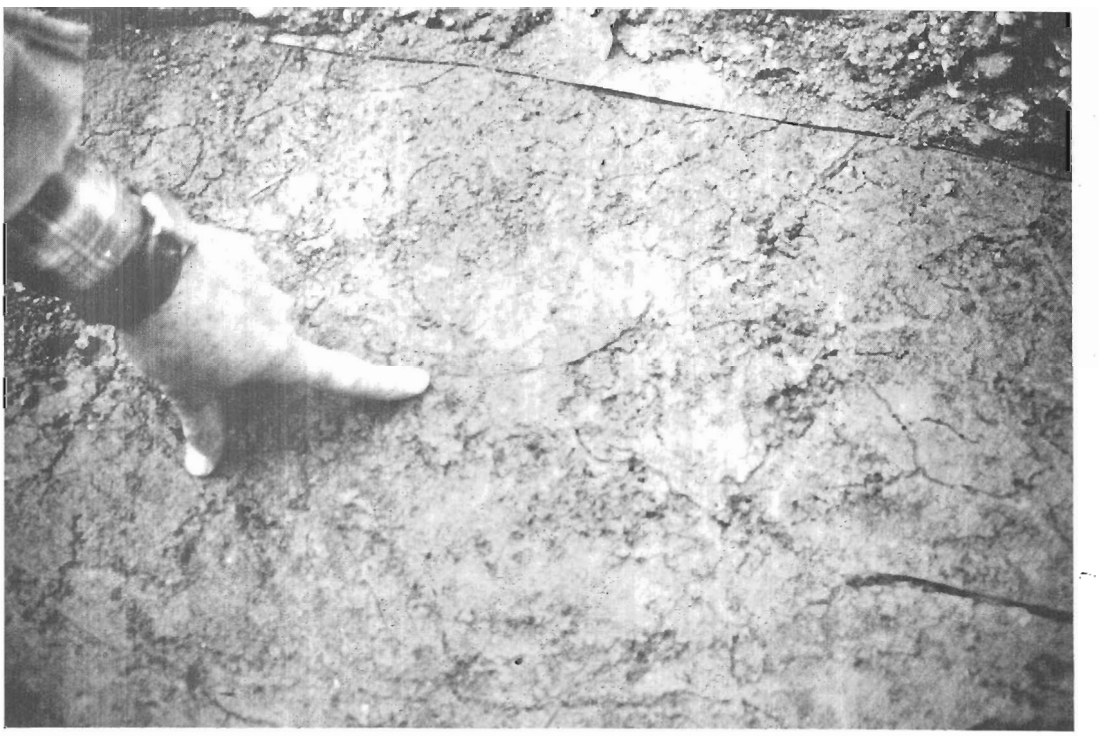


Figure 34.–View of subgrade below PVC lining on Lateral GM96, station 150+00. Note root growth. No evidence that vegetation had penetrated lining. Photo P801-D-80420

Figure 35.–View of PVC lining at bottom of Lateral GM96, station 150+00, Sun River Project, Montana. Photo P801-D-80421

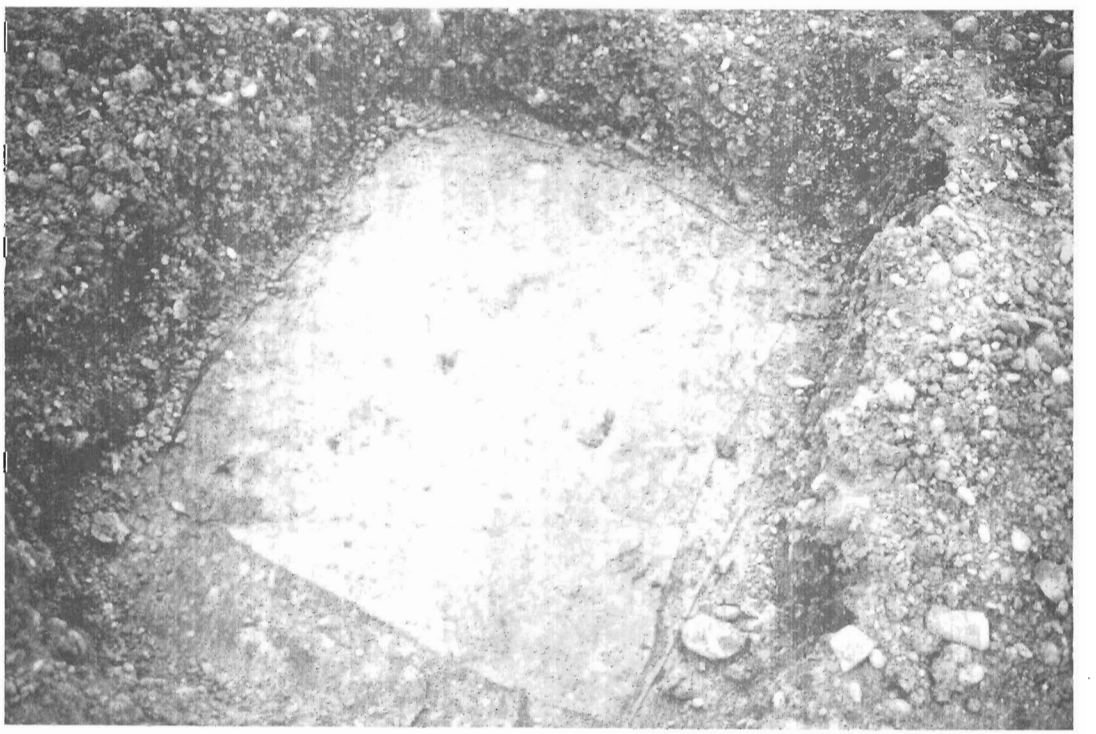
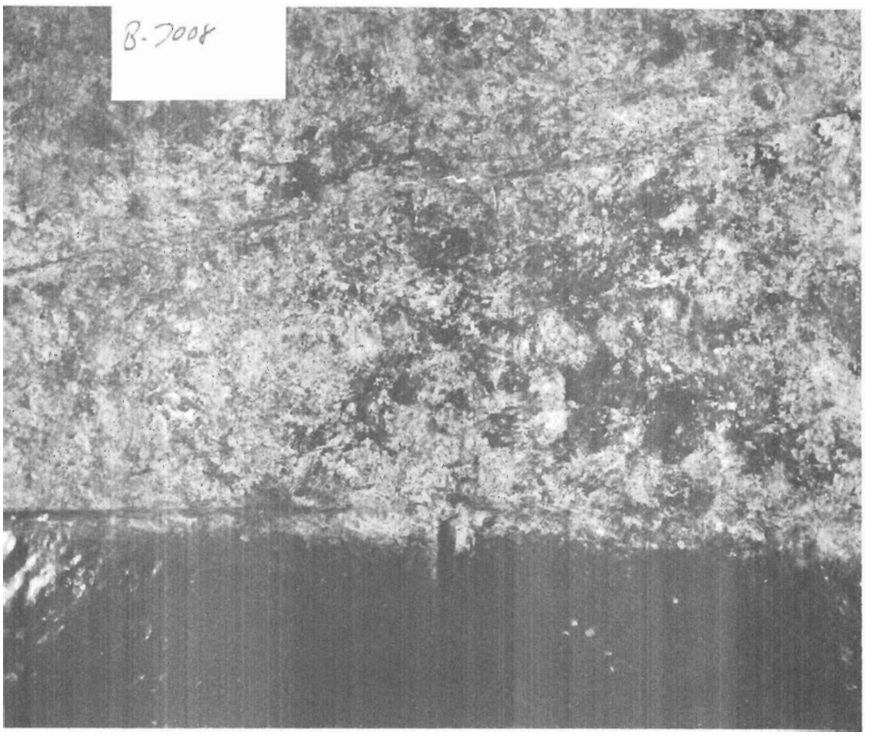
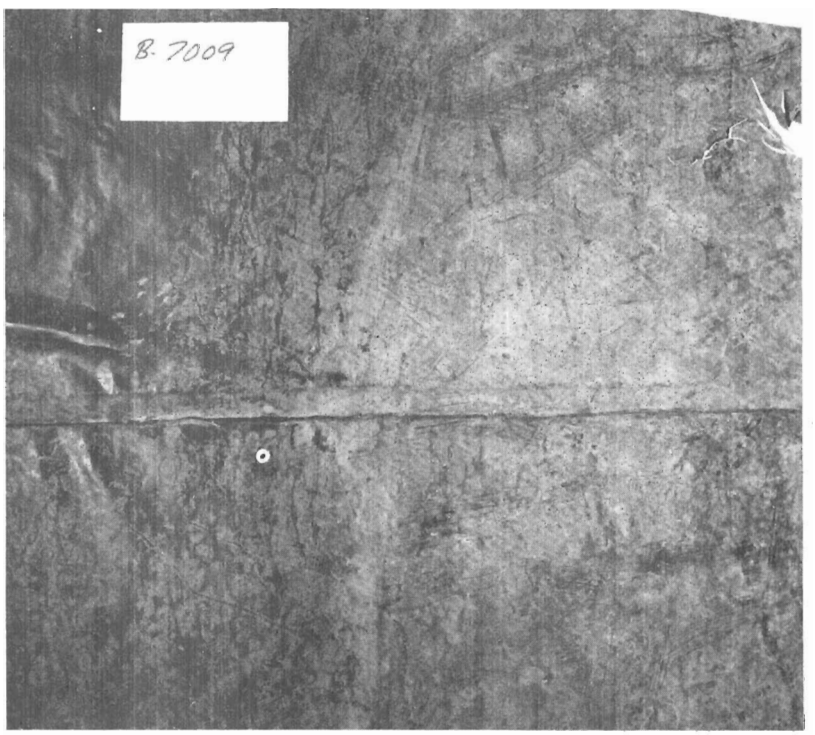


Figure 36.–Closeup view of subgrade below PVC lining on Lateral GM96, station 150+00. Photo P801-D-80422



a. Sample B-7008. Photo P801-D-80423



b. Sample B-7009. Photo P801-D-80424

Figure 37.–Condition of 13.5-year-old PVC samples from Lateral GM96. Sun River Project, Montana.

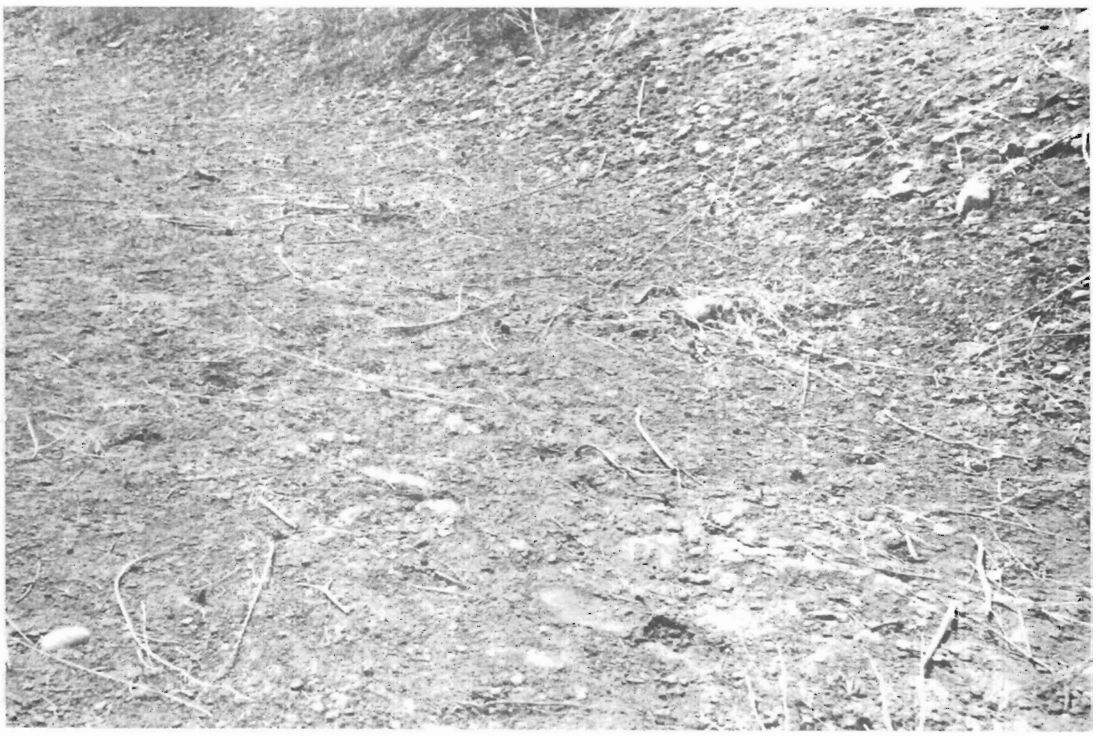


Figure 38.–View of Bugg Lateral near station 232+50 looking downstream prior to excavation. Tucumcari Project, New Mexico. Photo P801-D-80425

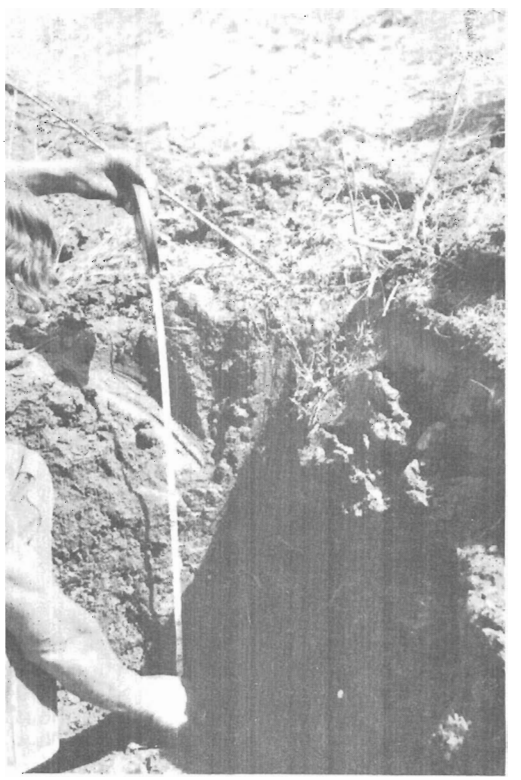


Figure 39.–View of PVC lining at bottom of Bugg Lateral. Depth of cover is about 460 mm (18 in). Top 100 to 150 mm (4 to 6 in) is accumulated silt since 1962. Station 232+50, Tucumcari Project, New Mexico. Photo P801-D-80426

Figure 40.–View of plastic lining in bottom of Bugg Lateral near station 232+50. No tears were noted except for one made during removal of cover material. Tucumcari Project, New Mexico. Photo P801-D-80427

Figure 41.–View of cover material above waterline near station 232+50 on Bugg Lateral. Depth of cover is about 350 mm (14 in), Tucumcari Project, New Mexico. Photo P801-D-80428

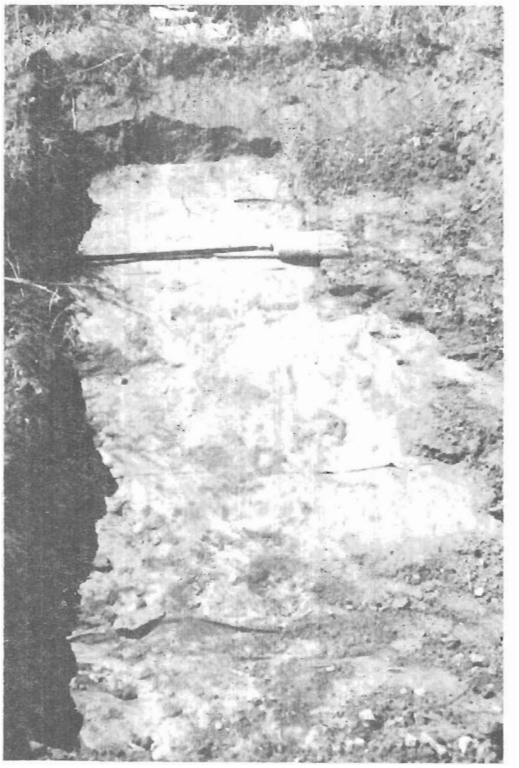


Figure 42.–View of fully exposed plastic lining on side slope near station 232+50 on Bugg Lateral. The broom indicates the approximate waterline. Tucumcari Project, New Mexico. Photo P801-D-80429

