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# Performance Assessment of Test Liners for Petroleum Product Storage Areas in Northern Canada

Technology Development Report

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Environmental Impact Control Directorate

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**PERFORMANCE ASSESSMENT OF TEST LINERS FOR PETROLEUM  
PRODUCT STORAGE AREAS IN NORTHERN CANADA**

EBA Engineering Consultants Ltd.  
Edmonton, Alberta

**A Report Submitted To:**

Environmental Emergency Division  
Environmental Protection Service -  
Northwest Region  
Department of Fisheries and the Environment  
Edmonton, Alberta

EPS-4-EC-78-6  
May, 1978

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## ABSTRACT

In early 1976 the Environmental Protection Service of Fisheries and Environment Canada started assessment of liner systems appropriate for containing petroleum products. The study was directed toward suitable liners that could be placed economically in existing northern petroleum storage facilities located on pervious ground.

Test sections of four potential liner materials were installed at a tank farm near Yellowknife, N.W.T. during the summer of 1976. The four liner systems were: a processed bentonite, which was mixed with in-situ soils; a molten, spray-applied sulphur, which formed a rigid liner; two urethane coatings, spray-applied onto a fabric backing; and two types of urethane foams.

EBA Engineering Consultants Ltd. undertook an assessment of the test sections during the summer of 1977 in order to evaluate performance of the various materials after a year of exposure to the harsh northern climate. The report culminating that study contains a summary of procedures used and problems encountered during installation of the test sections. Detailed field observations taken during the summer of 1977 are documented. Results of laboratory testing on samples of the liner materials are reported. Based on these data, suitability of the four liner systems is appraised.

Proper equipment is necessary to mix and compact the bentonite liner correctly. Because such equipment cannot be used in congested areas, this material is not considered appropriate for existing tank farms. The sulphur liner exhibits a propensity to crack, at least in its present stage of development. An unacceptably high level of maintenance would likely be required to maintain liner integrity. The urethane coatings performed adequately over one year, but now show initial signs of weathering damage. Their use in limited term installations only is prudent until the ultimate degree of weathering can be assessed. Urethane foam liners show good potential for use as liners in petroleum product storage areas.

## RESUME

Au début de 1976, le Service de la protection de l'environnement du ministère des Pêches et de l'Environnement du Canada a entrepris d'évaluer divers genres de revêtements convenant au stockage des produits pétroliers. L'étude a porté sur les matériaux dont pourraient être équipés à peu de frais les réservoirs de pétrole, construits dans le Nord, sur un sol perméable.

Au cours de l'été 1976, quatre revêtements ont été installés à titre expérimental dans un parc à réservoirs, près de Yellowknife. Il s'agissait de bentonite mélangée sur place avec différents sols; de soufre fondu, vaporisé pour former une garniture ridige; d'uréthane vaporisé à deux reprises sur une trame de toile; et de deux sortes de mousse d'uréthane.

A l'été 1977, la firme EBA Engineering Consultants Ltd. a entrepris de mesurer la résistance des revêtements après un an d'exposition aux rigueurs du Nord. Le rapport de cette étude résume les méthodes employées, les difficultés d'installation des revêtements et fournit des renseignements bibliographiques concernant les observations détaillées faites sur place durant l'été 1977. Il comprend aussi les résultats des essais en laboratoire des échantillons de revêtements. L'évaluation s'est faite à partir de l'ensemble des ces données.

Dans les parcs à réservoirs existants, la bentonite ne convient pas parce que l'équipement pour la mélanger et la tasser y est difficile à manier. Quant au soufre, il a tendance à se fissurer, du moins dans l'état actuel de la technique. Il faudrait beaucoup trop d'entretien pour le garder en bon état. L'uréthane s'est bien comporté durant l'année d'essai, mais les agents atmosphériques commencent à l'altérer. En attendant de savoir combien de temps il pourra résister, il est mieux de l'utiliser uniquement pour des installations provisoires. Par ailleurs, l'emploi de mousses d'uréthane dans les parcs de stockage de produits pétroliers semble prometteur.

## **FOREWORD**

EBA Engineering Consultants Ltd. conducted this study under contract to the Department of Fisheries and the Environment. Mr. R.H. Weir of the Environmental Protection Service, Northwest Region, and Mr. P.J. Blackall, Environmental Emergency Branch in Edmonton, acted as scientific authorities.

Helpful contributions were also made by Dr. D.E. Thornton and other members of the Northern Dyking Committee; Mr. J.E. Paulson of the Chevron Research Company; and Mr. M. Bertane of the American Colloid Company.

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## **1 INTRODUCTION**

### **1.1 Background**

Over the past three years the Environmental Protection Service of Fisheries and Environment Canada has undertaken the assessment of newly developed liner systems with potential to be placed in existing petroleum storage areas in northern Canada. During the summer of 1976, a test site was established at the Gulf Oil Canada tank farm at Yellowknife, N.W.T. By the summer of 1977, test sections had been subjected to one cycle of the harsh northern climate. This study ensued because it was felt that further data regarding the suitability of the various products would be gained by an assessment of the weathering damage.

### **1.2 Products**

Table 1 describes the products placed at the test site, and Figure 1 shows the location of the various test sections at the site.

### **1.3 Site Description**

The test sections are located at the Gulf Oil Canada Ltd. tank farm in Kam Lake Industrial Park, approximately 3 km (2 miles) southwest of Yellowknife, N.W.T. The area surrounding the tank farm is undulating and tree covered with spruce, some pine, and poplar ranging up to 4 m (13 ft) in height. Evidence remains from a fire 15 to 20 years ago. The natural ground surface is hummocky, moss covered, and generally dry, with the exception of a low area immediately southwest of the tank farm. No evidence of groundwater was noted, nor do streams or dry stream beds exist nearby.

Surficial organic soil, 7 to 15 cm (3 to 6 in) thick, overlies a stiff, greyish-brown silty clay that is estimated to be at least 2 m (6 ft) thick. Precambrian bedrock outcrops at several locations just east of the tank farm and is therefore believed to exist at shallow depth below the site.

It is understood that the tank farm was constructed during the winter of 1974-75 by stripping surficial soil, levelling the site, and then building up a gravel pad approximately 1.5 m (5 ft) thick. Pad thickness beneath buildings and tanks was somewhat greater. Dykes were constructed of silty clay soil from the site and covered with a gravel dressing. The tank farm is generally well drained, with the exception of an area outside the dykes in the extreme southeast corner. This area is adjacent to a natural depression and is apparently flooded during spring runoff.

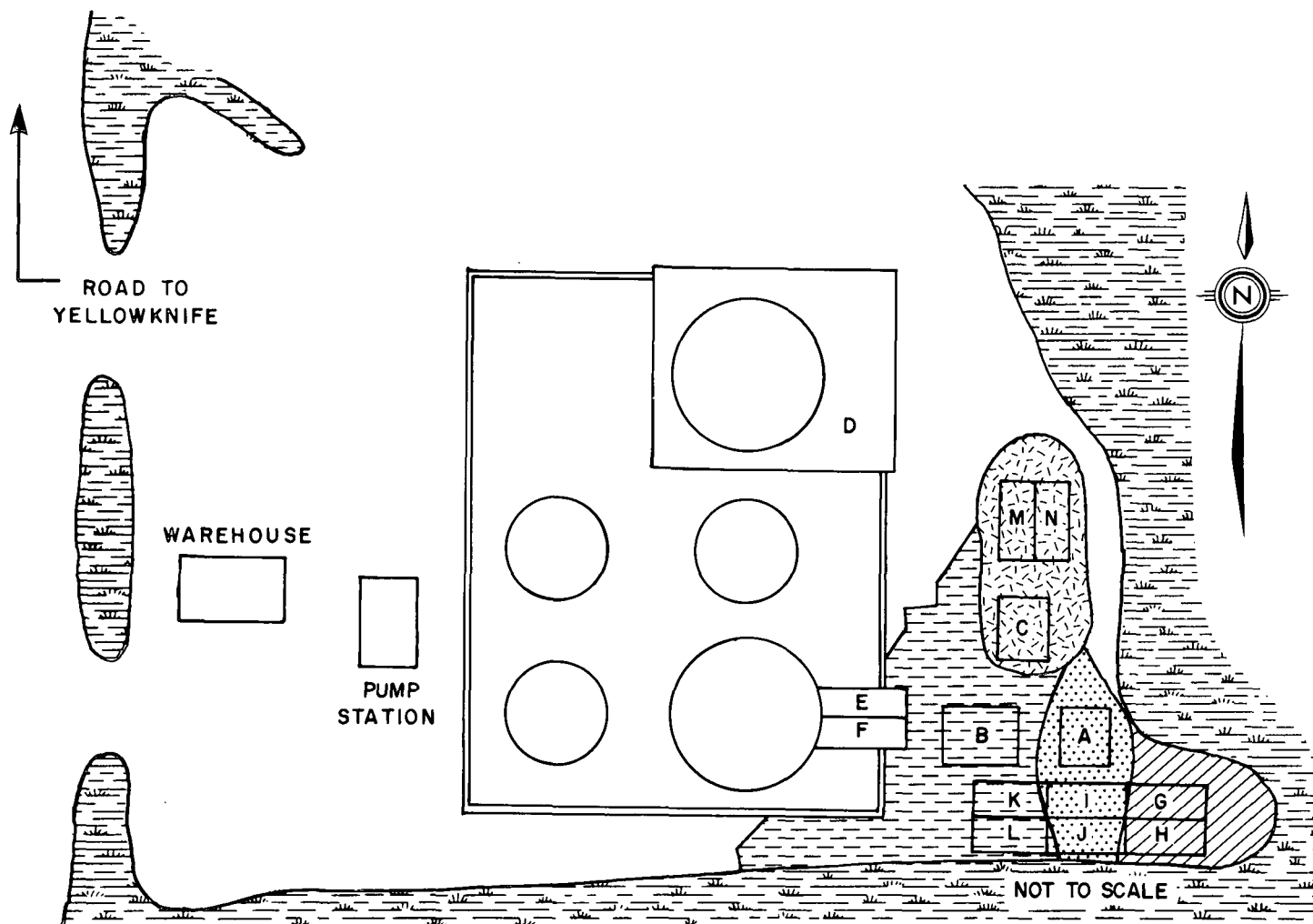
## **2 SITE PREPARATION AND PRODUCT INSTALLATION PROCEDURES**

All of the liner test sections were installed at the Yellowknife tank farm during August of 1976.