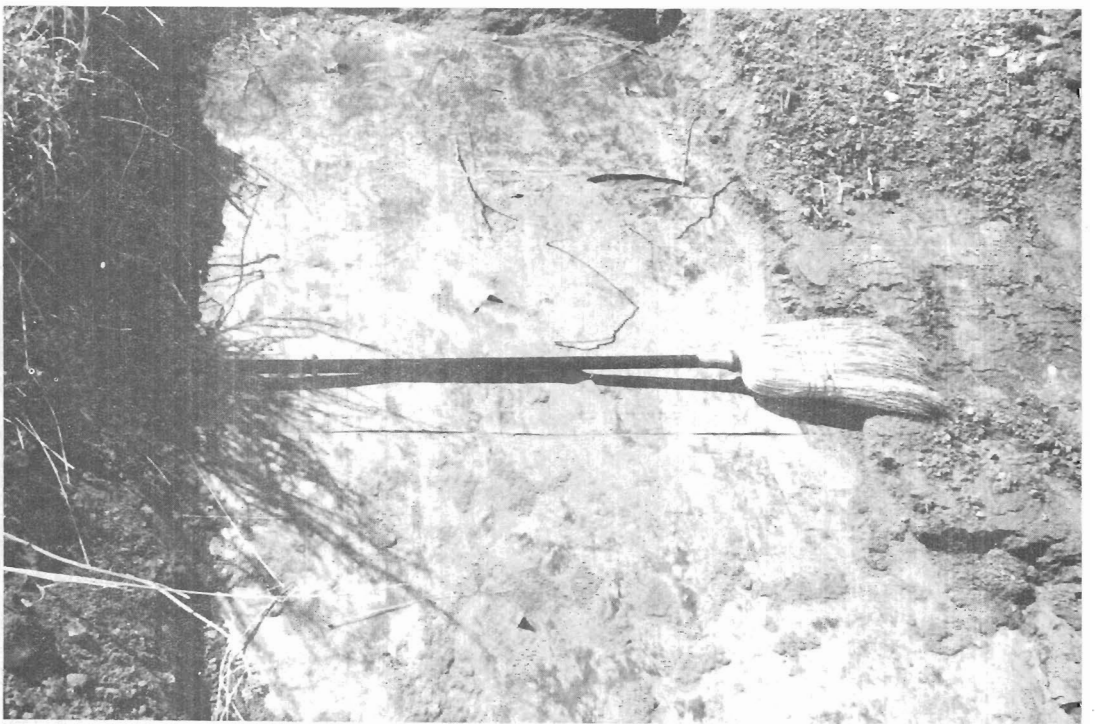


Figure 43.–Closeup view of exposed lining on side slopes near station 232+50 on Bugg Lateral. There were no tears or ruptures below the waterline in the excavation. Above the waterline, note root penetration and tension tear in upper righthand corner. Tucumcari Project, New Mexico. Photo P801-D-80430

Figure 44.–Condition of 19-year-old PVC sample from bottom of Bugg Lateral near station 232+50. Tucumcari Project, New Mexico. Photo P801-D-80431

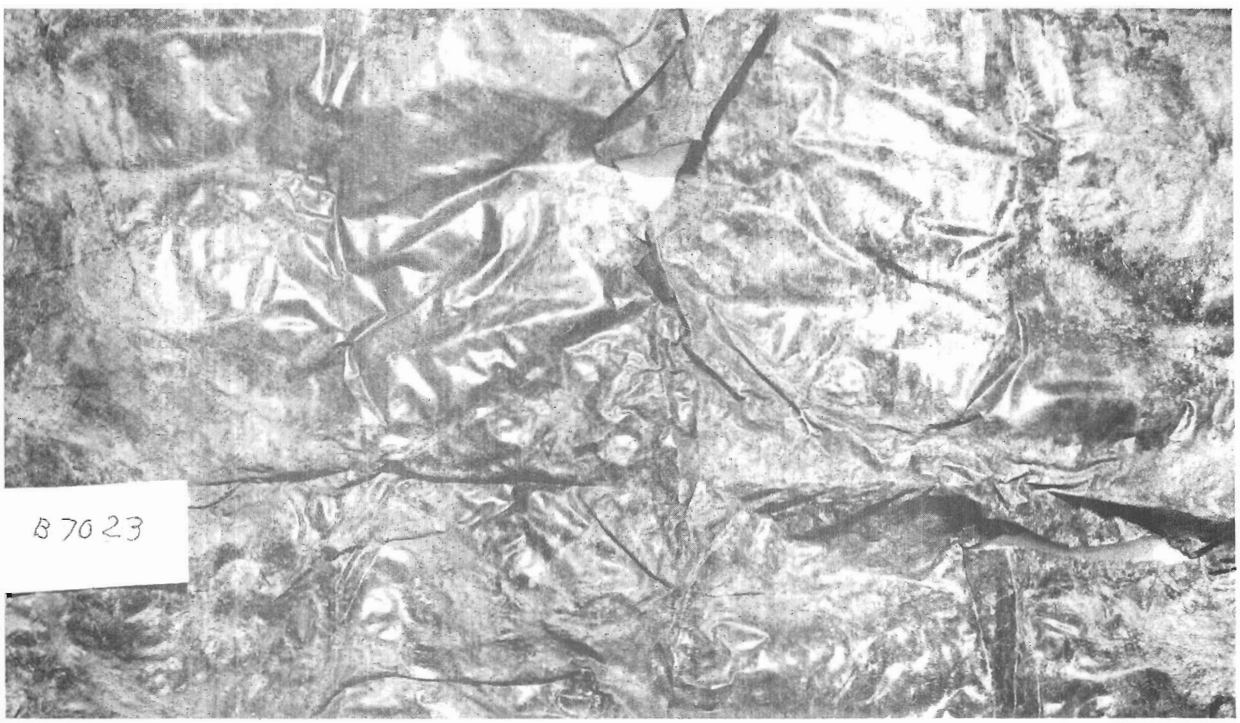


Figure 45.–Condition of 19-year-old PVC sample from side slope above waterline on Bugg Lateral near station 232+50. Tucumcari Project, New Mexico. Photo P801-D-80432

Figure 46.–View of plastic lining at bottom of McCaskey Lateral. About 4.6 m (15 ft) upstream of turnout 51R. Tucumcari Project, New Mexico. Photo P801-D-80433

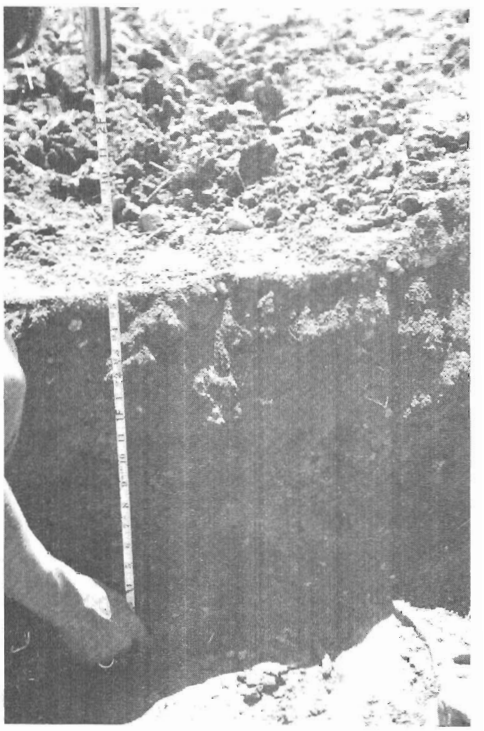


Figure 47.–View of cover material in bottom of McCaskey Lateral. About 4.6 m (15 ft) upstream of turnout 51R. Depth of cover was about 430 mm (17 in). Tucumcari Project, New Mexico. Photo P801-D-80434

Figure 48.–View of fully exposed plastic lining on side slope of McCaskey Lateral. About 4.6 m (15 ft) upstream of turnout 51R. The broom indicates approximate waterline. Tucumcari Project, New Mexico. Photo P801-D-80435

Figure 49.–View of cover material on side slopes of McCaskey Lateral. About 4.6 m (15 ft) upstream of turnout 51R. Depth of cover was about 460 mm (18 in). Tucumcari Project, New Mexico. Photo P801-D-80436

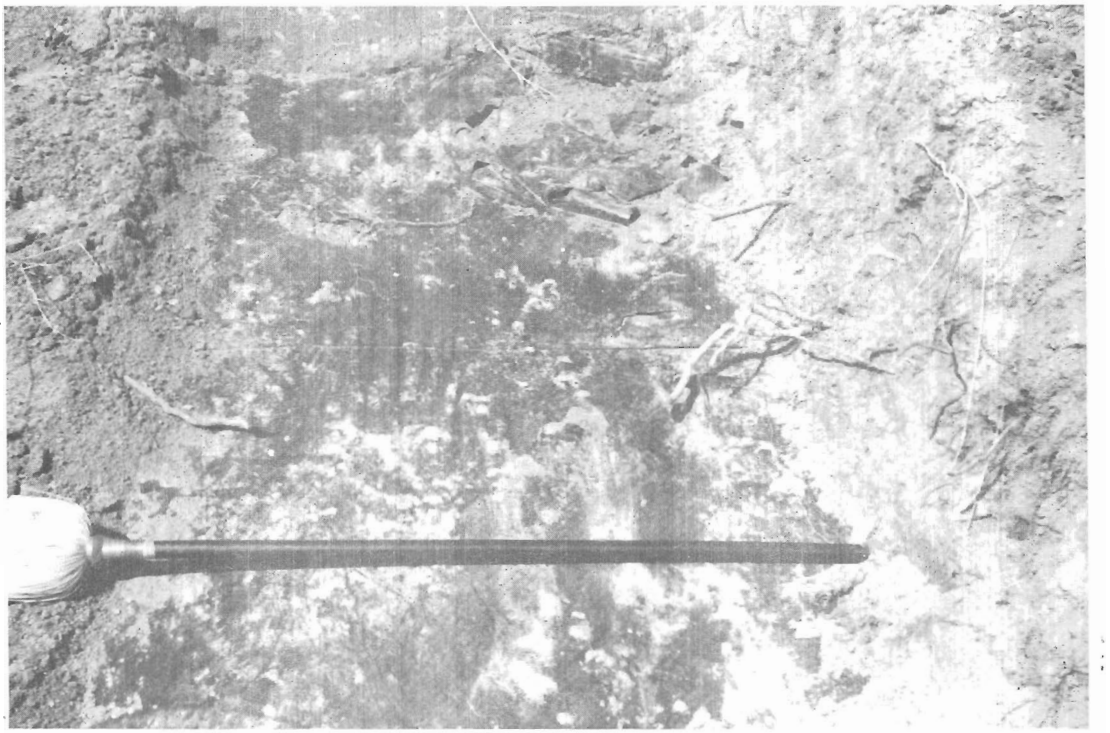


Figure 50.–View of plastic lining above waterline on side slope of McCaskey Lateral. About 4.6 m (15 ft) upstream of turnout 51R. Tucumcari Project, New Mexico. Photo P801-D-80437

Figure 51.–Closeup view of area above waterline as shown in figure 50. Note root and ant damage. McCaskey Lateral, Tucumcari Project, New Mexico. Photo P801-D-80438

Figure 52.–Closeup view of area shown on figure 51 that was damaged by red ants. McCaskey Lateral, Tucumcari Project, New Mexico. Photo P801-D-80439

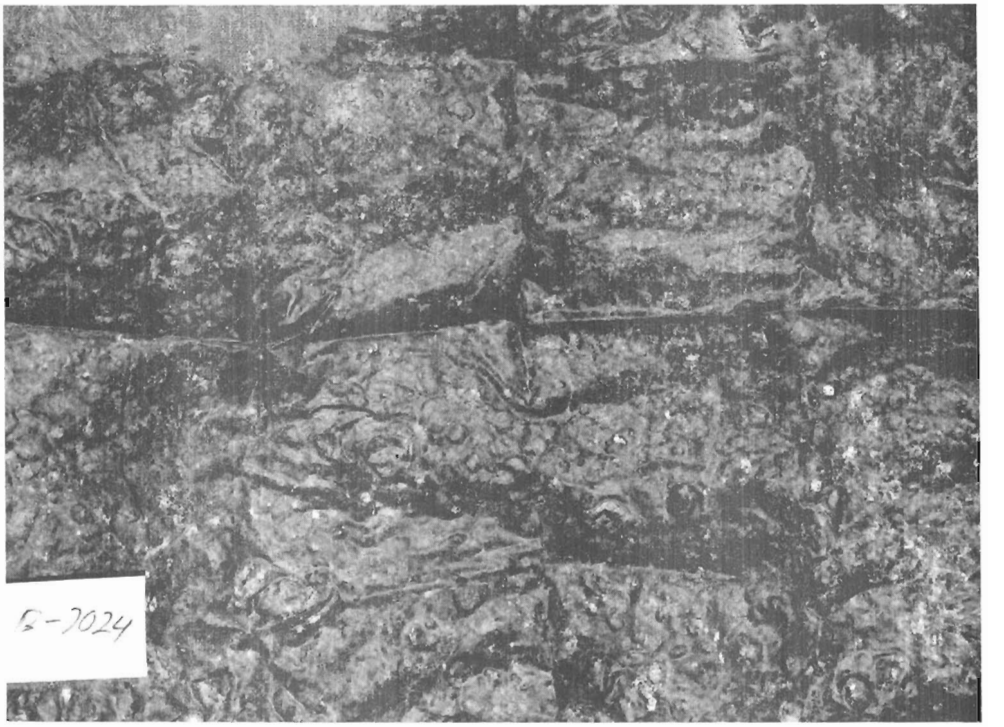
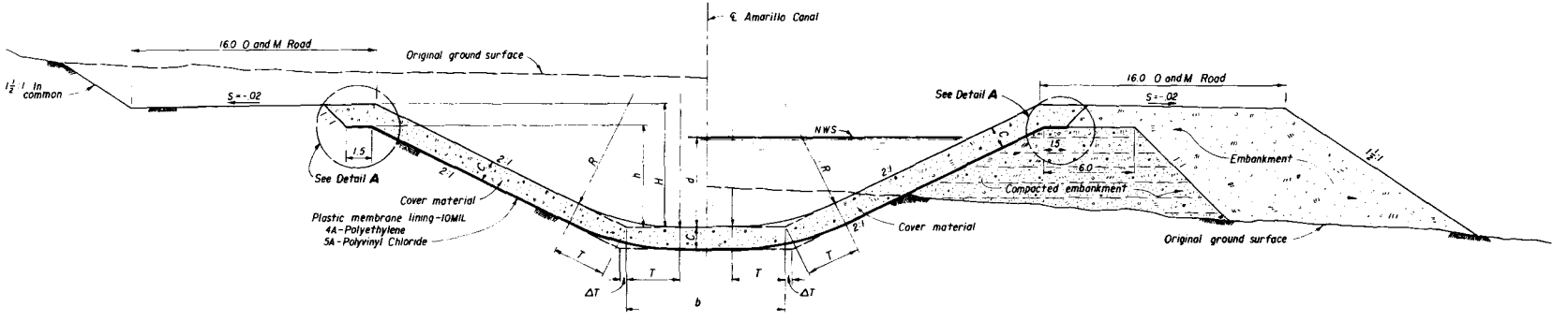


Figure 53.–Condition of 18-year-old PVC sample from bottom of McCaskey Lateral. About 4.6 m (15 ft) upstream of turnout 51R. Tucumcari Project, New Mexico. Photo P801-D-80440

Figure 54.–Condition of 18-year-old PVC sample from side slope above waterline on McCaskey Lateral. About 4.6 m (15 ft) upstream of turnout 51R. Sample contained a factory seam. Tucumcari Project, New Mexico. Photo P801-D-80441

HYDRAULIC PROPERTIES

CANAL SECTION	TYPE	A	V	Q	r	n	s	b	d	h	H	C	T	R	ΔT
4A	PE	125.50	1.51	190	3.48	.0225	.0001	10.5	5.72	6.60	8.10	1.33	3.5	14.83	.315
5A	PVC	86.02	1.98	170	2.83	.0225	.00025	10.75	4.40	5.25	6.70	1.25	3.5	14.83	.295



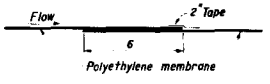
TYPICAL CANAL SECTION WITH PLASTIC MEMBRANE LINING

NOTES

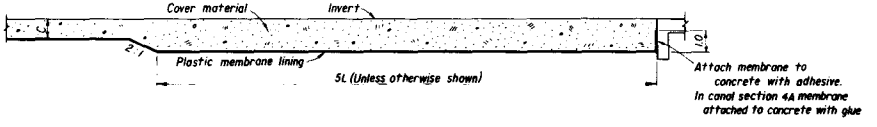
For general notes, see 809-D-1113.

For location of canal section 4A, and 5A, see Plan and Profile sheet.

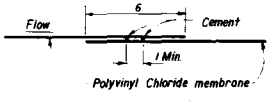
Cover material was placed using excavated canal (Section 4A) and borrow (Section 5A) cover material in the bottom one-half layer between stations 403+97.47 and 426+00, and station 569+96 and 594+00. Sand and gravel was used for all other cover material. Cover material was rolled between station 416+00 and 426+00, and station 584+50 and 594+00.



POLYETHYLENE



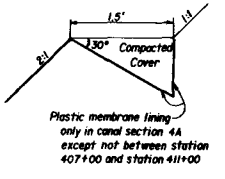
DETAIL OF MEMBRANE BONDING TO INLINE STRUCTURE



POLYVINYL CHLORIDE

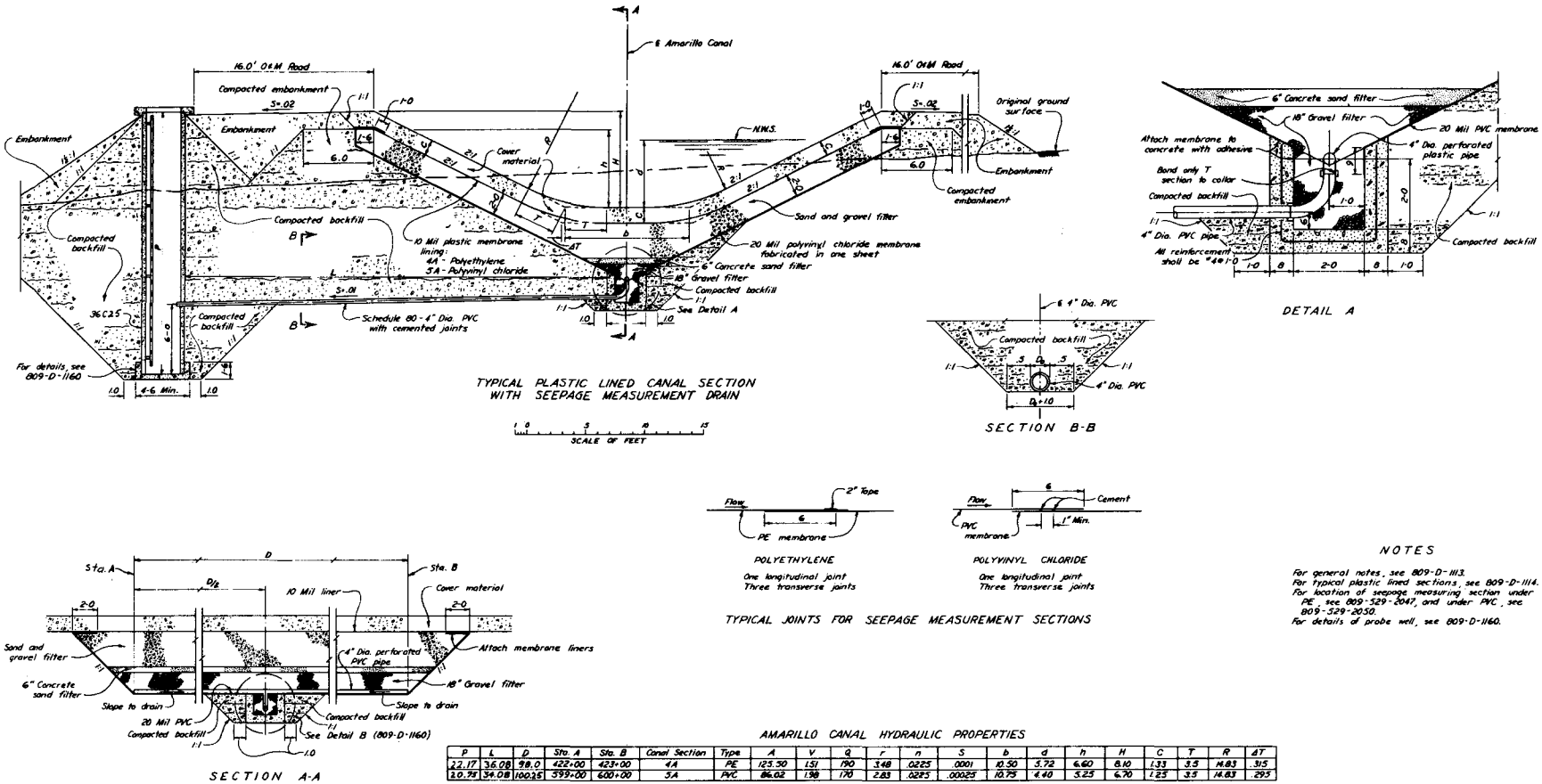
TYPICAL JOINTS FOR PLASTIC MEMBRANE LINING

DETAIL OF MEMBRANE BONDING OTHER THAN INLINE STRUCTURES



DETAIL A

Figure 55.–Details of plastic lining on Amarillo Canal.



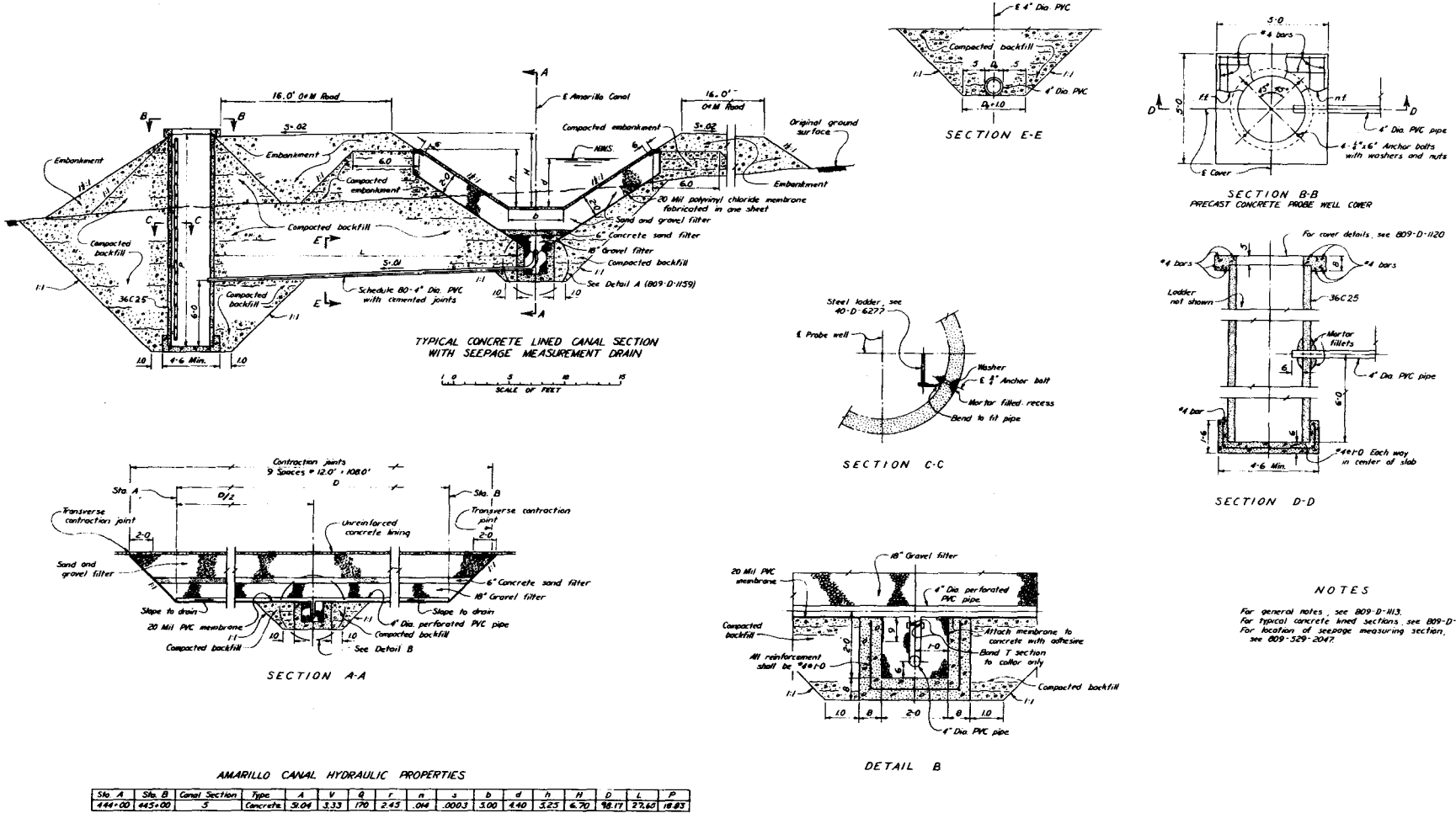
NOTES

For general notes, see 809-D-1113.
For typical plastic lined sections, see 809-D-1114.
For location of seepage measuring section under PE, see 809-529-2047, and under PVC, see 809-529-2050.
For details of probe well, see 809-D-1160.

AMARILLO CANAL HYDRAULIC PROPERTIES

P	L	D	Sta. A	Sta. B	Canal Section	Type	A	V	Q	r	n	S	b	d	h	H	C	T	R	ΔT
22.17	36.08	98.0	422+00	423+00	4A	PE	125.50	1.51	190	3.48	.0225	.0001	10.50	5.72	6.60	8.10	1.33	3.5	14.83	.315
20.78	34.08	100.25	599+00	600+00	5A	PVC	86.02	1.98	170	2.83	.0295	.00025	10.75	4.40	5.25	6.70	1.25	3.5	14.83	.295

Figure 56.–Seepage measuring section for plastic-lined portion of Amarillo Canal.



AMARILLO CANAL HYDRAULIC PROPERTIES

Sta. A	Sta. B	Canal Section	Type	A	V	Q	r	n	s	b	d	h	H	D	L	P
444+00	445+00	5	Concrete	51.04	3.33	170	2.45	.014	.0003	5.00	4.40	5.25	6.70	98.17	27.60	18.83

Figure 57.–Seepage measuring section for concrete-lined portion of Amarillo Canal.

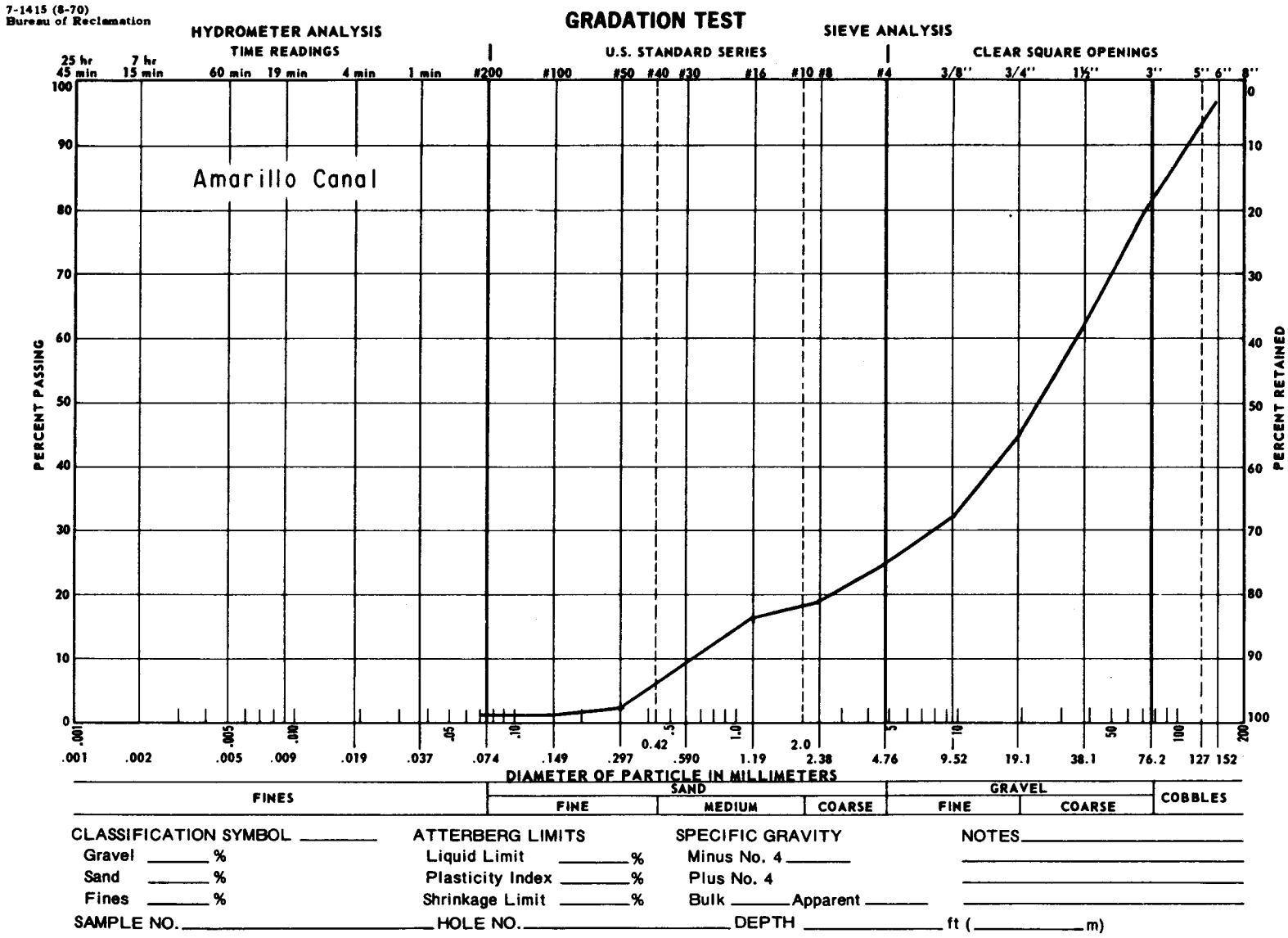


Figure 58.–Gradation of soil cover on Amarillo Canal.

Figure 59.–View of O&M crew uncovering 10-mil PVC lining on Amarillo Canal. Section 5A near station 599+50. Photo P802-D-80159

Figure 60.–View of section 5A looking upstream from station 600+20 on Amarillo Canal. Note difference in elevation (at arrows) of uncovered 10-mil PVC. Photo P801-D-80160.