TABLE 1 LINER TEST PRODUCTS

GENERIC CATEGORY	PRODUCT DESCRIPTION
Processed Bentonite	<p>Volclay TFS-81 produced by American Colloid Company, Skokie, Illinois.</p> <p>Volclay is a high-swelling bentonite which has been treated to resist reversal of swelling (and increase in permeability) caused by attack of various chemical contaminants. It is mixed in dry form with the existing pervious soil, then hydrated to induce swelling so that all voids are filled and an impermeable soil blanket is formed.</p>
Processed Sulphur	<p>Chevron SUCOAT Coating Compound produced by Chevron Chemical Company, San Francisco, California.</p> <p>Sucoat consists of sulphur modified by chemical additives to improve strength characteristics, resistance to chemical attack, and other properties. It is spray applied in molten form, hardening to a rigid liner as it cools.</p> <p>Four formulations were used:</p> <ul style="list-style-type: none"> <li>I Basic formulation (Sucoat 100) mixed with modifier components on site.</li> <li>II Basic formulation, but mixed with modifier concentrate prepared previously.</li> <li>III Basic formulation with reinforcing material added to improve mechanical properties.</li> <li>IV Plasticizer component modified to improve low-temperature performance.</li> </ul>
Urethane Coatings	<p>Carboline X1304-173 produced by Carboline Co., St. Louis, Missouri.</p> <p>Elastuff 504 produced by United Coatings, Spokane, Washington.</p> <p>Both coatings are two-component, rapid-curing urethane polymers. Application onto a woven polypropylene scrim was achieved using high-pressure spray equipment.</p>
Urethane Foams	<p>"Normal" foam - 250 Spray System: nominal <math>32 \text{ kg/m}^2</math> (<math>2.0 \text{ lb/ft}^2</math>) density. Canadian Industries Limited, Mississauga, Ontario.</p> <p>"Slow" foam - 252 Spray System: nominal <math>48 \text{ kg/m}^3</math> (<math>3.0 \text{ lb/ft}^3</math>) density. Canadian Industries Limited, Mississauga, Ontario.</p> <p>Both foams are two-component, rigid urethane foams with relatively low densities. "Normal" and "Slow" refer to the time lapse between application and initiation of foaming action. Specialized spray equipment is utilized in application.</p>



BASE MATERIAL COMPONENTS

		MINE MUCK	BEACH SAND	4 cm CRUSHED GRAVEL	2 cm CRUSHED GRAVEL	OTHER PREPARATIONS
LINER MATERIAL	BENTONITE	•	A	B	C	•
	SUCOAT	•	•	•	•	D
	CARBOLINE	•	•	•	•	E
	ELASTUFF 504	•	•	•	•	F
	NORMAL FOAM	G	I	K	M	•
	SLOW FOAM	H	J	L	N	•

Fig.1 - SITE—GULF OIL CANADA TANK FARM, YELLOWKNIFE, N.W.T.

## 2.1 Processed Bentonite

The following section is based upon notes and observations made by Dr. D.E. Thornton of the Environmental Protection Service at the time of the bentonite test cell installation.

Bentonite test cells were prepared utilizing three base materials: beach sand, a very uniform fine sand; 2 cm (3/4 in) crushed gravel; and 4 cm (1.5 in) crushed gravel. These cells were approximately 20 to 30 m<sup>2</sup> (225 to 325 ft<sup>2</sup>) in size, each surrounded by a low dyke. Each cell was hand raked to a smooth surface, and vegetation, large rocks and other debris discarded. A cell prepared in this manner is shown in Plate 1. The supplier had recommended bentonite admixture quantities for each base soil. Bentonite was spread uniformly over the base material in each cell in the amounts shown in Table 2. The bentonite was then mixed with the top 10 cm (4 in) of base soil by repeatedly being turned over with shovels and raked, as shown in Plates 2 and 3, until the mixture was visually uniform.

Processed bentonite was shipped to the site in 45 kg (100 lb) bags, which were temporarily stockpiled under a tarp for protection from rainfall.

TABLE 2 BENTONITE TEST CELLS

BASE SOIL	BEACH SAND	2 CM CRUSH	4 CM CRUSH
Area m <sup>2</sup> (ft <sup>2</sup> )	21 (225)	21 (225)	30 (325)
Bentonite Loading kg/m <sup>2</sup> (lb/ft <sup>2</sup> )	17.6 (3.6)	19.0 (3.9)	20.5 (4.2)
Protective Soil Cover Type	Beach Sand	2 cm Crush	2 cm Crush
Protective Soil Cover Thickness cm (in)	2/3 of cell 8-10 (3-4)	2/3 of cell 8-10 (3-4)	1/4 of cell No Overburden
	1/3 of cell 15-20 (6-8)	1/3 of cell 15-20 (6-8)	1/3 of cell 8-10 (3-4)
			Remainder 15-20 (6-8)
Volume of Water to Flood m <sup>3</sup> (gal)	1.6 (350)	1.6 (350)	3.4 (750)

The mixture was then compacted with two to three passes of the mechanical tamper shown in Plate 4.

In order to protect the bentonite layer from excessive drying, the cells were covered with varying thicknesses of protective soil cover, as noted in Table 2. Finally, each cell was filled with potable water in order to hydrate the bentonite (see Plate 5).



Plate 1      Prepared test cell prior to application of the dry bentonite.

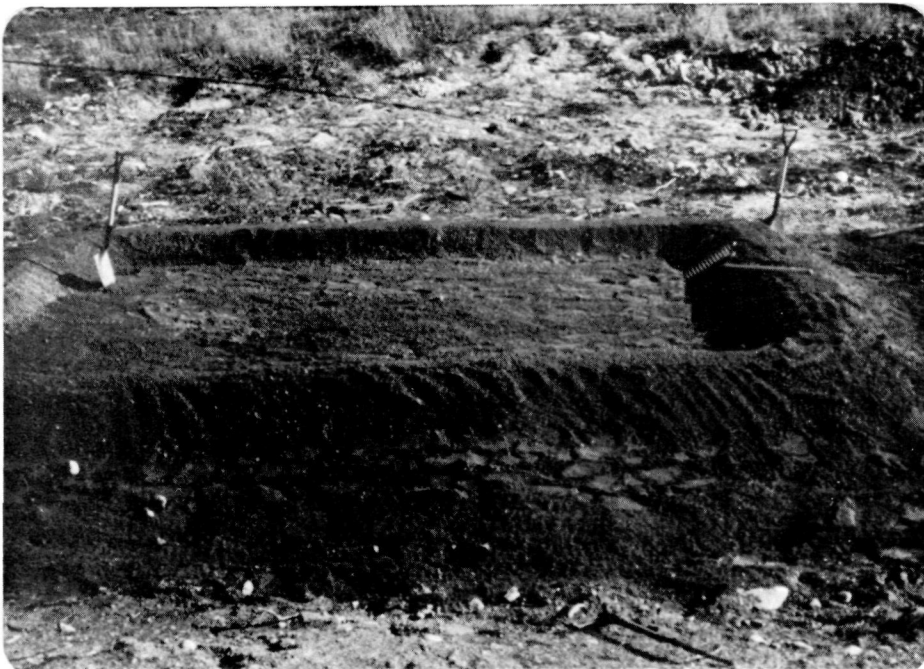


Plate 2      The correct number of sacks of bentonite (to achieve the nominal recommended loading) were placed in each prepared cell.



Plate 3      The dry bentonite was spread evenly around the cell, then mixed by repeated spading and raking until a visually uniform mixture was obtained.

Little can be inferred from these test cells about mixing and placement rates other than that hand mixing is a time-consuming operation. The three cells cover a total area of about  $70 \text{ m}^2$  ( $800 \text{ ft}^2$ ). Approximately eight man-days of preparation were required. Under normal circumstances, grading, spreading and mixing would be mechanized to the greatest possible extent, with hand work being employed in inaccessible corners only. No particular problems were reported during application. The weather was cool and dry.

## 2.2      **Processed Sulphur**

Detailed observations on the installation of the sulphur test liner are contained in the report "Yellowknife Containment Basin Project - Chevron Sucoat Coating Test Installation - August 1976" (J.E. Paulson, Chevron Research Company and J.W. Ankers, Chevron Chemical Company). The following section summarizes pertinent aspects of that report.

The base material in the northeast corner of the tank farm was a sandy gravel, with a top size of approximately 4 cm (1.5 in). In preparation for the sulphur test section, this area was hand raked smooth.

The test section was divided into 13 panels, as noted in Figure 2, ranging in size from  $5 \text{ m}^2$  ( $55 \text{ ft}^2$ ) to  $63 \text{ m}^2$  ( $680 \text{ ft}^2$ ). Most panels were separated from adjoining panels by wooden forms. One lap joint was constructed in which the upper lap was separated from the lower by a layer of mastic sealant. This layer eliminated bonding which would prevent independent movement between the panels.