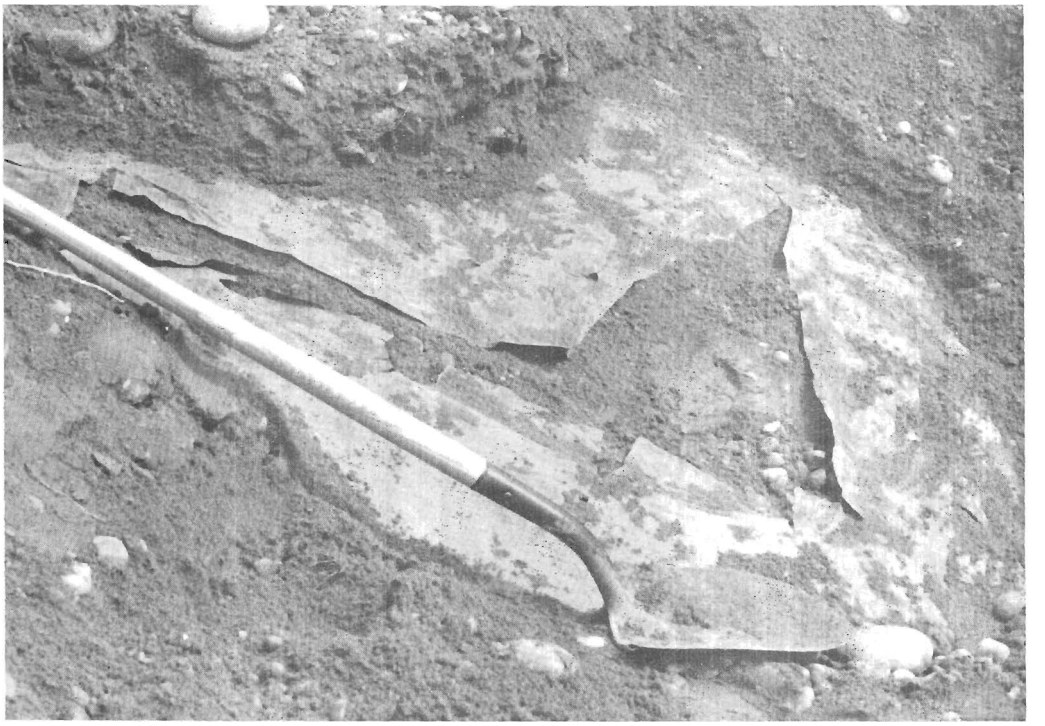


Figure 61.–View of hole found in PVC lining on right slope of Amarillo Canal. Section 5A near station 599+50. This hole, about 0.26 m² (2.8 ft²) in size, was probably the primary reason for the high seepage noted in this test reach. Navajo Indian Irrigation Project, New Mexico. Photo P801-D-80161

Figure 62.–View of uncovering operation in section 4A of Amarillo Canal. About 1.2 m (4 ft) of cover material was removed from the PE lining. Design cover depth was 410 mm (16 in). Navajo Indian Irrigation Project, New Mexico. Photo P802-D-80163

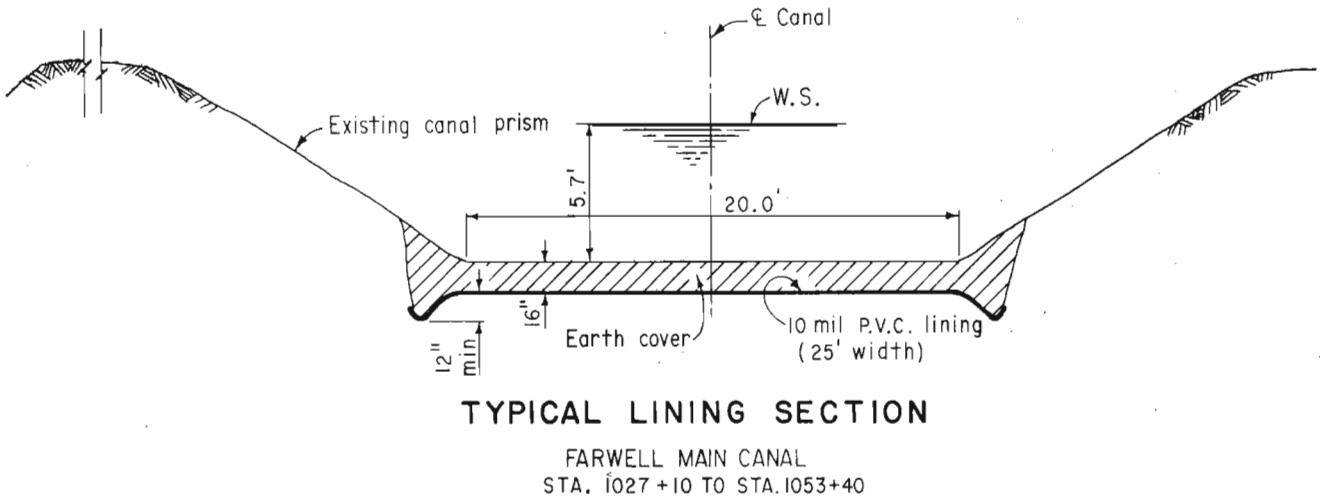


Figure 63.–Typical lining section on Farwell Main Canal. Middle Loup Division, Farwell Unit, Nebraska.

Figure 64.–Excavation in bottom of Farwell Main Canal prior to installation of bottom membrane lining. Photo P801-D-80442

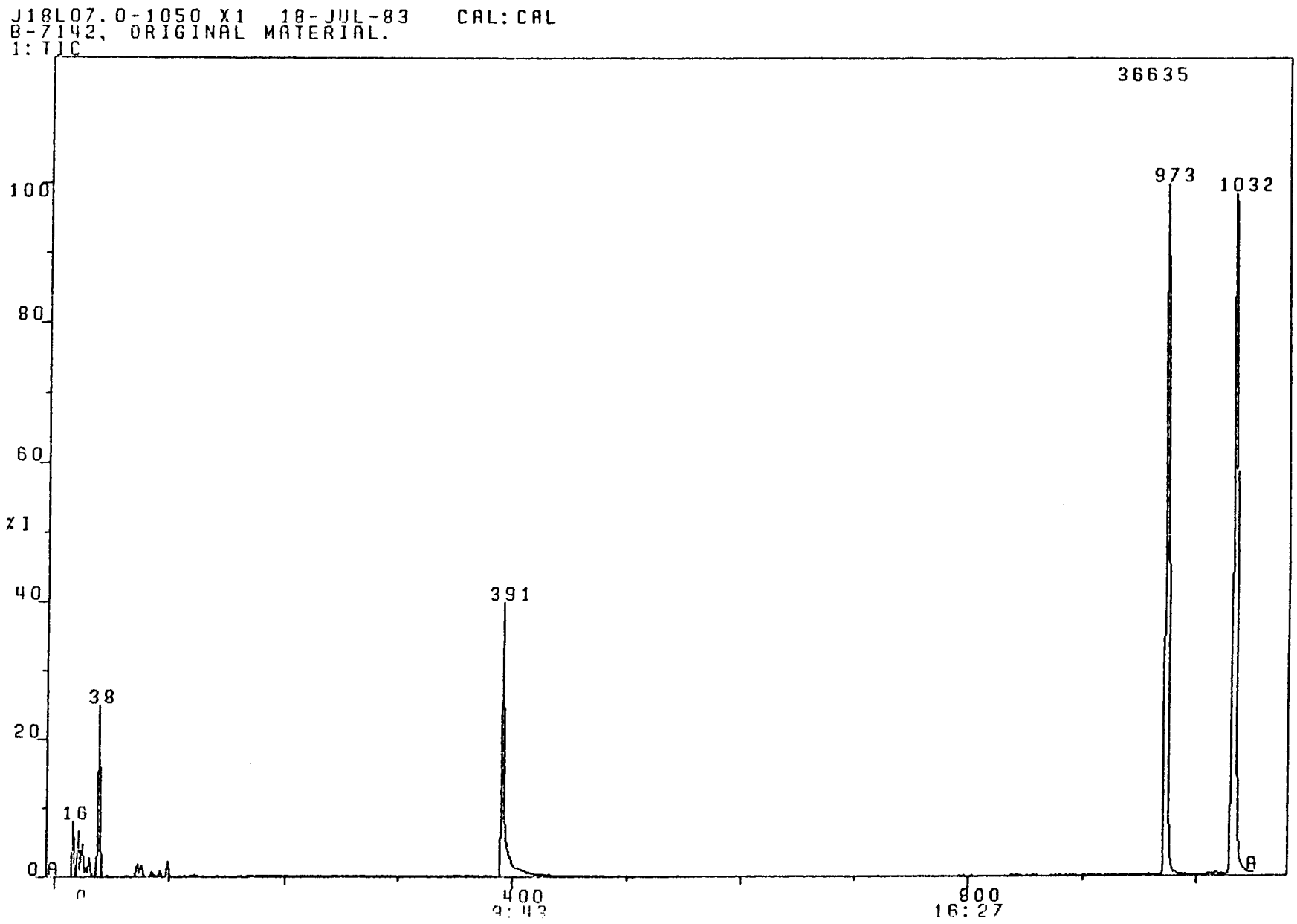


Figure 65.–Total ionization current for sample B-7142, original material.

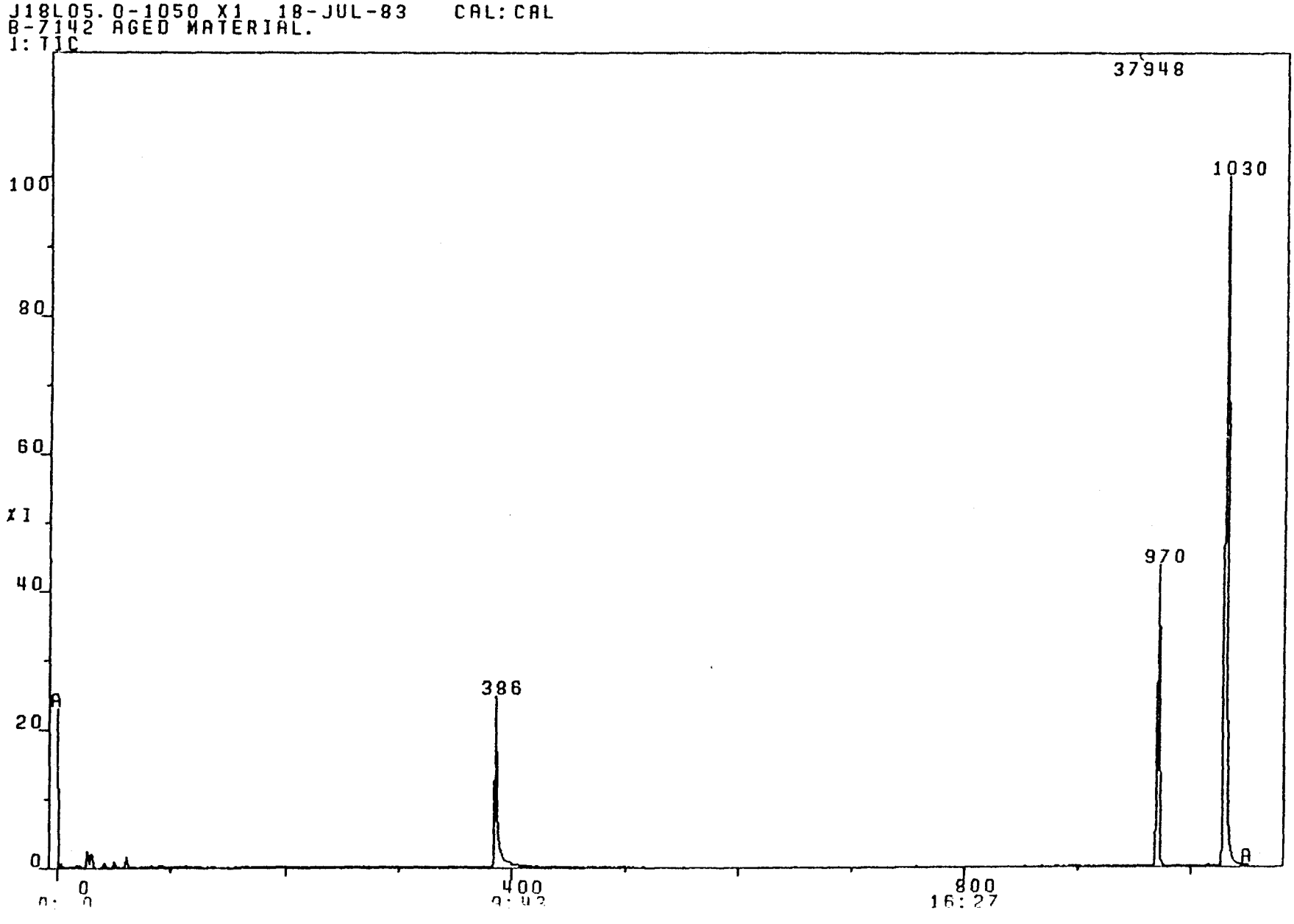


Figure 66.–Total ionization current for sample B-7142, aged material.

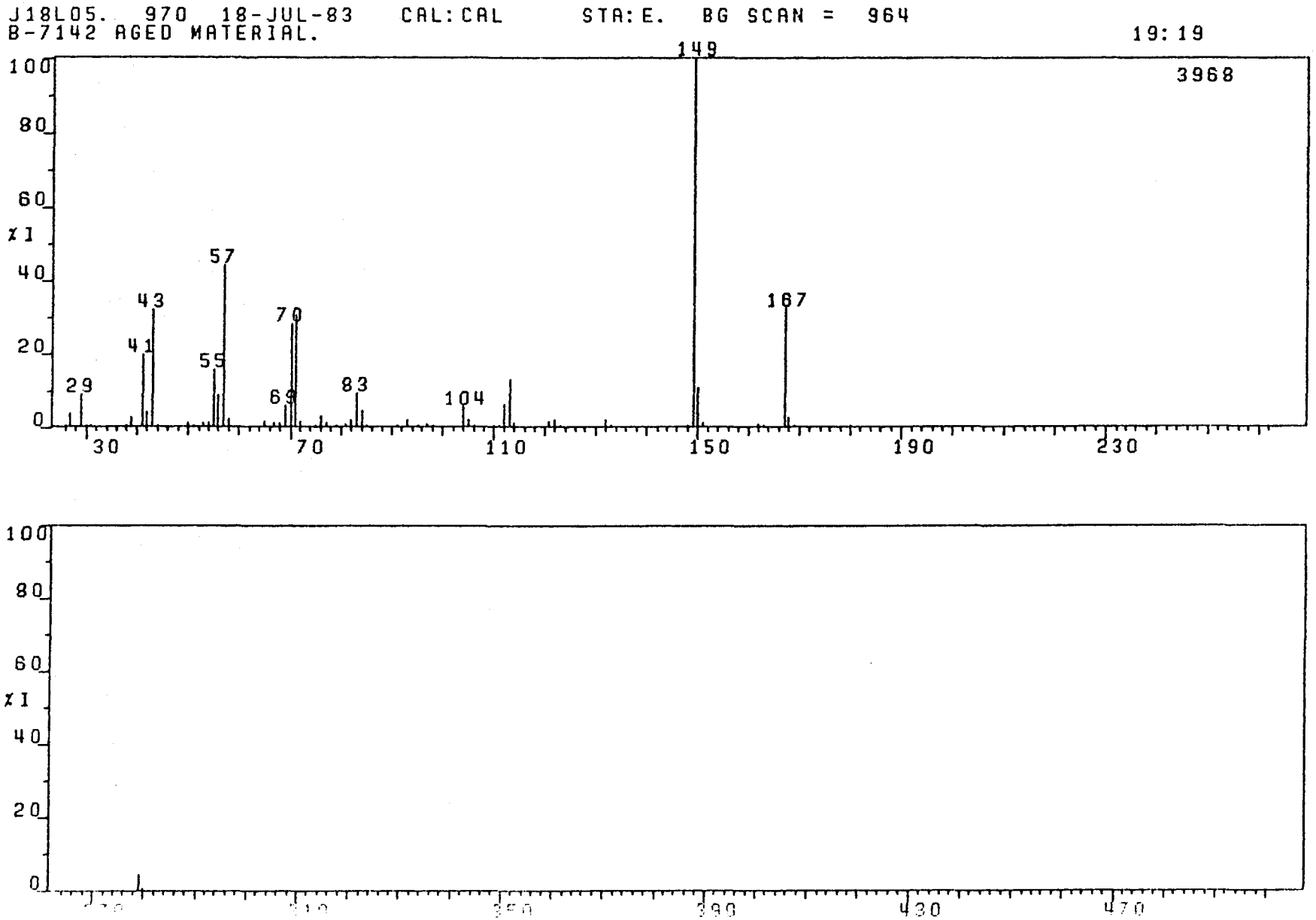


Figure 67.–Mass spectrum (peak 970) for diisooctyl phthalate.

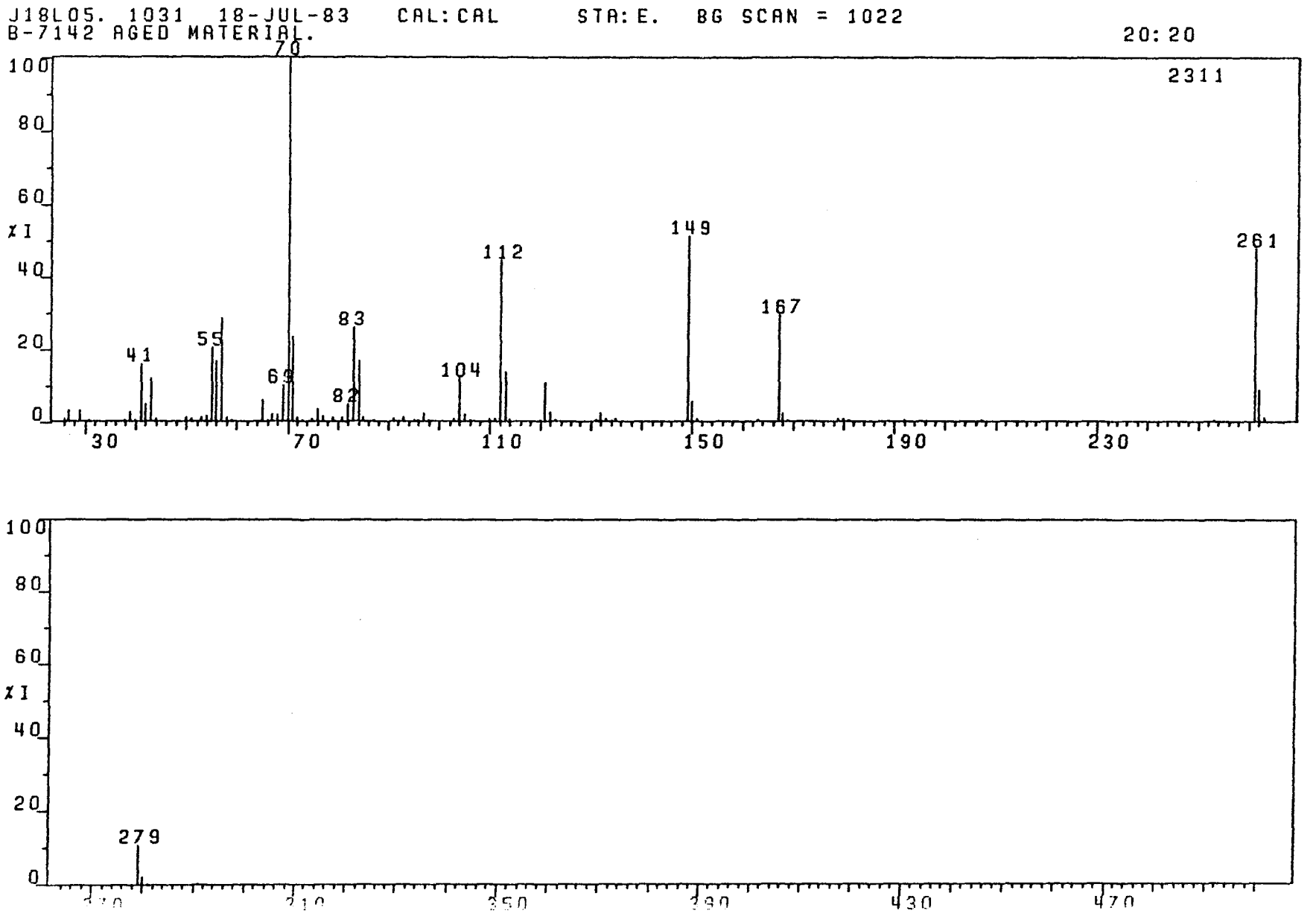


Figure 68.–Mass spectrum (peak 1031) for unknown component of sample B-7142.

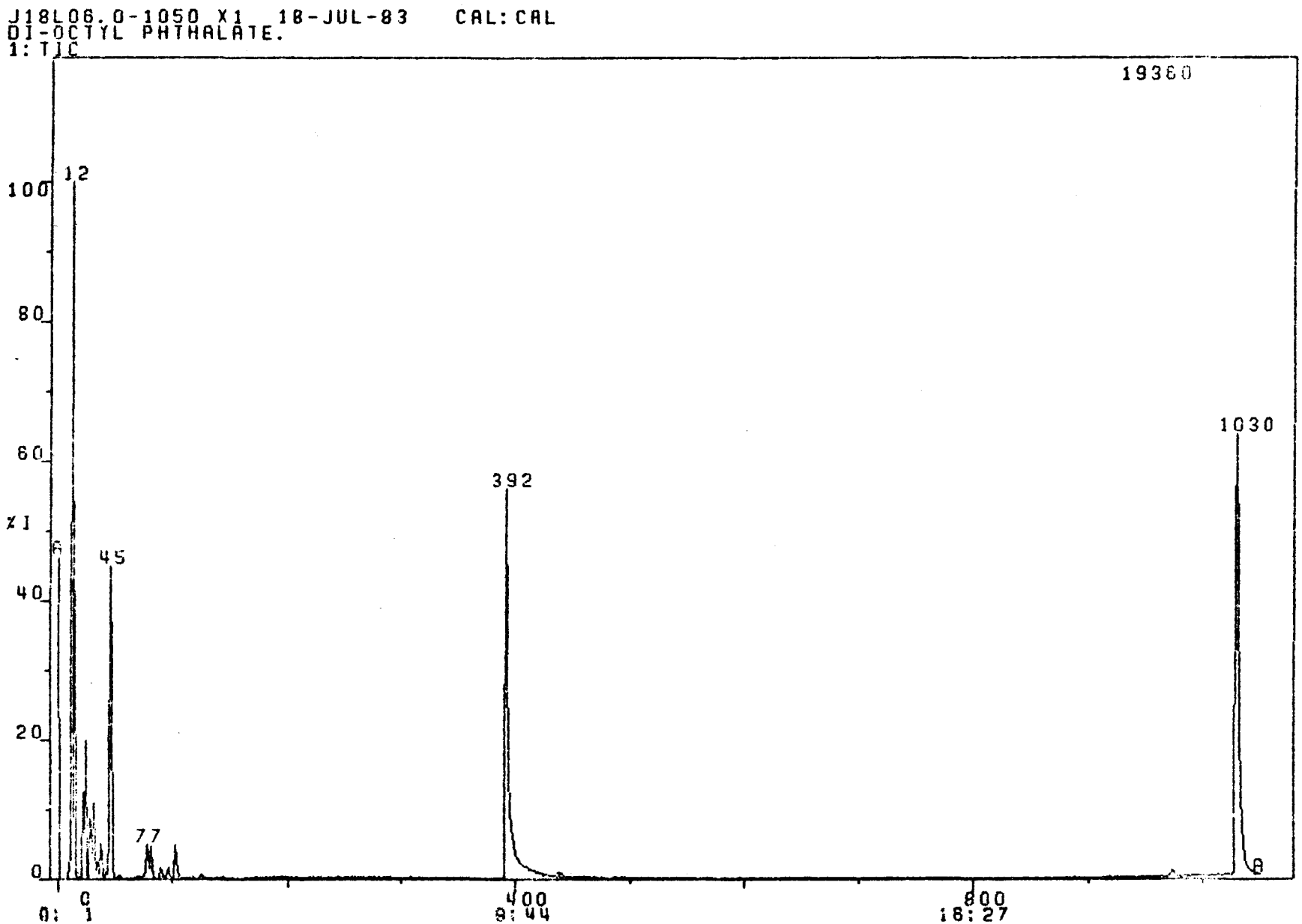


Figure 69.–Total ionization current for dioctyl phthalate (standard).

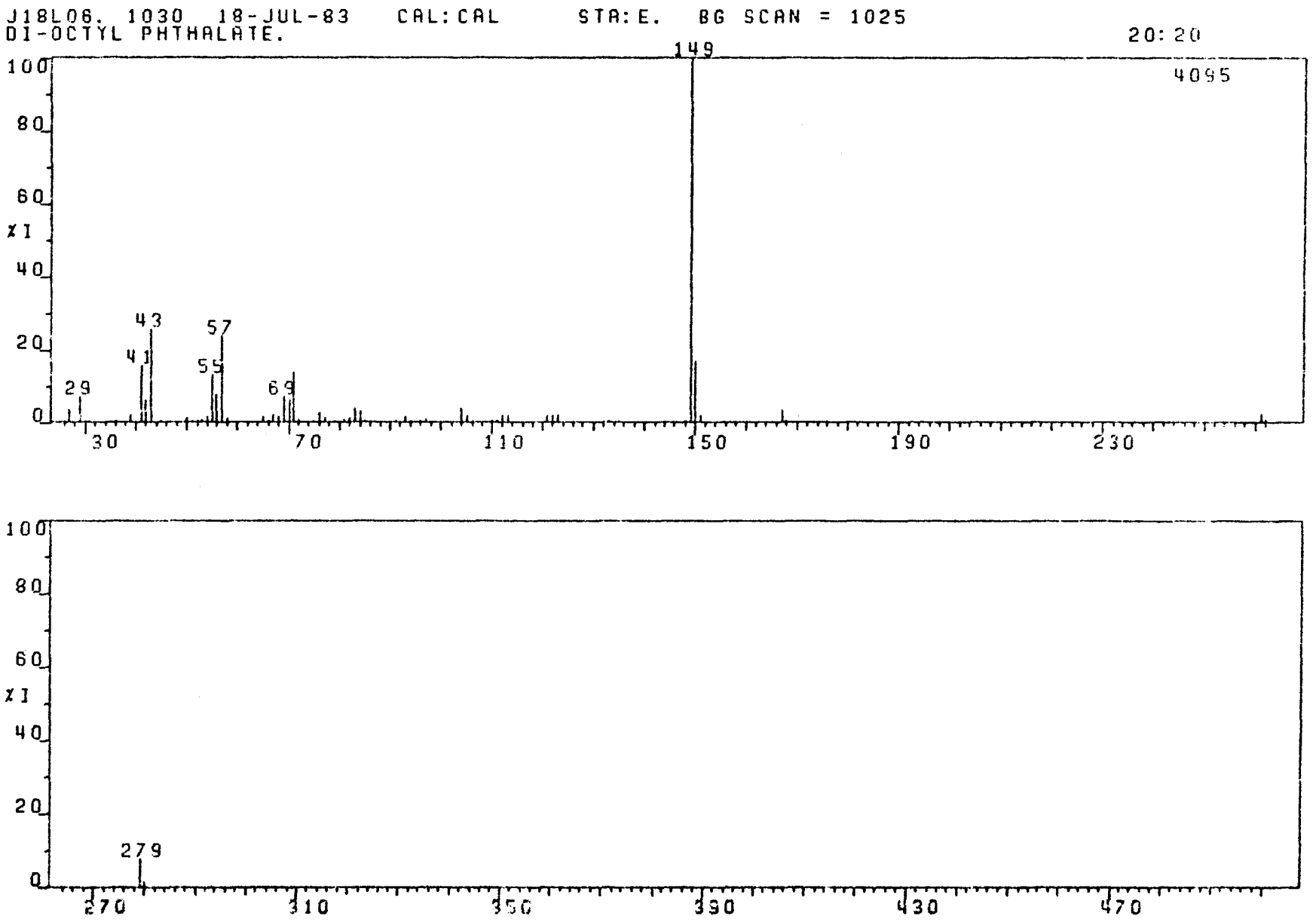


Figure 70.–Mass spectrum for dioctyl phthalate (standard).

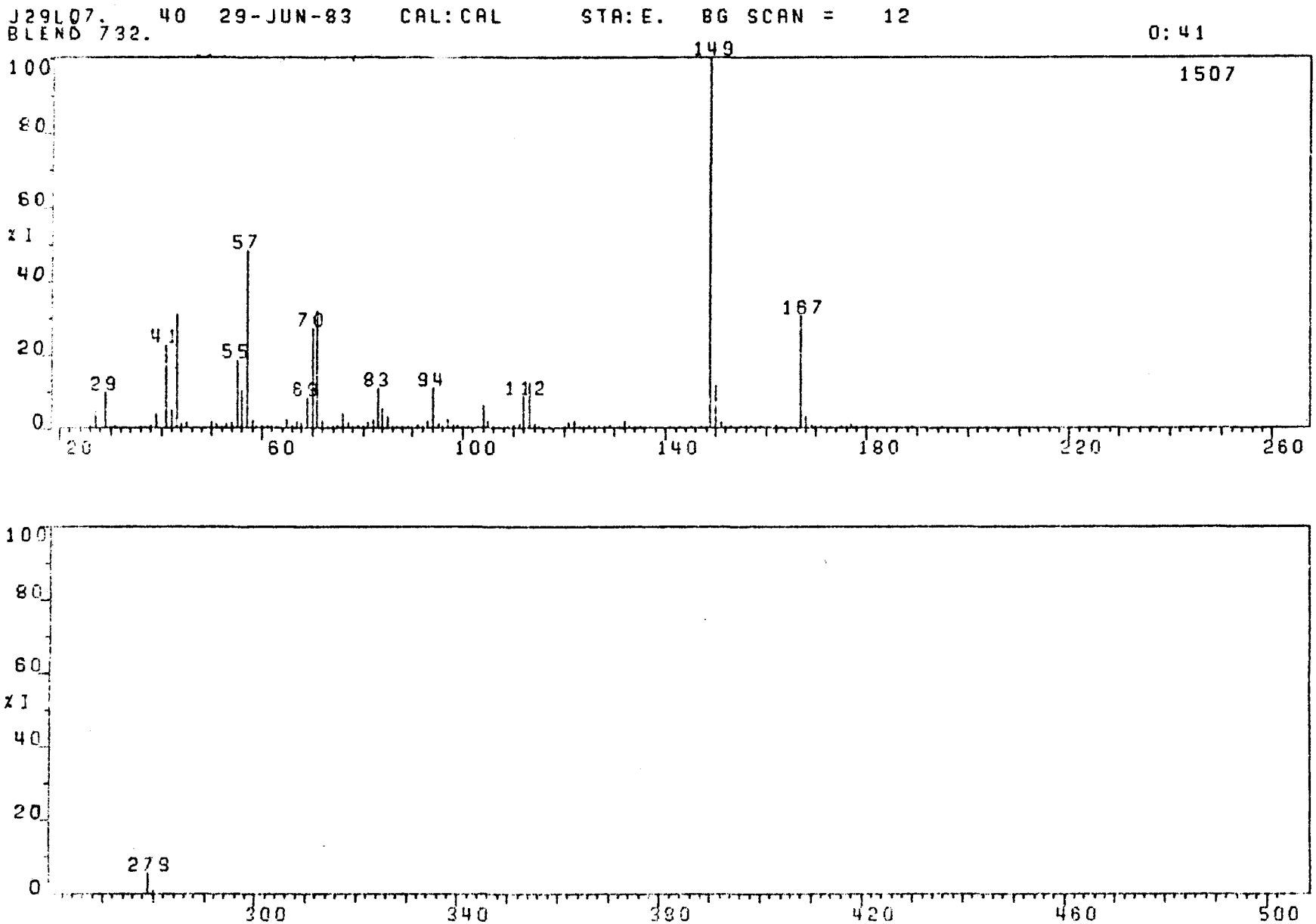


Figure 71.–Mass spectrum for diisooctyl phthalate (standard).