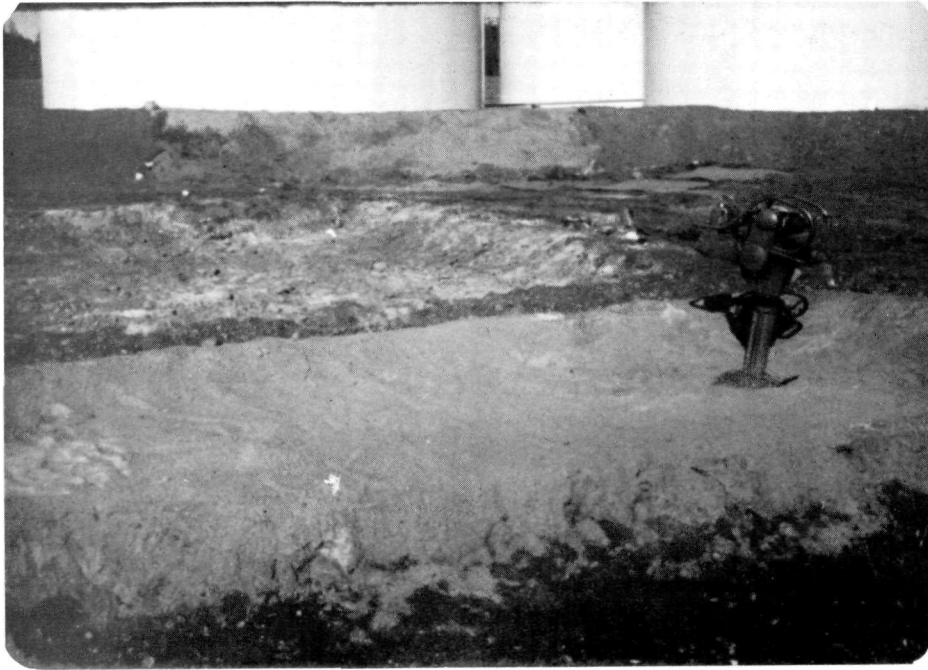


Plate 4      The bentonite-soilmixture was compacted using a mechanical tamper.



Plate 5      The compacted bentonite liner was hydrated with potable water in order to induce swelling in the clay, thus activating the liner.

Raw sulphur from Alberta was delivered to the site by truck. This material, shown in Plate 6, was stockpiled on the ground and covered with a tarp for protection from rainfall.

Plate 7 shows prototype equipment used to apply the sulphur lining. It included a skid-mounted melter-mixer with two tanks, a pump and manifold system, and a 30 m (100 ft) heated spray hose. All were mounted on a flatbed trailer for transport. Also used were a steam boiler, an electrical generator, a hopper and auger for charging the melt-mix tanks with raw sulphur, and a loader for moving raw sulphur from the stockpile to the auger.

The Sucoat was mixed in batches by charging the melt-mix tank with raw sulphur, melting this material and raising the tank temperature to 140°C (285°F) and mixing in the chemical modifiers, as shown in Plate 8. This procedure took two to three hours. Actual application temperatures were in the range of 125 to 140°C (260 to 285°F), and pump pressure was maintained at 275 to 345 kPa (40 to 50 psi). Nozzles nominally rated at 1.1, 1.5 and 3.0 l/s (15, 20 and 40 gpm) were used. Instantaneous spray rates ranged from 2.7 to 4.0 kg/sec (360 to 530 lb/min). Including pauses for shifts in hose position, average application rates were 1.1 kg/sec (150 lb/min) or about two hours spraying time per batch. Plate 9 shows the molten sulphur being applied. A total of 350 m<sup>2</sup> (3773 ft<sup>2</sup>) was lined with 21,400 kg (47,200 lb) of Sucoat prepared in four batches. Average thicknesses of the lining ranged from 2.0 to 4.0 cm (0.75 to 1.60 in). Approximately six passes with the 1.1 l/s (15 gpm) nozzle were required to build up a 2.5 cm (1 in) thickness.



Plate 6 Raw sulphur stockpiled on site was transferred to the melting apparatus by way of a front-end loader.



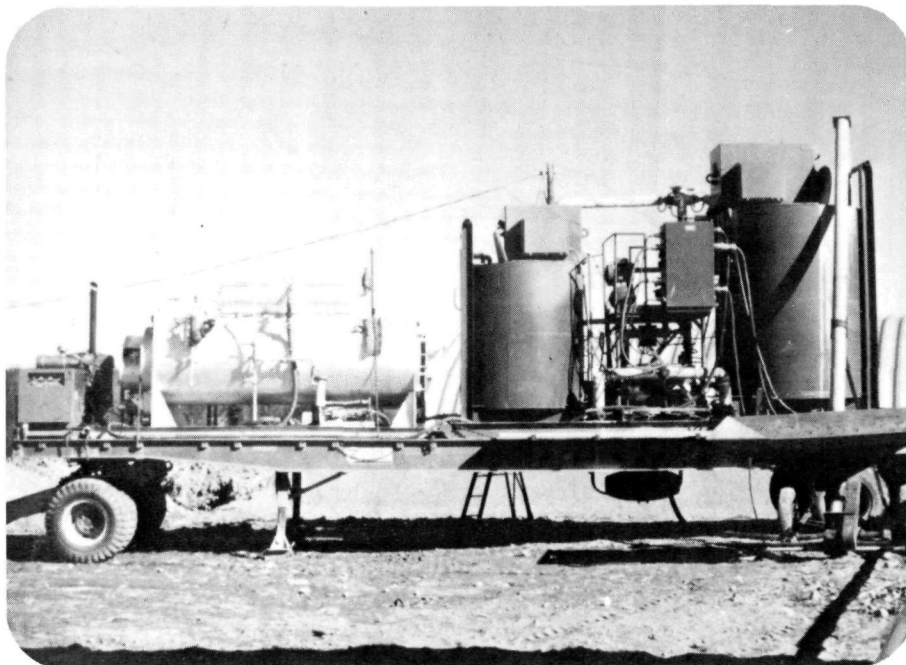


Plate 7 Trailer-mounted equipment for spray sulphur application: melter-mixer with tanks, pump and manifold system, steam boiler and auger.

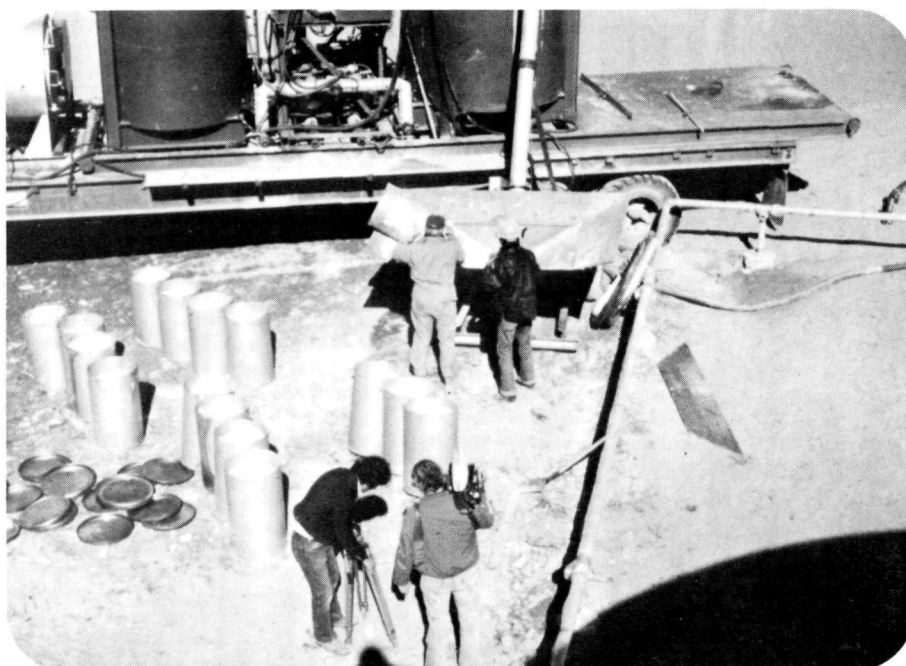
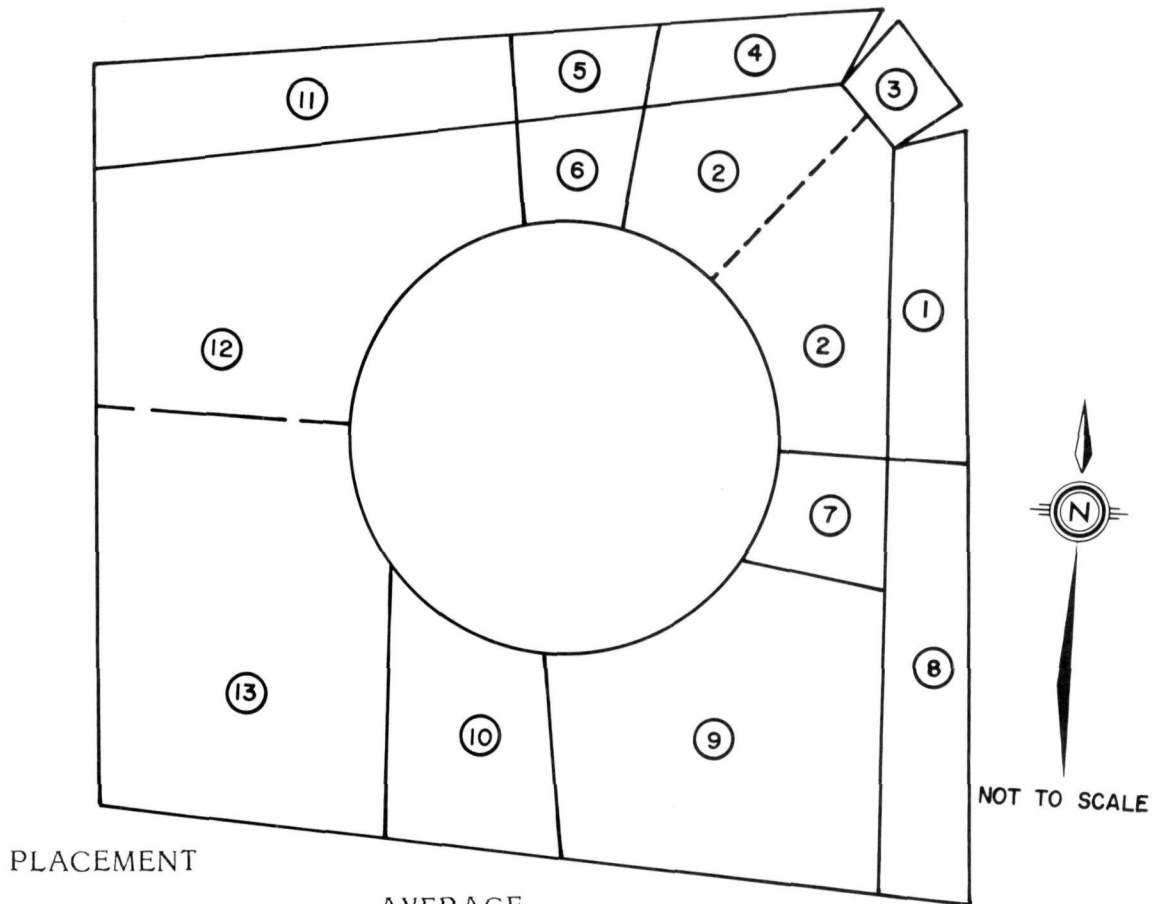


Plate 8 Once the raw sulphur had been melted, chemical modifiers were mixed in to form the Sucoat product.





PLACEMENT

PANEL	AREA m <sup>2</sup>	(ft <sup>2</sup> )	AVERAGE THICKNESS mm (in)	BATCH NO.	SUCOAT FORMULATION	kg (lb) APPLIED
1	19.5	(210)	32(1.25)	1	II	5260 (11600)
2	34.0	(365)	32(1.25)		II	
3	5.0	(55)	32(1.25)		II	
4	13.0	(140)	32(1.25)		II	
5	7.5	(80)	32(1.25)		II	
6	6.0	(65)	32(1.25)		II	
7	10.0	(105)	19(0.75)	2a	I	6600 (14550)
8	26.0	(280)	30(1.2)		I	
9	55.5	(600)	30(1.2)		I	
10	27.0	(290)	30(1.2)		I	
11	26.0	(280)	23(0.9)	2b	IV	1110 (2450)
12	58.0	(625)	41(1.6)	3	I	4540 (10000)
13	63.0	(680)	32(1.25)	4	III	3900 (8600)
Totals	350.5	(3775)	32(1.25)			21410(47200)

FIGURE 2 DETAILS OF SULPHUR TEST SECTION

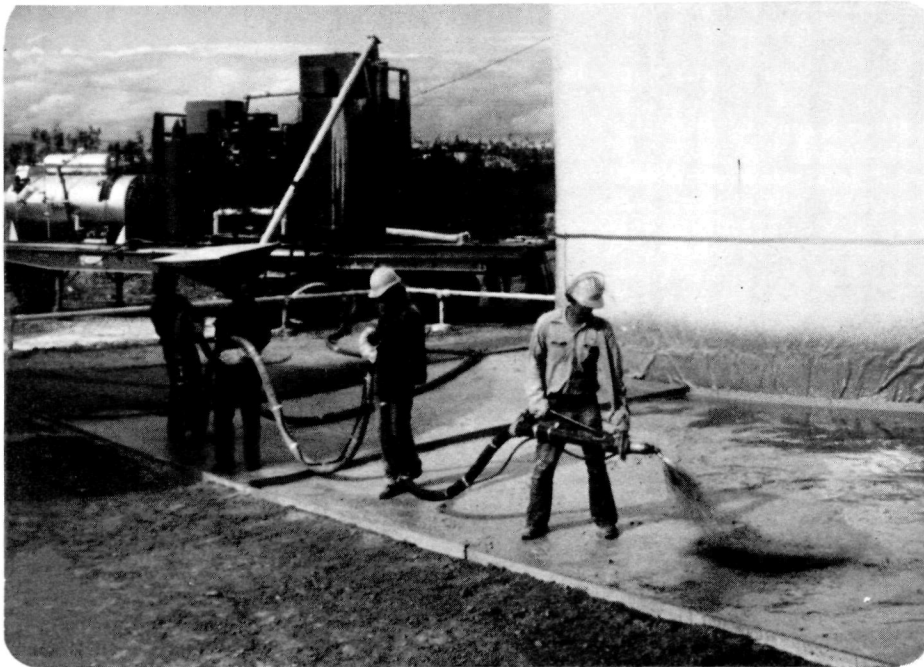


Plate 9      Work crew applying molten sulphur.



Plate 10      Cracks along the wooden forms, resulting from shrinkage upon initial cooling.



Plate 11      Panel edge, exposed after removal of a wooden form. Joints such as this were partially filled with sand, then covered with an elastic sealant.

Initial shrinkage upon cooling often resulted in formation of cracks along the wooden forms, as shown in Plate 10. When the panels had cooled, the wooden forms were removed, as illustrated in Plate 11; sand was poured in to within 1 cm (0.5 in) of the surface of the lining, and sealant was trowelled into the joint. Joint details are depicted in Figure 3. An asphalt-based sealant, Domtar Fibregum Plastic Cement, was used in the majority of the joints. Oil-based DAP Architectural Grade Caulking compound was used between panels 2 and 4, and DAP Butyl Gutter and Lap Sealer was used between panels 2 and 6.

Eight days were needed to complete the initial sulphur application; three days for setup, three days for base preparation and liner application, and two days for joint work, cleanup and equipment disassembly. Actual crew size ranged from three to seven; five men seemed to be an optimal size.

Some problems were encountered with hose mobility during spray operations. One nozzleman and three hose holders were necessary. The lack of maneuverability of the hose limited application rates, especially with the higher capacity nozzles. The authors of the Chevron report estimate that with lightweight hoses or mechanical hose supports, two hose holders could be eliminated and application rates doubled. The large batch plant used was selected on the basis of availability even though smaller capacity, more maneuverable units do exist. Because the areas of some panels were overestimated, some oversize batches were prepared, resulting in the construction of thicknesses slightly greater than those intended by design.

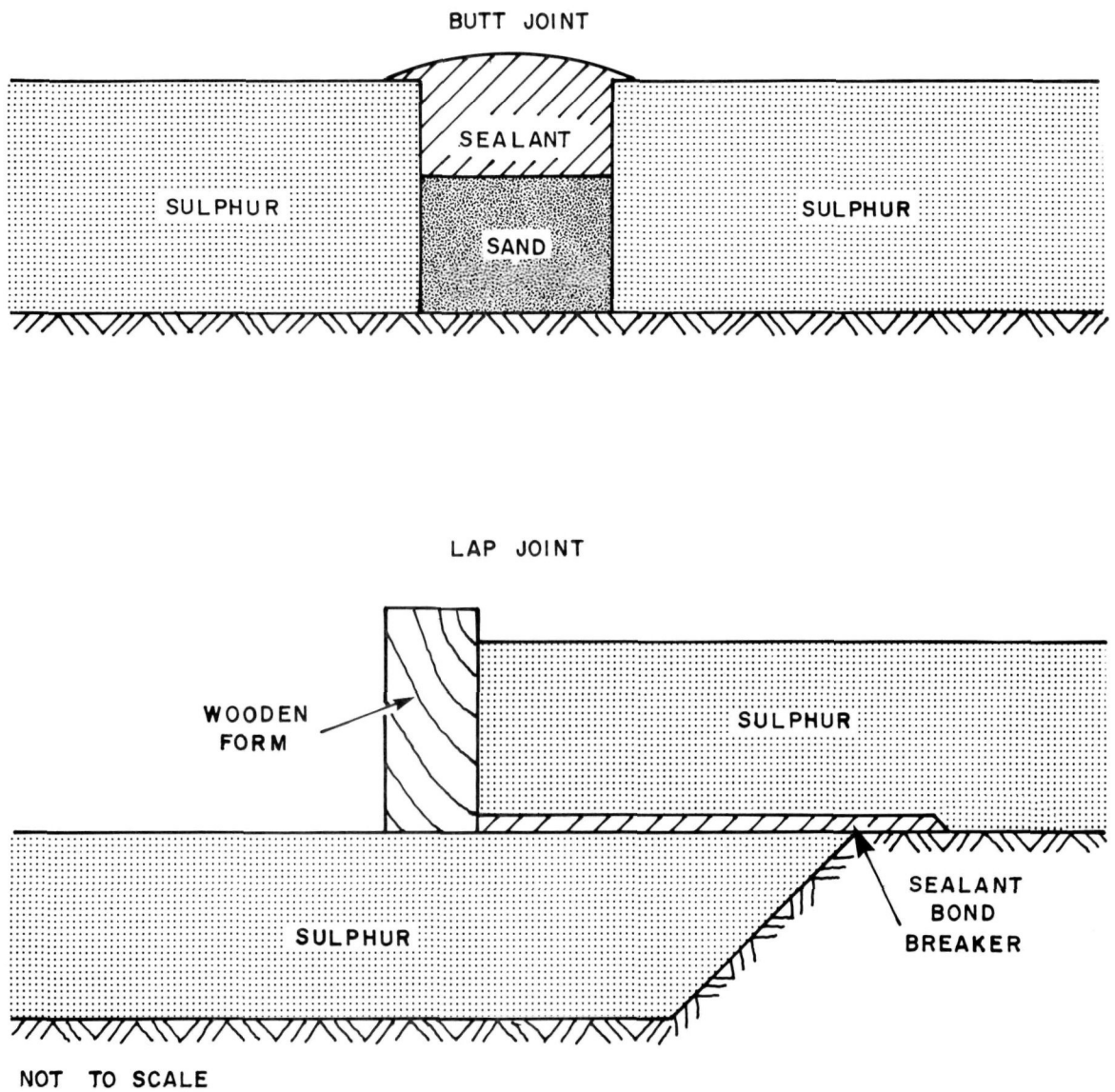


Fig.3 - SULPHUR PANEL JOINT DETAILS

No fire retardants were included in any of the four formulations. The Fire Marshall in Yellowknife requested that fire-resistant paint be applied over the sulphur liner. In the spring of 1977, Triathon, an elastomeric coating, was applied to panels 2, 3, 4, 5, 6, 9, 10, 11, 12 and 13. Diathon, a water-based acrylic, was applied to panels 7 and 8. Albi 107X and Albi 144, a two-coat intumescent system, was applied to panels 1 and 2. Portions ( $9 \text{ m}^2$  ( $100 \text{ ft}^2$ )) of panel 9 were left unpainted and were covered with a few centimetres of 2 cm crush gravel.