Figure 72.–Overall view of automated hydrostatic test facility. Vessels (tops removed) on left and controller on right. Vessels are 610 mm (24 in) in diameter, and capable of testing lining materials over any subgrade and under variable hydrostatic or hydrodynamic loading conditions. Photo P801-D-79755

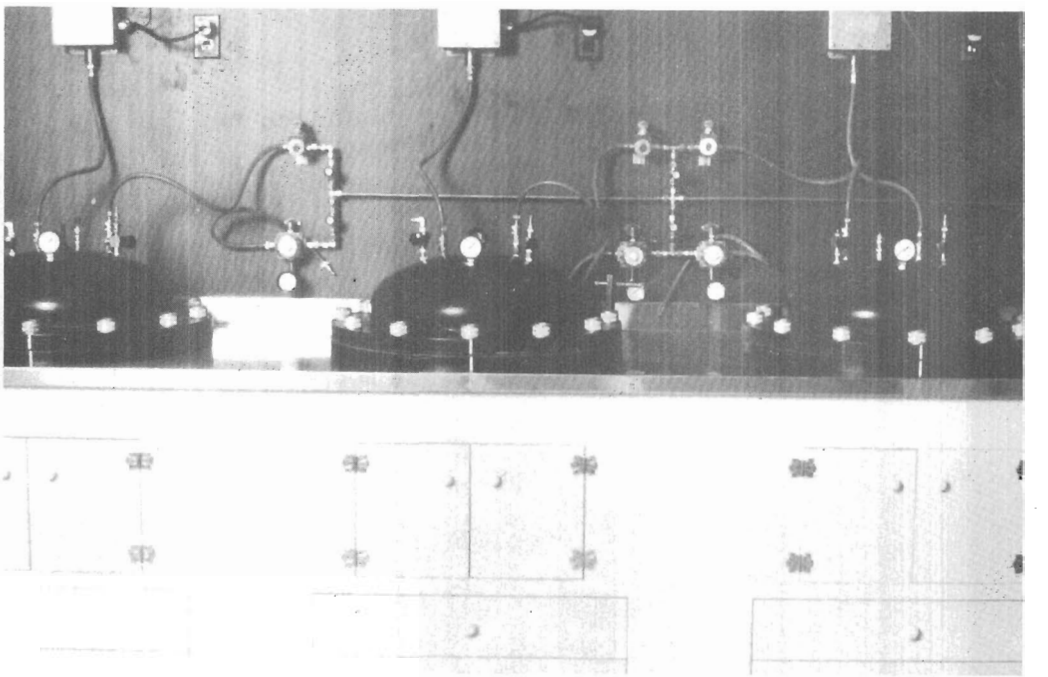


Figure 73.–Hydrostatic vessels, with tops in place, in operation. Photo P801-D-79756

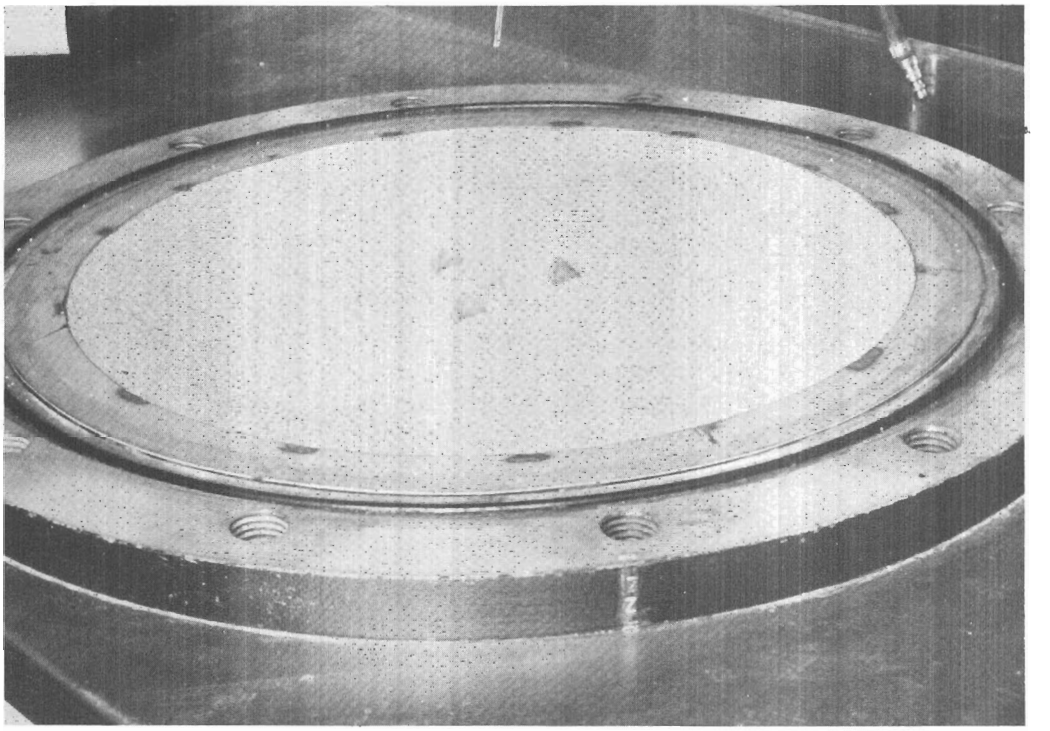


Figure 74.–View of reproducible, puncture-type subgrade for hydrostatic testing of membrane linings. Sand depth can be adjusted to vary pyramid height. Photo P801-D-80443

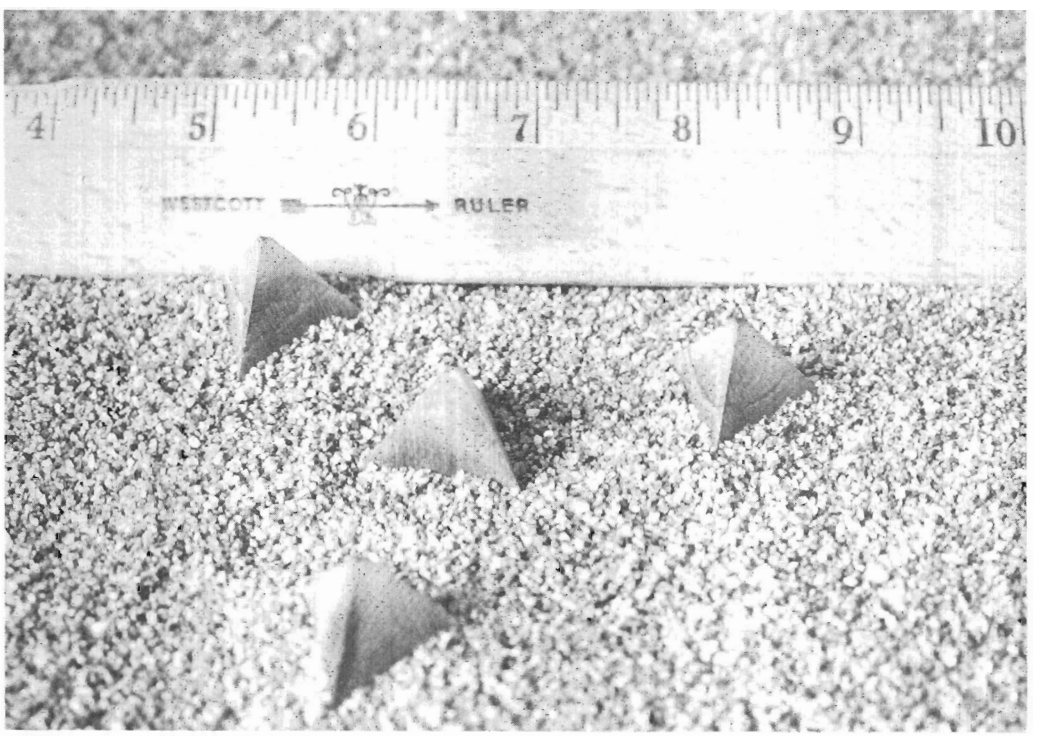


Figure 75.–Closeup view of plastic pyramids. Photo P801-D-80444

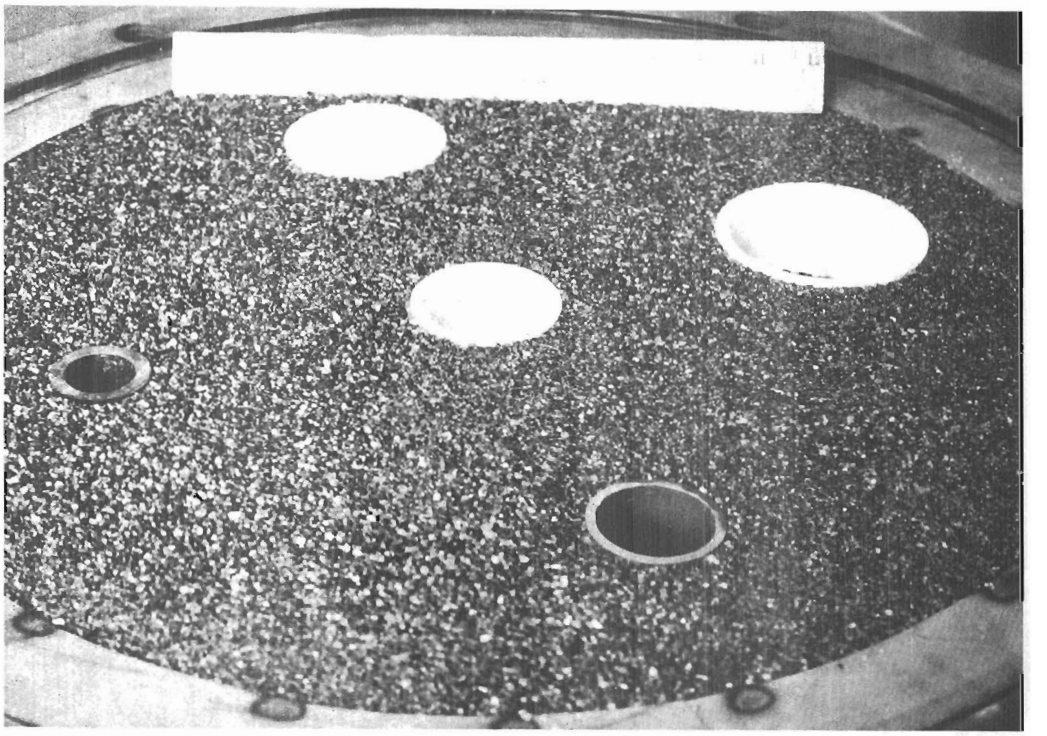


Figure 76.–View of subgrade fabricated with plastic pipes of different diameters to simulate interstitial voids. Photo P801-D80445

Figure 77.–View of gravel subgrade used in hydrostatic testing. Aggregate size can be varied to represent different subgrade conditions. Photo P801-D-80446

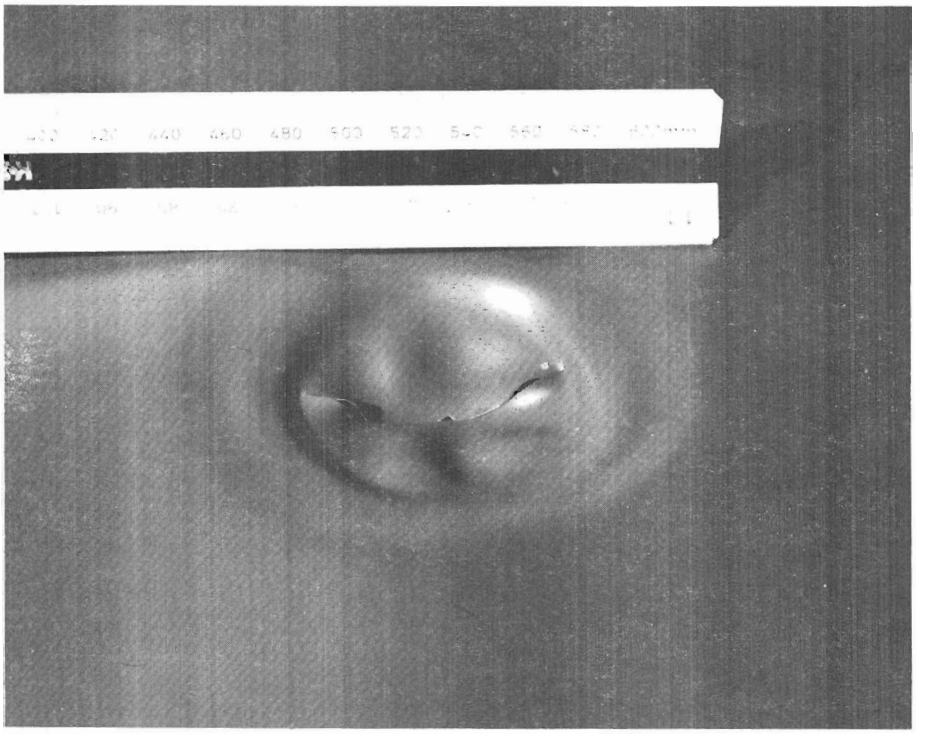


Figure 78.–View showing typical failure of PVC lining over a 75-mm (3-in) diameter void. Photo P801-D-80447

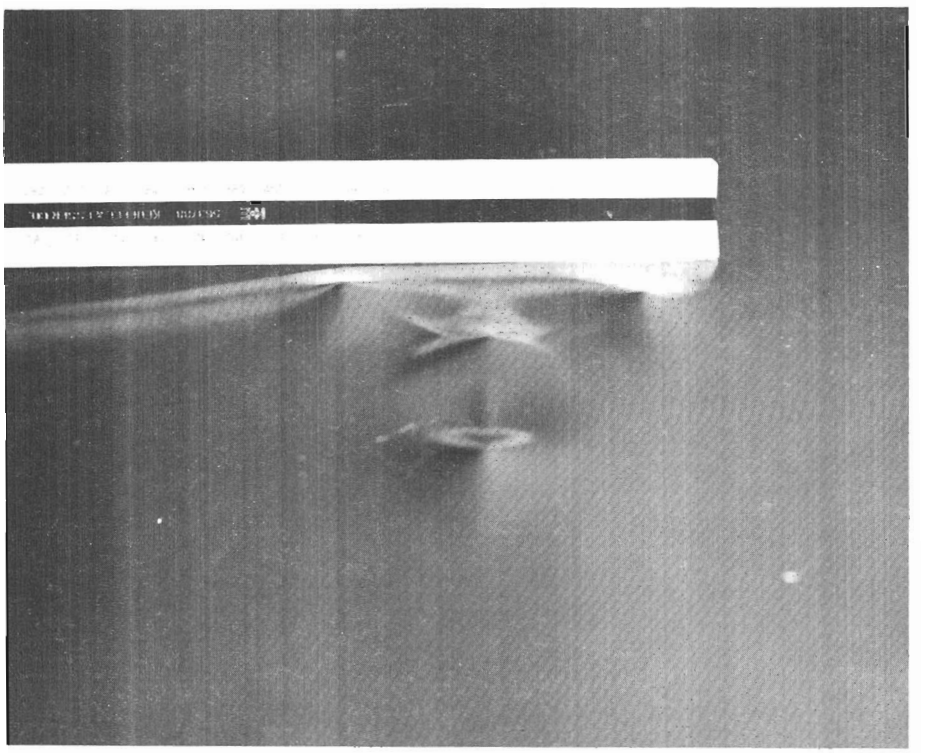


Figure 79.–View showing PVC lining conforming to plexiglass pyramids. Photo P801-D-80448

Photo P801-D-80449

Photo P801-D-80450

Figure 80.–Two views of 10-mil PVC lining in bottom of Amarillo Canal showing conformable property of PVC. The soil clod which the PVC encapsulates is about 75 mm (3 in) in size. Navajo Indian Irrigation Project, New Mexico.