Weather during application was relatively warm and sunny, with only light winds.

### 2.3 Urethane Coatings

The following section is summarized from "A Study of Spray-On Liners for Petroleum Product Storage Areas in the North" (EPS-4-EC-77-2, February 1977).

The base material in the test area was a sandy gravel with a top size of approximately 4 cm (1.5 in). In preparation for the urethane coatings test sections, this area was hand raked to a smooth profile, and debris discarded.

The respective components of each of the two urethane coatings were contained in one gallon tins. A woven polypropylene fabric, Tufton, was used as a backing fabric. Materials and application equipment were transported to the site by truck from Vancouver, British Columbia.

The Tufton backing, provided in a 3 m (10 ft) wide roll, was placed quickly and easily by a three-man crew. It should be noted, however, that full-sized rolls needed on larger projects would require machine assistance. The Tufton scrim, shown in Plate 12, was joined to the tank by a strip of urethane foam which adhered to both the fabric and the tank. The urethane coatings were then applied continuously from the base of the tank, over the urethane foam and across the Tufton.

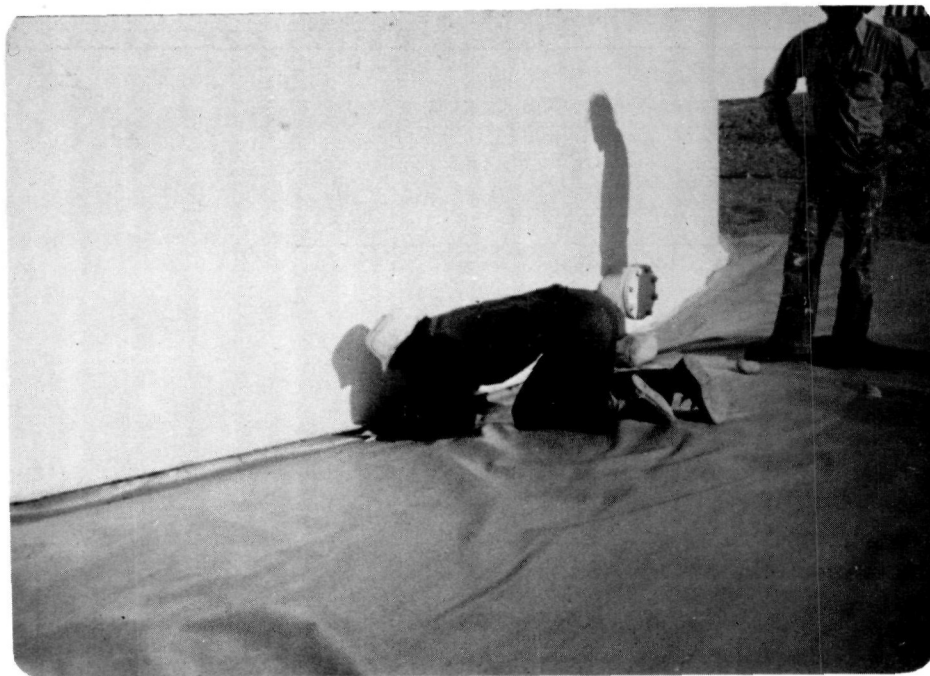


Plate 12 The Tufton backing fabric was hand-fitted around the tank: urethane foam was used to bond the fabric to the tank. The urethane coatings were applied monolithically from the base of the tank over the foam and across the Tufton.

Application equipment consisted of a 30:1 spray machine boosted with a 5:1 supply pump. A nozzle pressure of 170 kPa (2400 psi) was used. Although the Elastuff 504 was easily sprayed, the Carboline had to be diluted with approximately 10% methyl ethyl ketone to reduce viscosity. Because of the short pot life of both coatings, small batches of 20 l (5 gal) were used. Average thicknesses of film for both urethane coatings were in the range of 0.3 to 0.5 mm (10 to 30 mils). Yields were 1.1 m<sup>2</sup>/l (55 ft<sup>2</sup>/gal) for Carboline and 1.2 m<sup>2</sup>/l (60 ft<sup>2</sup>/gal) for Elastuff 504. Both sections were tack-free within two to four hours after placement.

The rate of application for a three-man crew should fall in the range of 75 to 100 m<sup>2</sup>/hr (800 to 1100 ft<sup>2</sup>/hr). Some improvement in this rate could be achieved if two mixing containers were used to permit spraying and mixing simultaneously.

Joints were made in the Tufton backing by bonding two layers of Tufton with urethane material, as shown in Plate 13. Then an additional coating of urethane was sprayed over the surface of the joint. Plate 14 illustrates this final step. Details of the liner-tank seal and lap joints are given in Figure 4. Plate 15 shows a wrinkle where the upper layer did not adhere properly. The outer end of the test sections was anchored by keying into a trench at the outside base of the dyke. The edges and centre of the test section were weighted down with sandbags. Some problems were encountered in forming well-bonded joints. It was concluded that it would be more appropriate to join sheets of the Tufton backing with a suitable adhesive rather than with urethane material.

Originally, each section was to be sprayed with a light tack coat. Then a thin course of sand was to be applied to the surface to act as an inflammable layer and traction course. Unfortunately, heavy rain delayed application of the tack coat and sand for several days. When the tack coat was finally applied, it was difficult to get the surface completely dry or free of dirt. As a result, the bond between the tack coat and the original coating was very poor.

When the test sections were viewed before the tack coat was applied, a number of small (1 mm) punctures were apparent in the coating. These punctures, which did not penetrate through the Tufton, were apparently the result of foot traffic scuffing the liner over the high points of the uneven gravel base.

Other than the rain, which delayed application of the tack coat, the weather was warm and sunny. Winds gusting to 30 km/h (20 mph) were potentially strong enough to cause problems with application and overspray, but the tanks and dykes offered sufficient shelter.

## **2.4 Urethane Foams**

The following section is further summarized from "A Study of Spray-On Liners for Petroleum Product Storage Areas in the North" (EPS-4-EC-77-2, February 1977).





Plate 13 Joints were formed by spraying the lower piece of Tufton, then pressing the upper piece into the tacky urethane material.



Plate 14 After the upper layer of Tufton was pressed into the tacky urethane material, an additional coat was sprayed over the entire joint. Note that Carboline is a lighter green than the Elastuff 504 in the foreground: compare with Plate 37.

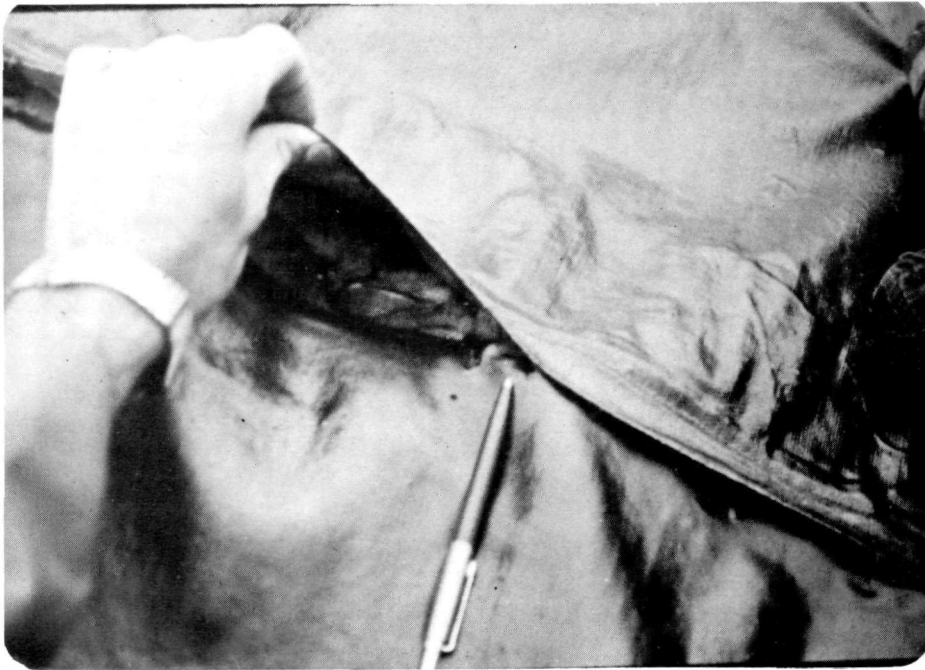
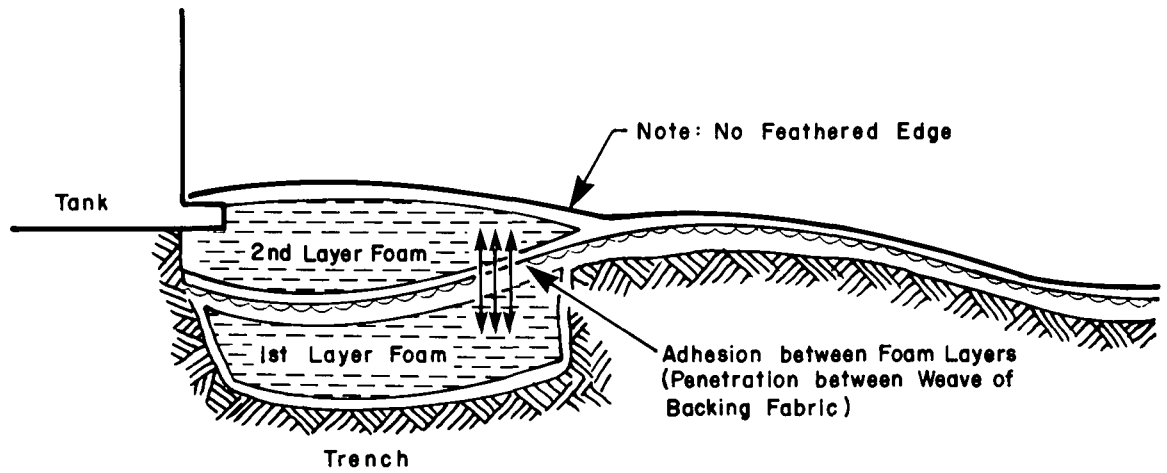


Plate 15      Localized areas of the joints did not adhere properly, leaving loose edges. The use of an adhesive compatible with the backing fabric would probably be more appropriate than urethane material.

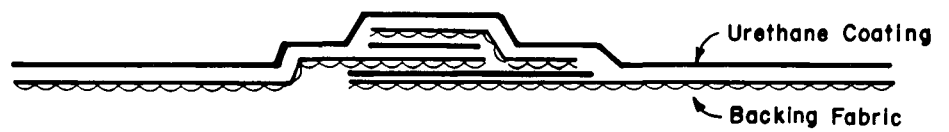
The urethane foams were applied over four base materials:

1.    **Mine Muck:**    very coarse waste from local mining operations. Individual gravel and boulders ranged from a maximum dimension of 40 cm (16 in) down to 1 cm (0.5 in) or less, and all particles were extremely rough and angular. Sand, with some silt, filled the voids between the coarse fragments in most areas. In two areas, about 0.5 m (1.5 ft) in diameter, no fines were present. In these areas, large voids extended to a depth of more than 20 cm (8 in). Because of the presence of cobbles and boulders, the surface of this material was extremely irregular.
2.    **Beach Sand:**    a very uniform, fine sand. Individual grains were rounded. This material was loose and appeared to have been dumped, then levelled with a small tractor.
3.    **2 cm Crush:**    a sandy, crushed gravel with a top size of approximately 2 cm (0.75 in). This loose material was placed in a similar manner to the sand and was subjected to little or no vehicle or foot traffic. The surface was levelled by hand raking.
4.    **4 cm Crush:**    a clean, crushed gravel with a top size of about 4 cm (1.5 in). This material was dense and had been hand raked smooth on the surface. Just prior to foam application, gravel 3 cm and larger was placed on the surface to simulate a situation in which the fines had been washed away.



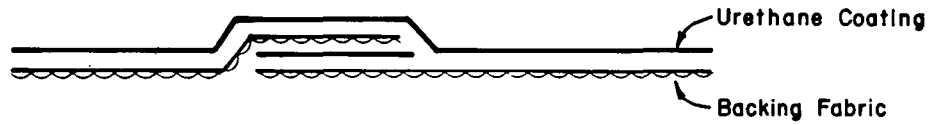


DETAILS OF LINER - TANK SEAL

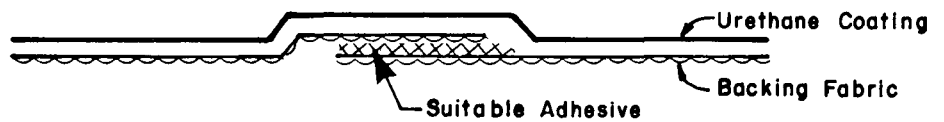


DOUBLE LAP

DETAILS  
OF  
URETHANE  
COATING  
JOINTS



SINGLE LAP



SUGGESTED SINGLE LAP JOINT

NOT TO SCALE

Fig.4 - URETHANE COATINGS—JOINT AND SEAL DETAILS

The foams applied over these base materials were a "normal" foam ( $32 \text{ kg/m}^3$ ) ( $2 \text{ lb/ft}^3$ ) and a "slow" foam ( $48 \text{ kg/m}^3$ ) ( $3 \text{ lb/ft}^3$ ). Normal foam infers that foaming action takes place almost immediately after leaving the nozzle, whereas with slow foam, 10 to 15 seconds may elapse before foaming action begins.

Components of each of the two urethane foams were contained in 45 gallon drums. Materials and application equipment were transported by truck to the site from Vancouver, British Columbia, and included a continuous mix proportioner with electrically heated hoses to maintain reagent temperature to the nozzle. The components were combined in the nozzle, initiating the foaming reaction as they were sprayed.

During actual application, little penetration into any of the base materials was noted for either "normal" or "slow" foam. The initial layer of foam in contact with the ground generally exhibited lower rise than the subsequent layers, probably because the ground acted as a heat sink, inhibiting the foaming reaction. Both foams adhered firmly to the base aggregate. In all cases, adhesion between the foam and rock exceeded cohesive strength of the foam. Coarse aggregate adhering to the bottom of the foam firmly anchored the liner to the ground; hence, there was no need for sandbags or other weights. On the sand base, the weight of the particles bonded to the underside of the foam was not sufficient to hold the liner down, as illustrated in Plate 16. The foam flexed freely under foot traffic.

Normal foam became firm within one minute of spraying, while slow foam took slightly longer to set. The higher density slow foam was considerably stiffer than the normal foam. Other comparative observations on foam application are summarized in Table 3.

In order to limit exposure of the foam to sunlight, two methods were used to coat the surfaces of test sections. About  $1 \text{ m}^2$  ( $10 \text{ ft}^2$ ) of sections built of the normal and slow foams was covered with Carboline; the remainder was covered with a tack coat of slow foam followed by a surface course of sand, as shown in Plate 17. It was necessary to use slow foam for the surface course because the normal foam did not remain tacky long enough to allow sand to stick. Both the Carboline and the sand were strongly bonded to the surface of the foam and appeared to cover the surface adequately. The sand surface also provided a non-slip covering. Approximately  $1 \text{ m}^2$  on each of the normal and slow foams was left uncovered for comparative purposes.

The degree of roughness of the base has a profound effect on application rates. On smooth surfaces, three layers may be applied at a rate approaching  $50 \text{ m}^2$  ( $550 \text{ ft}^2$ ) per hour. The surface roughness of the sorted, 4 cm crush gravel slowed the rate somewhat, as some spot spraying was required to fill individual voids. The extreme case was the mine muck substrate - an average application rate on this material might be as low as 15 to  $25 \text{ m}^2/\text{hr}$  ( $160$  to  $270 \text{ ft}^2/\text{hr}$ ). In addition to the extensive spot spraying required, as is evident in Plate 18, a higher degree of care is necessary on the part of the operator to ensure uniformity of coverage. Also, in the order of 50% more foam per unit area was needed to adequately cover the extremely uneven surface.

TABLE 3 OBSERVATIONS ON URETHANE FOAM APPLICATIONS

	MINE MUCK		BEACH SAND		4 cm CRUSH		2 cm CRUSH	
	Normal	Slow	Normal	Slow	Normal	Slow	Normal	Slow
Number of Coats	3 +Spot Spraying +Tack Coat	4 +Spot Spraying +Tack Coat	2 +Tack Coat	3 +Tack Coat	3 +Tack Coat	4 +Tack Coat	3 +Tack Coat	3 +Tack Coat
Uniformity of Coating	Variable -thin on top of large rocks, deep in low areas	Variable	Uniform	Somewhat Variable -excess thickness in a few locations	Somewhat Variable -thinner over large rocks -not as pronounced as mine muck	Somewhat Variable	Uniform	Uniform
Average Coating Thickness (cm)	3.8/3.8/3.0/4.3 Av = 3.7	4.0/3.3/4.3 Av = 3.9	3.5/3.3/3.8/ 3.5 Av = 3.3	3.8/3.5/2.5 Av = 3.3	3.8/3.3/ 3.0/3.8 Av = 3.5	3.5/3.0/ 3.0/4.5 Av = 3.5	2.5/3.0/ 3.0/2.8 Av = 2.8	2.3/2.0/ 2.5/2.0 Av = 2.2
Penetration into Substrate	Some penetration into larger surface voids	Good penetration into larger surface voids Blocked by fines	Low penetration into sand Some particles lifted 0.5 to 1 cm as foam rose		Good penetration into larger voids in sorted surface layer Low penetration into well-graded material below		Low penetration	Some penetration Top 0.5 to 1 cm well cemented together
Surface Appearance	No visible voids Uneven - follows contours of substrate		No visible voids Smooth - substrate was smooth		No visible voids Slightly uneven		No visible voids Smooth	
	Moderate resistance to cutting (also difficult to cut around large rocks)		Moderate resistance to cutting		Moderate resistance to cutting		Moderate resistance to cutting	
	Adhesion to aggregate in excess of foam cohesive strength		Adhesion to aggregate in excess of foam cohesive strength		Adhesion to aggregate in excess of foam cohesive strength		Adhesion to aggregate in excess of foam cohesive strength	
Test Section Area (m <sup>2</sup> )	6.8	5.0	5.3	3.8	4.7	3.5	6.6	6.6
Application Time (excluding tack coat) (minutes)	13	14	12	5	7	10	4	4
Material Used (kg)	16.6	35.4	9.7	11.4	10.2	19.0	8.8	22.5
Density of Application	2.4 kg/m <sup>2</sup>	7.1 kg/m <sup>2</sup>	1.8 kg/m <sup>2</sup>	3.0 kg/m <sup>2</sup>	2.2 kg/m <sup>2</sup>	5.4 kg/m <sup>2</sup>	1.3 kg/m <sup>2</sup>	3.4 kg/m <sup>2</sup>



Plate 16 The weight of beach sand adhering to the underside of the foam layer was not sufficient to hold the liner down; such raised areas could sustain fatigue cracking under repeated foot traffic.



Plate 17 Sand was sprinkled into a tack coat of slow foam to form both a friction surface and an opaque coating to reduce exposure of the foam to sunlight.

An unusual problem developed. Ravens were attracted to the Carboline covering. The birds pecked several holes through the Carboline and into the foam the first night after the coating had been applied. After a few days, the uncoated sections of foam also showed evidence of damage. The sand-coated section was left untouched.

Fatiguing damage could result from traffic on urethane foam liners applied over relatively fine-grained materials. For this reason, the use of a sufficiently large granular base would be considered advantageous in securely anchoring the liner.