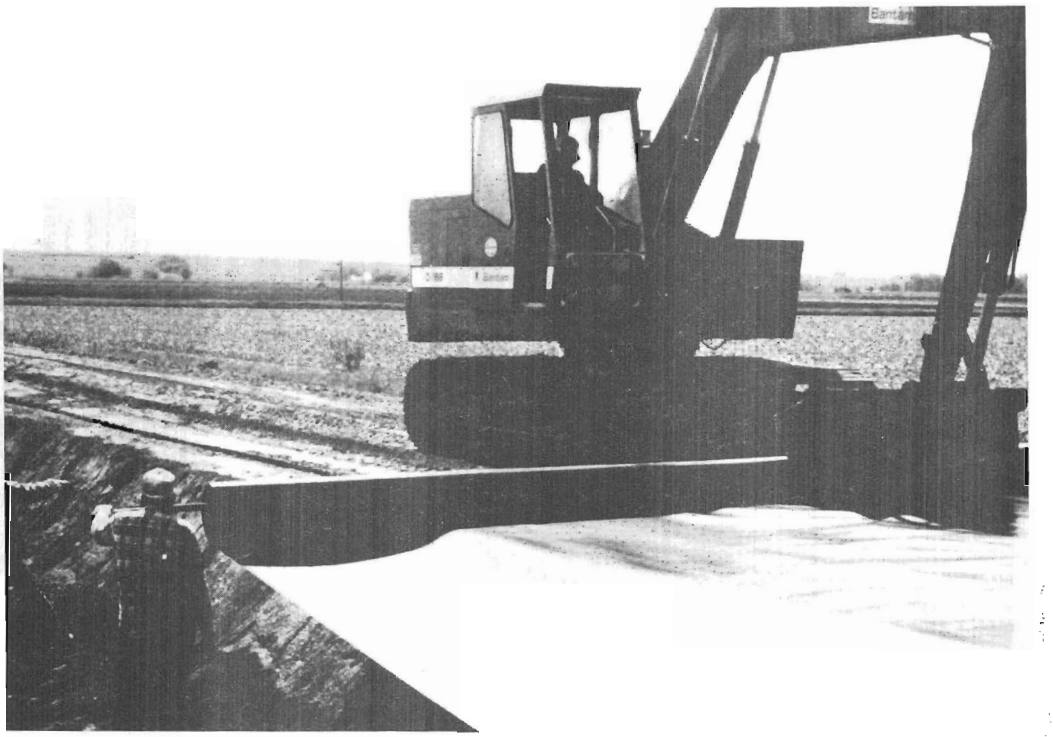


Photo P801-D-80451

Photo P801-D-80452

Figure 81.–Two views of unrolling the 30-mil HDPE lining for Whiterock Extension Canal, Courtland Unit, Kansas. The lining was supplied in one sheet 244 m (800 ft) in length by 6.86 m (22.5 ft) wide.

Figure 82.–Positioning HDPE lining for installation in Whiterock Extension Canal. Note anchor trench at right side of photograph. Photo P801-D-80453

Figure 83.–View of completed HDPE lining installation on Whiterock Extension Canal. Sideslopes will be left exposed. Photo P801-D-80454

APPENDIX A

SAMPLE CONSTRUCTION SPECIFICATIONS FOR BURIED PVC LINING

SECTION_____ BURIED PVC LINING FOR EXISTING CANAL

_____. GENERAL

PVC lining shall be installed on a subgrade under the canal prism and covered with earth, sand, and gravel material as shown on the drawings. Excavation in the existing canal shall be performed in accordance with paragraph_____ (Excavation). Before installing the lining, the subgrade shall be prepared in accordance with paragraphs_____ (Preparing Subgrade in Earth Material) and_____ (Preparing Subgrade in Hard or Unsuitable Foundation Material). The lining shall be installed over the prepared subgrade in accordance with paragraph_____ (Installation of PVC Lining). Earth cover shall then be placed over the installed lining to the prescribed depth. Sand and gravel cover material shall then be placed over the earth cover to the prescribed depth. Earth cover shall be in accordance with paragraph_____ (Earth Cover), and the sand and gravel cover material shall be in accordance with paragraph_____ (Sand and Gravel Cover).

_____. EXCAVATION

a. General.–The Contractor shall excavate the canal for installation of the PVC lining to the prescribed subgrade as shown on the drawings. Excavation shall include the removal of material for transitions of bottom widths as shown on the drawings. Excavation immediately adjacent to structures shall be done by hand methods, as required, to prevent damage to the structures and to conform to the lines and grades as shown on the drawings.

Material moved in excavation shall be wasted or deposited in approved areas. Where stockpiling adjacent to operating roads is permitted, the road shall be maintained in a condition suitable for motor vehicle traffic throughout the period that construction operations are in progress. The berms and spoil banks shall be finished so as to provide adequate drainage, and shall be graded to provide a uniform appearance. The required berms and operating roads shall be as shown on the drawings. Any leveling, grading, or widening of the berms or roads required for convenience of the Contractor shall be performed within the right-of-way boundaries, and the cost of such work shall be at the Contractor's expense. Any damage to the berm drains caused by operations of the Contractor shall be corrected by and at the expense of the Contractor.

b. Collecting ditches.–All necessary work in the vicinity of the existing collecting ditches and berm drains shall be performed in a manner that will minimize damage to the ditches. Any damage to the existing collecting ditches shall be corrected and the ditches shall be restored as nearly as practicable to their original condition. Additional collecting ditches shall be constructed as shown on the drawings or as directed. Ditches

shall be constructed within right-of-way boundaries and generally adjacent to the toe of embankments.

Ditches may be V-shaped as would be accomplished by angle dozing or by other approved methods, and shall be constructed to provide a continuous drainage slope toward drain inlets into the canal. No earth shall be piled on the upper side of collecting ditches that would prevent proper accumulation of surface drainage. Materials excavated from collecting ditches may be disposed of by distribution along the outer toe of canal banks or in other locations as approved. No payment will be made for constructing collecting ditches; the costs shall be included in the unit price bid in the schedule for excavation.

c. Additional excavation and refill.–Where sections of hard or unsuitable foundation materials are encountered which, in the opinion of the Contracting Officer, cannot be excavated and trimmed efficiently by excavating and trimming machinery, and through sections containing large, sharp gravel or cobbles which will not provide the desired foundation, the canal shall be excavated so that there will be not less than 3 inches between any point of the excavated surface and the buried lining. This additional excavation below the lining shall be refilled with sand and gravel material in accordance with paragraph_____ (Preparing Subgrade in Hard or Unsuitable Foundation Material). Special care shall be taken to prevent overbreakage outside of the limits to which measurement for payment is made. Any such overbreakage and refill shall be at the expense of the Contractor. In the event the finished subgrade line is above the existing canal bottom or side slopes, the spaces between the required finished subgrade and the bottom and/or side slopes of the existing canal shall be filled with sand and gravel material in accordance with paragraph_____ (Preparing Subgrade in Hard or Unsuitable Foundation Material).

d. Disposal of materials.–Excess material resulting from excavation of the canal and which is suitable for bank construcion, shall be used to strengthen the banks on either side of the canal, as may be directed. Other suitable materials shall be stockpiled at points convenient to the placing operations, as necessitated by the Contractor's sequence of operations, for later use as selected sand and gravel cover, bedding, and refill material. Material removed in excavation and not suitable for canal banks, sand, gravel cover, or refill above lining; and any suitable material not required for the work under these specifications, shall be deposited in waste banks on right-of-way owned by the Government at points directed by the Contracting Officer. Waste banks shall be left with reasonably even and uniform surfaces, as approved by the Contracting Officer. Except as provided for overhaul, the cost of all work described in this subparagraph shall be included in the unit price bid in the schedule for excavation.

e. Measurement and payment.–Measurement for payment of excavation, except as provided in this subparagraph, will be made to the neatlines of the underside of the buried lining as shown on the drawings.

Where the Contractor is directed to perform additional excavation through sections of hard or unsuitable foundation materials, as described in subparagraph c. above, measurement will be made to lines parallel to and 5 inches below the underside of the lining.

Payment for excavation will be made at the unit price per cubic yard bid in the schedule, which unit price shall include the costs of constructing collecting ditches, blasting or ripping, placing the material along the canal embankment at locations as directed, or otherwise disposing of the excavated material as described in subparagraph d. above, of pumping or unwatering, and all work necessay to maintain the excavations in good order during construction, except that required overhaul will be paid for as provided in paragraph_____ (Overhaul).

The unit price bid in the schedule for excavation shall also include the cost of placing selected materials in stockpiles for use in the earth cover, sand and gravel cover, and bedding for the lining. Payment for furnishing and placing the excavated materials in the cover and bedding for lining will be made as provided in paragraphs_____ (Preparing Subgrade in Hard or Unsuitable Foundation Material),_____ (Earth Cover), and_____ (Sand and Gravel Cover).

_____. OVERHAUL

a. General.–A mile cubic yard of overhaul is defined as a cubic yard of excavated material hauled 1 mile in excess of the free-haul limit. The free-haul limit is 2,000 feet.[1] Payment for overhaul will be made only for excavated materials directed to be wasted beyond the limit of free haul. The entire cost of hauling materials any distance up to the free-haul limit from the original position shall be included in the price bid in the schedule for excavation of the material.

b. Measurement and payment.–Measurement and payment for overhaul will be made as specified herein regardless of the methods and types of equipment used in excavating and hauling.

Where material is taken from canal excavation and deposited or wasted within 150 feet from the centerline of the canal, the length of haul will be measured along the

[1]The 2,000-foot limitation may be changed for adoption to available right-of-way limits, size of canal, depths of thorough cut, or other local conditions.

centerline of the canal from the center of gravity of the material as found in excavation to the center of gravity of the material as deposited. Regardless of haul routes actually traveled, the above lengths of haul will be the distance measured along the centerline between the center of gravity of the excavation as projected on the centerline and the center of gravity of the deposit as projected on the centerline.

Where excavated material is wasted or deposited at a distance greater than 150 feet from the centerline of the canal, at the direction of the Contracting Officer, the length of haul will be measured along the shortest practicable route, as determined by the Contracting Officer, between the center of gravity of the material as excavated in each 100-foot station and the center of gravity of the material as deposited.

In measuring quantities of overhaul for payment, the volume of overhauled material will be measured in excavation; the length of haul will be measured in station units of 100 feet. Payment for overhaul will be made at the unit price per mile cubic yard bid in the schedule.

_____. PREPARING SUBGRADE IN EARTH MATERIAL

a. General.–The subgrade upon which the buried lining is to be placed shall be prepared to produce a firm surface, reasonably even and smooth, and free of abrupt breaks and protruding materials exceeding 3/4 inch. Where the existing canal or lateral surface is below the membrane lining grade, approved excavated material shall be placed to the elevation of the underside of the membrane lining as shown on the drawings or as directed. Frozen materials shall not be used. In hard or unsuitable foundation material, the subgrade shall be prepared in accordance with paragraph _____(Preparing Subgrade in Hard or Unsuitable Foundation Material).

After the canal excavation has been completed to the approximate lines and grades of the subgrade, the subgrade surfaces shall be dragged and rolled, if required, as provided below.

b. Dragging subgrade.–Drags may be metal beams of structural shapes, sections of crawler-type tractor tread, or other approved devices. For hard subgrades, a heavy flexible-type drag, weighing about 100 pounds per foot of drag, shall be used. Chain drags shall not be used for such heavy dragging unless approved by the Contracting Officer.

The subgrade shall be dragged with two or more passes of the drag to produce a surface free of abrupt breaks and protruding material. If dragging does not produce the required surface, then the subgrade shall be rolled in accordance with subparagraph c.

Excess material accumulated on the bottom of the canal as a result of dragging or any other operation shall be removed prior to final preparation of the canal bottom.

c. Rolling subgrade.–Generally, rolling of the subgrade will not be required. When required to provide a firm, reasonably even, and smooth surface upon which to place the PVC lining, rolling the subgrade will be directed. The rollers used shall have smooth rolling surfaces and may be either vibratory or nonvibratory types, as approved by the Contracting Officer. The number of passes of the roller over the subgrade shall not be more than is required to produce the most suitable surface for the type of material being rolled.

If rolling of the subgrade is required, as determined by the Contracting Officer, an equitable adjustment will be made in accordance with the clause "Changes" of the General Provisions.

d. Sanding of subgrade.–Whenever lining is to be installed on a slick, wet subgrade and, in the opinion of the Contracting Officer, satisfactory lining stability cannot be attained, the Contractor shall apply about a 2-inch layer of sand over the subgrade. The Contractor shall obtain the sand from a source approved by the Contracting Officer.

e. Measurement and payment.–Measurement for payment of preparing subgrade for buried lining in earth material will be made on the number of square yards which have been prepared as herein prescribed within the canal prism, and no measurement will be made of areas not to be covered by buried lining or areas prepared in accordance with paragraph_____ (Preparing Subgrade in Hard or Unsuitable Foundation Material).

Payment for preparing subgrade for buried lining in earth material will be made at the unit price per square yard bid in the schedule, which price shall include the cost of dragging as described in subparagraph b.

Sand for sanding subgrade will be measured in place. Payment for sanding subgrade will be made at the unit price per cubic yard bid in the schedule, which unit price shall include the cost of loading, hauling, placing, and any incidental work connected therewith. The bid quantity was estimated from data obtained on dates shown on the drawings, and conditions encountered at the time of construction may increase or decrease this estimated quantity. The Contractor will be entitled to no additional allowance above the unit price bid in the schedule by reason of any amount or none of the work being performed under the sanding subgrade pay item of the schedule.

PREPARING SUBGRADE IN HARD OR UNSUITABLE FOUNDATION MATERIAL

a. General.–The provisions of this paragraph are applicable to the preparation of the subgrade for buried lining where the subgrade is hard or in unsuitable foundation material which cannot be excavated and trimmed efficiently by excavating and trimming machinery or will not result in the desired foundation, such as in areas of large sharp gravel or cobbles where the canal prism is excavated to an additional depth as specified in subparagraph_____ c. (Excavation).

The item of the schedule for preparing subgrade for buried lining in hard or unsuitable foundation material includes the filling of the additional excavation to the underside of the lining with a sand and gravel bedding. The material used for this bedding shall be the same as provided in subparagraph_____ a. (Sand and gravel cover), except that all material shall pass the 3/4-inch screen. The materials shall be placed, moistened if required, and rolled with two passes of the roller in accordance with subparagraph b. below; *Provided*, That where areas are found in the overexcavated subgrade that are in fissured rock or large gravel that will allow the fine fraction of the sand and gravel bedding to be leached out of the bed, as determined by the Contracting Officer, a special bedding material will be specified or special treatment of the overexcavated subgrade will be prescribed by the Contracting Officer. An equitable adjustment will be made in accordance with the clause of the General Provisions entitled "Changes."

The handling, transporting, and placing of the sand and gravel bedding material shall be subject to approval and shall be such as to result in a uniform mixture of the material being placed without separation or segregation. Gravel shall be obtained from borrow pits approved by the Contracting Officer or from suitable material from required excavation in the canal prism.

Where gravel is procured from privately owned lands, the Contractor shall make all necessary arrangements with the landowners. Any royalties or other charges required to be paid for materials taken from deposits not owned or controlled by the Government and under the control of the Bureau of Reclamation shall be paid by the Contractor.

b. Rolling bedding.–Rolling shall be performed using a smooth cylindrical roller. Two passes of the roller over the areas of the bedding surface will be required. Unless otherwise approved, the width of the roller drum shall not exceed 4 feet, and the weight of the roller drum, when fully loaded, shall not be less than 50 pounds per linear inch of drum width. A roller may consist of two adjacent drum units; *Provided*, That a flexible coupling between the drums is used and the space between drums shall not exceed 12 inches. Single-drum rollers shall overlap each roll by one-half the width of the roller

and two-drum rollers shall overlap each roll by one-half the width of the roller plus 1 foot. The overlap will be considered as the second pass.

The Contractor may submit other roller designs for consideration by the Contracting Officer and, if deemed acceptable, will be approved for use under these specifications.

c. Measurement and payment.–Measurement for payment of preparing subgrade in hard or unsuitable foundation material will be made on the finished subgrade surfaces of the canal over which buried lining is prescribed and actually prepared for buried lining, as provided in this paragraph. Payment for preparing subgrade for buried lining in hard or unsuitable foundation material will be made at the unit price per square yard bid in the schedule, which unit price shall include the cost of furnishing or procuring, hauling, placing, moistening, and rolling the sand and gravel bedding, and of all other operations required for the preparation of the subgrade as specified. No additional allowance, above the unit price per square yard bid in the schedule for preparing the subgrade in hard or unsuitable foundation material, will be made on account of lesser or greater amounts of this work being required.