The normal foam of lower density was more effective as a first layer. Its thicker rise filled voids more efficiently. Furthermore, the fast rise allowed the operator to rapidly evaluate the adequacy of the coating thickness. This reduced application time and material costs slightly, since only the necessary amount of foam was applied. An optimal arrangement is believed to be two layers of low-density foam to coat the surface and fill all voids, followed by a layer of a dense ( $48$  to  $80 \text{ kg/m}^3$ ) ( $3$  to  $5 \text{ lb/ft}^3$ ) foam to provide resistance to foot traffic.

Foam application took place on a warm, sunny day, with a light breeze. Soil temperatures were  $16^\circ$  to  $18^\circ\text{C}$  ( $60^\circ$  to  $65^\circ\text{F}$ )  $1 \text{ cm}$  ( $0.5 \text{ in}$ ) below the surface, and about  $3^\circ$  to  $4^\circ\text{C}$  ( $5^\circ$  to  $7^\circ\text{F}$ ) cooler at a depth of  $8 \text{ cm}$  ( $5 \text{ in}$ ).

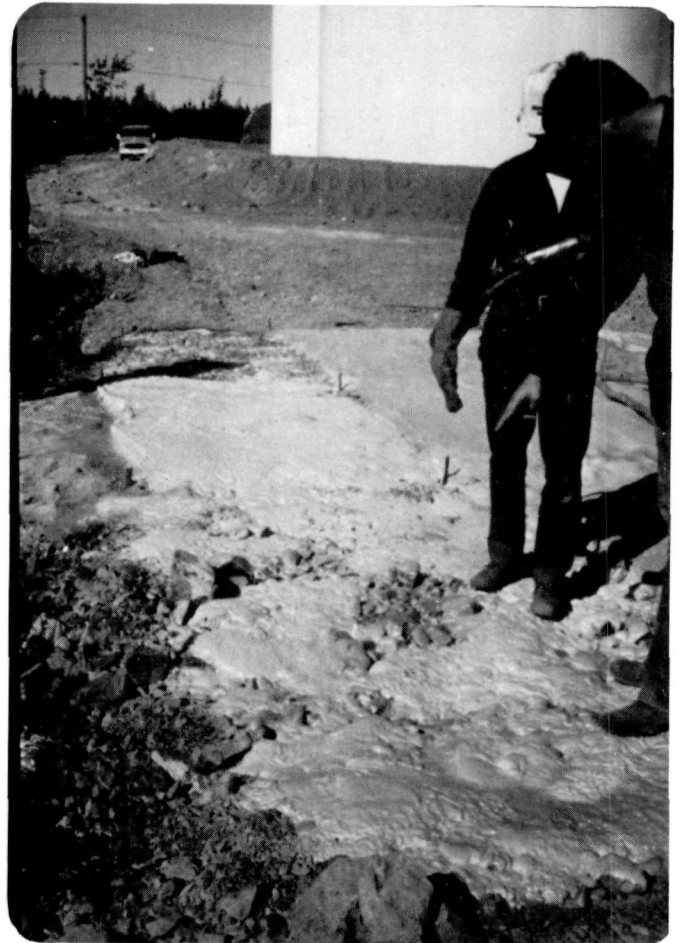


Plate 18      The rough mine-muck base required extensive spot spraying to ensure effective coverage.

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Plate 18      The rough mine-muck base required extensive spot spraying to ensure effective coverage.

## 2.5 Discussion

Installation of the various test sections went smoothly, with the exception of rain delaying the application of the tack coat on the urethane coatings.

Feasibility of large-scale, mechanized application of bentonite liners has been demonstrated on projects in more southerly latitudes, many of which are illustrated in product literature. However, the installation of a bentonite liner in congested tank farm areas where machinery is not easily maneuvered is not appropriate for two reasons: first, labour-intensive operations are extremely expensive in northern Canada and second, uniformity of mix is difficult to achieve without proper mechanical assistance. Although small rototillers or similar equipment would be an improvement over the manual methods described in Section 2.1, much heavier equipment is needed to achieve the uniformity necessary for a continuous liner. Also, compaction of the mixed soil is an important step in liner installation. Proper density standards should be established, quality control procedures adopted, and equipment capable of achieving the required density utilized.

Problems associated with installation of the sulphur liner, such as difficulties with hose mobility, arose from the large prototype equipment used for this installation. Application equipment in a variety of sizes is apparently available, at least on a limited basis. The degree of surface preparation necessary for this liner is slightly higher than that required for the others because wooden forms must be laid out to create appropriately sized panels. Additional work involves removing the forms after the sulphur hardens, and placing sealant in the joints. The incorporation of suitable fire retardants into sulphur formulations would eliminate a further step in future installations i.e., the necessity of applying a fire-resistant coat of paint.

The installation of urethane coatings and urethane foams represented a new application of technology. Successful fabrication of the field test sections demonstrated that construction of spray-on liners from these materials is technically feasible.

Minor problems with achieving a durable seal around the tank, with joints in the fabric backing, and with avoiding low viscosity of the urethane material were identified during installation of the urethane coatings test sections. It is believed that small modifications in methodology will overcome these difficulties in subsequent applications. Of more concern, however, is the phenomenon of small punctures resulting from foot traffic. It is believed that such damage could be avoided by utilizing a different type of fabric backing, and by prohibiting all traffic from the liner until the coating is fully cured, likely a few days after application. Permanent board walkways should be placed along high-traffic routes. Difficulties arose in achieving a bond between the initial coat and the tack coat because moisture and dust were present between the two coats; these could have been avoided if all coats had been applied more rapidly in succession.

No difficulties were encountered in the application of the urethane foams. It is possible to cover very rough bases with foam, although material usage rises and production rates drop as roughness increases. The optimal configuration appears to be

an initial layer of low-density foam to act as a filler over the uneven base material, then a higher density foam to resist weathering and act as a wearing surface. Brightly coloured surface coatings appear to be undesirable because they attract ravens.

Summer conditions are required for installation of all four liner systems. The bentonite and sulphur liners are somewhat less sensitive to temperature than urethane coatings or urethane foams, which require ambient temperatures of 15°C (60°F) or higher. None of the systems are to be installed during rainy weather. The three spray-applied liners may be placed as long as the surface of the base is relatively dry and no puddles are present. With bentonite, the base soil must be virtually dry so that the bentonite does not hydrate before thorough mixing and compaction are completed.

Bentonite poses no flammability hazard. The other three liner systems are basically combustible, but the respective formulations may be chemically modified to inhibit flame spread. The latter three types of liners may also be buried under a protective soil cover to eliminate fire hazard, but this is an added expense, making the liners inaccessible for maintenance. No definitive standards exist on this subject. The appropriate Fire Marshall should be consulted before a large-scale application is undertaken.

Logistics associated with each of the products are of interest. All liner systems would utilize local labour for base preparation. The bentonite liner would require importation of one or two supervisors; the other three systems, importation of two or three expert applicators and supervisors. It should be noted that the quality of the three spray-on liners is highly dependent upon the skill of the application crew. A summary on the equipment and materials required is given in Table 4.

TABLE 4 EQUIPMENT AND MATERIAL QUANTITIES

	LINER TYPE			
	Processed Bentonite	Processed Sulphur	Urethane Coatings	Urethane Foams
Equipment	Construction-type grading, mixing and compacting equipment (presumably available near site)	Melt/mix apparatus (transportable by truck, possibly by air in components)	Small mixers and spray equipment (easily air transportable)	Small spray equipment (easily air transportable)
Materials				
kg/m <sup>2</sup>	15 to 25	50 to 70	1 to 3	3 to 6
(lb/ft <sup>2</sup> )	3 to 5	10 to 14	0.2 to 0.6	0.6 to 1.2



The urethane coatings and foams offer significant advantages with regard to the amounts of materials that must be transported to the site - a major consideration in northern Canada.

### **3 PERFORMANCE ASSESSMENT: ONE YEAR AFTER INSTALLATION**

After detailed field observations on the weathered test sections were made during early September 1977, selected samples were laboratory tested.

#### **3.1 Weather Data for Yellowknife, N.W.T.**

Temperature and precipitation data for Yellowknife are summarized in Figure 5. Although temperatures were somewhat warmer than normal and precipitation substantially less than that experienced during "average" years, the weather was still representative of northern exposure.

#### **3.2 Field Observations on Processed Bentonite Test Cells**

The three bentonite test cells were in relatively good condition, except for 15 cm (6 in) deep motorcycle tire ruts in the beach sand and 4 cm crush cells. None of the cells developed ponds of water.

Several weeds were growing in each cell, with roots generally extending through the protective soil cover and into the bentonite layer, presumably to tap the available moisture. Plate 19 shows a variety of weeds growing in the 4 cm crush cell. Root systems of the larger weeds penetrated through the liner and into the base soil, as shown in Plate 20. All of the test cells felt soft underfoot (see Plate 21). In the beach sand cell one could sink 15 to 20 cm (6 to 8 in) into the extremely soft bentonite layer. This did not happen in the other cells because they were somewhat drier and because the gravel protective cover distributed foot pressure somewhat more evenly than the beach sand cover.

Table 5 summarizes density and moisture content data for the bentonite test cells. Moisture contents were very high in all cases; dry densities in the order of 1.5 to 2.0 gm/cm<sup>3</sup> (95 to 125 lb/ft<sup>3</sup>) would be expected in the unmixed substrate soils. The low dry densities of the bentonite layer are attributable to the high moisture retention characteristics of the bentonite.

One portion of the 4 cm crush cell was left without any protective soil cover. The exposed surface had desiccated and cracked, but only to a depth of a few millimetres despite relatively low levels of precipitation in the preceding months. Plates 22 and 23 show this surface layer beneath as damp but not saturated bentonite. In contrast, the bentonite layer beneath the protective soil cover on the remainder of the cell was saturated and extremely soft. The cover material was dry at the surface, and damp but not saturated at depth. The base soil was also damp, but not saturated. The thickness of the bentonite layer ranged from 5 to 12 cm (2 to 5 in); the top surface was relatively flat, as shown in Plate 24, but the bottom surface was undulating with nodules of unmixed substrate material protruding upward as much as 7 cm (3 in). Except for these nodules, the bentonite layer appeared to be uniformly mixed with no evidence of streaking. Compaction of this layer appeared to be relatively even: voids were not apparent.