_____. PVC LINING

a. General.–The lining material shall be PVC plastic film of 20-mil thickness. The lining shall be fabricated to a width to cover the canal cross section, allowing the necessary slack to prevent the lining from being taut when covered. (The lining material should be in convenient lengths of several hundred feet for ease of installation.)[2]

b. Sampling, testing, and approval.–

(1) Sampling.–The PVC membrane lining shall not be fabricated until the roll goods have been tested and approved by the Government. As directed by the Contracting Officer, samples of the roll goods shall be obtained by Government inspectors for testing and approval. One 3- by 6-foot sample for each 10,000 square yards, or fraction thereof, of roll goods proposed to be used in fabricating the lining shall be obtained for testing. The samples shall be identified as to manufacturer, date manufactured, and production lot numbers represented. In addition, a representative factory seam, 1 by 6 feet, shall be obtained for testing and approval. This factory seam should be fabricated so that peel strength tests (ASTM designation: D 413) can be conducted on the seam. This will require a wider than normal overlap, leaving 3 inches of PVC unbonded between the edge of one sheet and the bond area. The

[2]Delete if not applicable.

samples shall be submitted to: Assistant Commissioner, Engineering and Research Center, Attn: D-1521, P O Box 25007, Denver CO 80225.

The samples to be tested by the Government shall be available for testing at least 45 days before the lining is to be fabricated. When submitting the samples, the Contractor shall furnish certification that the samples submitted are representative of the material to be supplied for installation by the Contractor under these specifications. The accuracy of all certifications shall be guaranteed by the Contractor.

(2) Testing.–The physical properties of the PVC lining shall be determined by the test methods specified in table A-1.

Table A-1.–*Physical properties and test methods for PVC lining*

Property	Required	Test method
1. Thickness, min.	0.019 inch	ASTM: D 1593, para. 8.1.3
2. Specific gravity, min.	1.20	ASTM: D 792, method A
3. Tensile properties:		ASTM: D 882
a. Breaking factor, each direction, min.	46.0 lbf/in	
b. Elongation at break, each direction, min.	300%	
c. Modulus at 100 percent elongation, each direction, min.	18.0 lbf/in	
4. Tear resistance (Graves), each direction, min.	6.0 lbf	ASTM: D 1004
5. Low temperature impact	Not more than 5 specimens out of 10 shall fail at −15 °F	ASTM: D 1790
6. Directional stability, each direction, max.	5.0%	ASTM: D 1204, 15 min. at 212 °F
7. Plasticizer:		
a. Water extraction, max. percent weight loss	0.35%	ASTM: D 1239, immersion in 122 °F distilled water for 24 hours
b. Volatile loss, max.	0.9%	ASTM: D 1203, method A
c. Resistance to soil burial, increase in modulus at 100 percent elongation each direction, max.	10.0%	ASTM: D 3083, 30-day soil burial
*8. Bonded seam strength, tensile, each direction, min. percent of breaking factor	80%	ASTM: D 882
*9. Bonded shear strength, peel adhesion	Film tearing bond (FTB)	ASTM: D 413, strip specimen, type A, 180° peel, 2-inch width, 2 in/min

* Tests conducted on factory seams

A mass spectrometry chemical anaylsis shall be obtained on a sample of the roll goods approved for fabrication and on random field samples of the fabricated lining for purposes of verification of initial formulation submitted for approval.

(3) Approval.–Roll goods meeting the physical requirements listed in table A-1 shall be approved for use in fabricating the lining.

c. Material.–The PVC lining shall be suitably formulated from domestic virgin PVC resin; polyethylene-type resins are not acceptable. The plasticizer system used shall be such to ensure adequate resistance of the lining to mildew and bacterial degradation. The PVC lining shall be compounded with stabilizers and biocides to impart durability. The use of water-soluble compounding ingredients is prohibited. The PVC lining shall be pigmented with carbon black to produce an opaque film ranging from dark gray to black in color. The carbon black shall be evenly dispersed so as to produce a uniform color.

The lining shall have a smooth, dull, matte finish on both sides. The lining shall be uniform throughout and shall be free from dirt, oil, foreign matter, scratches, cracks, creases, bubbles, pits, tears, holes, pinholes, or other defects which may affect its serviceability.

The lining shall be fabricated from film widths of no less than 58 inches. The seams shall be factory bonded using a liquid cement or commercially accepted dielectric sealing devices. Lap seams shall be used with a minimum lap of 1/2 inch and an electrode (die) width of 1/2-inch minimum. No prepared adhesive tapes shall be used. The seams shall be watertight and the tensile strength of the bonded seam either in the machine or transverse direction of the lining shall not be less than 80 percent of the breaking strength of the lining when tested in a similar direction, and shall tear the parent material when tested in peel adhesion.

The lining shall be capable of being bonded to itself by liquid cement for making field splices and repairs. The manufacturer shall furnish a cement suitable for joining or repairing the larger pieces in the field. The cement shall have been tested for longevity against both sun and water exposure and shall result in no appreciable stiffening of the lining.

d. Packaging.–The PVC lining shall be packaged in rolls or accordion folded (in both directions) to fit commercial or other containers.

(1) Rolls.–Each roll shall be wound on a substantial core and shall be wrapped with at least one layer of 60-pound Kraft wrapping paper. Each wrapped roll shall be packed, snug-fitting in a recessed-end fiberboard drum.

(2) Accordion fold.–The accordion-folded lining shall be adequately packed into snug-fitting containers to prevent damage to the lining during transit. The containers shall be of materials and construction acceptable by common or other carriers for safe transportation to point of destination. The containers shall be supported with a bottom fitted with appropriately spaced lugs for easy handling with forklift trucks. Wooden containers, crates, or pallets shall be designed to prevent damage to the lining by nails, screws, or other fasteners.

_____. INSTALLATION OF PVC LINING

The lining shall be anchored along each side of the canal section as shown on the drawings and held in place by sandbags or other approved methods until the cover material has been placed. Care shall be taken to ensure that the lining is placed in a slackened condition in the canal so that it will conform to the contour of the subgrade surface without being taut when covered with the earth cover material, and the sand and gravel cover material. The installation shall begin at the downstream end of the work and progress upstream. The lining shall be installed with the longitudinal factory seams parallel to the centerline of the canal. Adjacent sheets of lining shall be joined using an uncemented joint of 3 feet and shall be accomplished so that the downstream ends of the adjoining sheets are overlapping on top of the adjacent sheets as shown on the drawings. The lining shall be covered on the same day that it is installed.

Where the PVC lining joins concrete structures, the lining shall be attached to the concrete with a vinyl-to-concrete adhesive as shown on the drawings. Before the lining is attached to a structure, the concrete surface to which the lining is to adhere shall be thoroughly cleaned with a wire brush. The adhesive shall be applied to the concrete in accordance with the manufacturer's instructions.

_____. PAYMENT FOR PVC LINING

The unit of measurement for furnishing and placing PVC lining will be the square yard; *Provided,* That "at curves" measurements will be made along the edge of the lining at the outside of the curves. No payment will be made for laps, joints, seams, or for extra width because of manufacturer's limitations resulting in the necessity of purchasing a slightly wider sheet or combination of sheets. Payment for furnishing and placing the 20-mil PVC lining will be made at the unit price per square yard bid in the schedule, which unit price shall include the cost of furnishing the cement for, and completing, the required

seams and joints, and all required hand excavation for exposing the existing membrane lining and for sealing the lining to the structures. The square yardage shown in the schedule for furnishing and placing the PVC lining is the estimated surface area to be covered and does not include material required to make the 3-foot overlapped joints.

_____. EARTH COVER

a. General.–Earth cover shall be placed over the lining along the bottom and side slopes of the canal to the depths shown on the drawings or to the depths prescribed by the Contracting Officer to allow for settlement. The material used for earth cover shall be approved material obtained from excavation. Inclusion in the earth cover material of rocks, boulders, vegetative matter, brush, large roots, or other objectionable foreign matter will not be permitted.

The method and manner of placing earth cover material over the lining shall be subject to approval by the Contracting Officer. The cover material may be stockpiled on the canal berms or other approved areas convenient to placing operations. Draglines or other approved equipment may be used for placing the cover material.

Insofar as practicable, the placing of the cover material on the bottom of the canal shall precede the placing of cover material on the side slopes by an appreciable distance, as approved. All cover material on the slopes shall be placed beginning at the bottom and proceeding towards the top. The sliding of cover material over the lining shall be avoided. Placing of cover material shall be conducted in such a manner that the lining will not be displaced or injured. Placing by blading the material over the berm will not be permitted, except for finishing operations or for installations where the height of the lining is 3 feet or less and the berm is 4 feet or less above the canal grade. Permission for blading material over the berm may be revoked if tearing, displacement, or other injury to the lining is caused by such operation. The earth cover material shall be finished to a uniform and trim condition by dragging, as provided for in paragraph_____ . Lining cover material shall not be placed when the temperature is below 32 °F unless the Contractor can demonstrate that the PVC lining will not be ruptured by the cover placing operation.

b. Measurement and payment.–Measurement for payment for placing earth cover material will be based on the area of the material in place on the lining and to the thicknesses shown on the drawings. Payment for placing earth cover material on lining will be made at the unit price per cubic yard bid in the schedule, which unit price shall include the cost of excavating the material from stockpiles, loading, handling, placing, and all other costs involved in placing the cover material; *Provided*, That cover material obtained from required excavation will be paid for at the applicable unit price bid in

the schedule for excavation for buried membrane lining and also as placing earth cover material.

_____. SAND AND GRAVEL COVER

a. General.–The Contractor shall furnish and place sand and gravel cover over the earth cover to the depths shown on the drawings or to the depths prescribed by the Contracting Officer. Inclusion in the sand and gravel cover material of boulders, vegetative matter, brush, large roots, and other objectionable foreign matter will not be permitted. The sand and gravel cover material shall be obtained from deposits approved by the Contracting Officer.

(The Contractor may procure sand and gravel for use in the cover without charge from Government-owned pits, as shown on the location map, to the extent that materials are available within the pits; *Provided*, That all costs of processing material from this source necessary to secure compliance with these specifications and all costs of stripping necessary to procure the material shall be borne by the Contractor.)[3]

Any royalties or other charges required to be paid for materials taken from approved deposits not owned or controlled by the Government shall be paid by the Contractor. The approval of deposits by the Contracting Officer shall not be construed as constituting the approval of all materials taken from the deposits, and the Contractor will be held responsible for the suitability of all such material used in the work.

Preparatory to placing the sand and gravel cover, the earth cover shall be dragged by one or more passes of the drag in accordance with the provisions of paragraph____. The method and manner of placing cover material on the lining shall be subject to approval. Placing of sand and gravel shall be conducted in such a manner that the lining and earth cover shall not be displaced. The cover material may be stockpiled on the canal berms or in other approved areas convenient to placing the cover material. The cover shall be finished to a uniform and trim condition by light dragging with chain drags or other approved devices.

b. Measurement and payment.–Measurement for payment of furnishing and placing the sand and gravel cover material will be based on the area of the material in place on the earth cover material and to the thicknesses shown on the drawings. Payment for furnishing and placing sand and gravel cover material will be made at the unit price per cubic yard bid in the schedule, which unit price shall include the cost of stripping borrow areas, furnishing, processing, hauling, and placing operations. Draglines or other

[3]Revise or delete as applicable.

approved equipment may be used for placing the cover material as described in this paragraph.

_____. REFILL ABOVE LINING COVER

Refill above the lining cover material shall be placed to the lines and dimensions shown on the drawings or as directed by the Contracting Officer. The material used for refill above the lining shall be selected material and obtained from required excavation; *Provided*, That the Contractor may use sand and gravel cover material for refill above the lining. Regardless of whether cover material or material from required excavation is used, payment will be made at the unit price per cubic yard bid in the schedule for refill above the lining cover.

Measurement for payment of refill above the lining cover will be made to the lines shown on the drawings or established by the Contracting Officer. Payment for refill above the lining cover will be made at the unit price per cubic yard bid in the schedule, which unit price shall include the cost of excavating from stockpiles, hauling, and placing the material. Refill material obtained from required excavation will be paid for both as excavation and as refill above the lining cover.

APPENDIX B

MATERIALS SPECIFICATIONS FOR PVC MEMBRANE CANAL LINING

MATERIALS SPECIFICATIONS

PVC Membrane Canal Lining

1. Scope

These specifications cover PVC flexible membrane canal lining in three thicknesses for use as a buried membrane in earthen canals and storage reservoirs to prevent loss of water by seepage or leakage.

2. Applicable Specifications and Standards

a. Other specifications applicable to these specifications are:

ASTM designation:	
D 413	– Rubber Property–Adhesion to Flexible Substrate.
D 618	– Conditioning Plastics and Electrical Insulating Materials for Testing.
D 792	– Specific Gravity and Density of Plastics by Displacement.
D 882	– Tensile Properties of Thin Plastic Sheeting.
D 1004	– Initial Tear Resistance of Plastic Film and Sheeting.
D 1203	– Loss of Plasticizer From Plastics.
D 1204	– Linear Dimensional Changes of Nonrigid Thermoplastic Sheeting or Film at Elevated Temperatures.
D 1593	– Nonrigid Vinyl Chloride Plastic Sheeting.
D 1755	– Poly (vinyl chloride) Resins.
D 1790	– Brittleness Temperature of Plastic Film by Impact.
D 3083	– Specifications for Flexible Poly (vinyl chloride) Plastic Sheeting for Pond, Canal, and Reservoir Lining.

3. Requirements

a. Material.–The membrane shall be suitably formulated from homopolymer vinyl chloride resin of type GP in accordance with ASTM designation: D 1755; and compounded with suitable plasticizers, fillers, and additives to impart durability. A biocide shall be incorporated into the material to provide resistance to biological degradation of the membrane. The membrane shall be compounded with carbon black and other ultraviolet stabilizers to provide resistance to ultraviolet degradation. The carbon black shall be evenly dispersed so as to produce a uniform color. The use of water-soluble compounding ingredients is prohibited.

The membrane shall be uniform throughout and shall be free from dirt, oil, foreign matter, scratches, cracks, creases, bubbles, pits, tears, holes, pinholes, or other defects which may affect the serviceability of the membrane, as determined by the Contracting Officer.

The PVC membrane lining shall be fabricated from a film width of no less than 58 inches.

The lap seams shall be factory bonded using a liquid cement or commercially accepted dielectric sealing devices. Hot-air seaming methods shall not be used. Lap seams shall be used and have a 3/4-inch minimum lap and a 3/4-inch minimum electrode (die) width. The seams shall be watertight, and the strength of the bonded seam in either the machine (longitudinal) or transverse direction of the film shall not be less than 80 percent of the breaking strength of the film when tested in a similar direction, or shall tear the parent material when tested in peel adhesion.

The film shall be capable of being bonded to itself by liquid cement for making field splices and repairs. The manufacturer shall furnish a cement suitable for joining or repairing the larger pieces in the field. The cement shall not be affected by sun or water exposure and shall not produce any detrimental effect to the film.

The PVC membrane lining shall meet the physical requirements of table B-1.

4. Sampling, Testing, and Approval

a. Sampling.–The PVC membrane lining shall not be fabricated until the roll goods have been tested and approved by the Government. As directed by the Contracting Officer, samples of the roll goods shall be obtained by Government inspectors for testing.

One 3- by 6-foot sample for each 10,000 square yards, or fraction thereof, of roll goods proposed to be used in fabricating the lining shall be obtained for testing. The samples shall be identified as to manufacturer, date manufactured, and production lot numbers represented. Each sample shall be clearly marked as to the longitudinal and transverse direction with respect to the manufacturing process. In addition, a representative 1- by 6-foot factory seam shall be obtained for testing and approval. This factory seam should be fabri-

ers shall be supported with a bottom filled with appropriately spaced lugs for easy handling with forklift trucks. Wooden containers, crates, or pallets shall be designed to prevent damage to the film by nails, screws, and other fasteners.

c. Package identification.–Unless otherwise specified each package shall be marked with the name of the material, the specifications symbol, lot numbers, the quantity contained therein as defined by the contract or order under which shipment is made, the name of the Contractor, and the number of the contract or order.

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