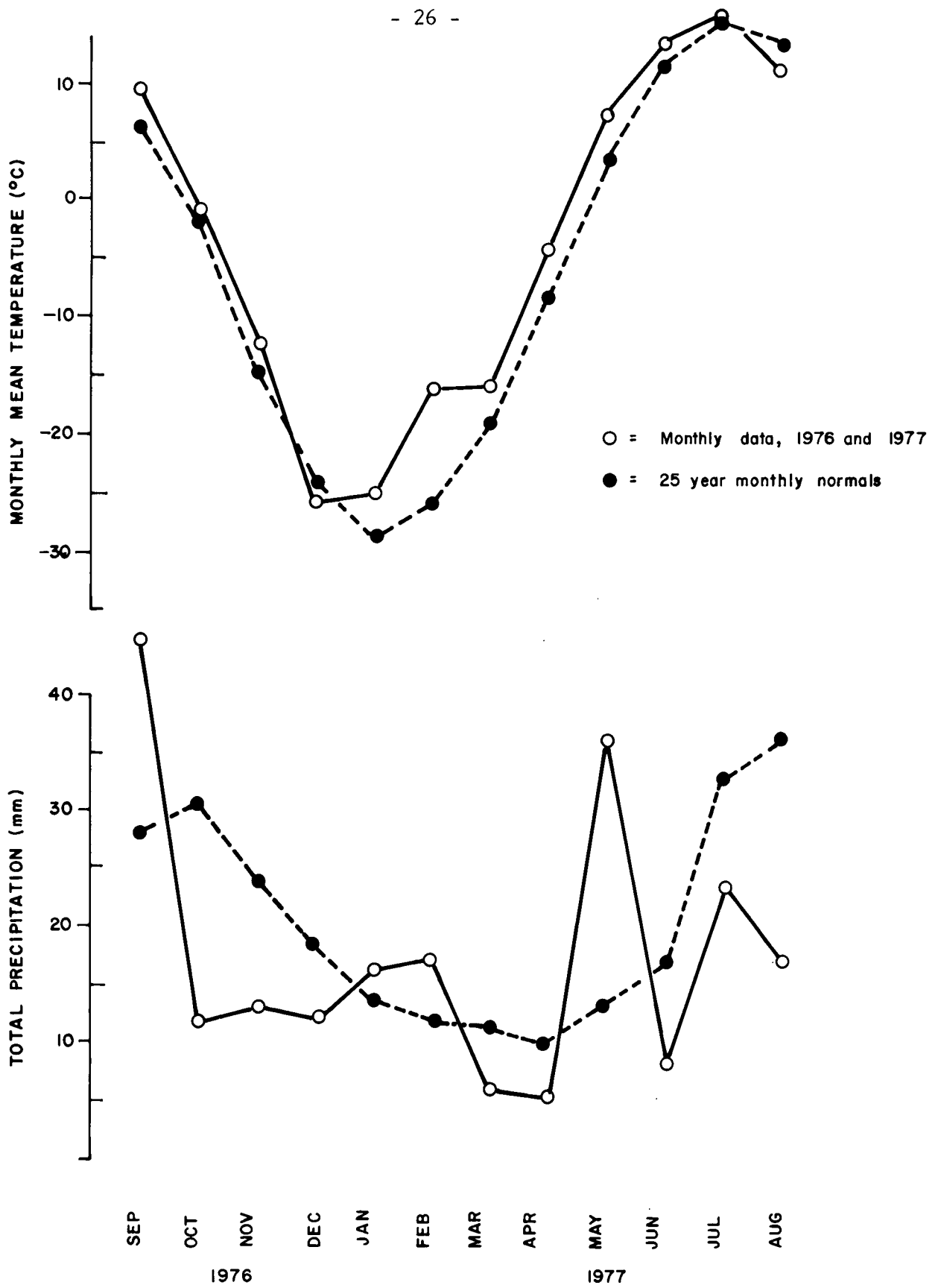


Fig.5 - WEATHER DATA—YELLOWKNIFE, N.W.T.



Plate 19 A variety of weeds grew in the 4 cm crush test cell, in some cases, penetrating completely through the protective soil cover and bentonite liner.



Plate 20 The deepest root tendrils of the weed shown above had penetrated through the bentonite layer. A high density of such weeds with roots in the bentonite layer may affect liner integrity through biological desiccation.



Plate 21      The beach sand cell was the softest of the three test cells: foot and motorcycle traffic penetrated through the soil cover and into the bentonite layer.

TABLE 5   DENSITY AND MOISTURE CONTENT OF BENTONITE LINER

LOCATION	MOISTURE CONTENT %	WET DENSITY gm/cm <sup>3</sup>	DRY DENSITY gm/cm <sup>3</sup> (lb/ft <sup>3</sup> )
4 cm Crush cell			
SE corner	62.4	1.61	0.99 (62)
NW corner	46.2	1.61	1.10 (69)
2 cm Crush cell			
N end	48.3	1.60	1.08 (67)
S end	32.8	1.75	1.31 (82)
Beach sand cell			
SW corner	81.5	1.47	0.81 (50)
NE corner	98.2	1.41	0.71 (44)



Plate 22      On the portion of the 4 cm crush test cell without any protective cover, the surface was desiccated, but the resulting cracks penetrated less than a centimetre.



Plate 23      Intact, moist bentonite gel was present immediately below the desiccated layer despite relatively low levels of precipitation in the preceding months.

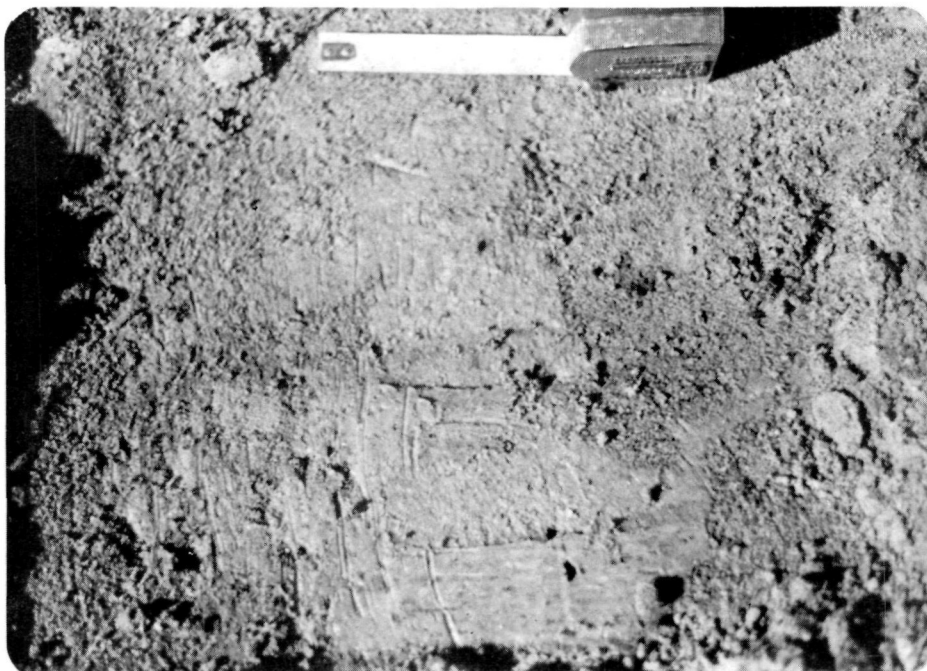


Plate 24 The upper surface of the bentonite layer was relatively planar, but the lower surface undulated. Nodules of unmixed base soil protruded into the bentonite, reducing the thickness by as much as 7 cm (3 in).

Observations of the 2 cm crush test cell were similar: the protective soil cover was damp to dry and the base, damp. The bentonite layer was saturated and very soft and had a thickness variable between 7 and 10 cm (3 to 4 in). The bentonite layer was evenly mixed and compacted, but the bottom surface was undulating. Visually, the proportion of bentonite appeared lower than that applied in the 4 cm crush cell.

Average thickness of the bentonite layer in the beach sand test cell was estimated at 7 cm (3 in). However, unmixed protruding nodules reduced this to 2 cm (1 in) in many places, as is evident in Plate 25. Several "pipes" of unmixed sand penetrated through the liner. These ranged in diameter from 1 to 5 cm (0.5 to 2 in) and were presumed to be the result of insufficient mixing of the substrate soil and bentonite at the time of application. This underlines the potential for uneven quality in manual work. A cross-section through the motorcycle rut, shown in Plate 26, illustrates that the effectiveness of this liner system was substantially decreased by this type of disturbance. The protective cover and base materials in this test cell were damp but not saturated. The bentonite layer was extremely wet and virtually without shear resistance. This test cell is located in a relatively low-lying area which was flooded during spring melt, and subsequently during heavy rainfall. Thus, abundant water was available on a periodic basis; the bentonite was evidently able to maintain its saturated state through several months of much drier conditions.

Field permeability tests (utilizing water as the test fluid) in the beach sand cell indicated that losses of 5,000 to 25,000 cm<sup>3</sup>/m<sup>2</sup>/hr (0.1 to 0.5 gal/ft<sup>2</sup>/hr) could occur in the initial hours. Loss rates would be expected to decrease as substrate soils become saturated. It may be theoretically demonstrated that permeable sand "pipes" through an otherwise relatively impermeable blanket could allow such losses, even if the cumulative area of the "pipes" is only 1 to 2% of the total area. Thus, these seemingly very minor imperfections in the bentonite liner profoundly affect overall integrity.





Plate 25      Note nodule of unmixed sand which reduces effective thickness of the bentonite to approximately 2 cm (1 in).



Plate 26      Cross-section showing rutting from motorcycle tires which sheared into the bentonite layer, reducing the effective depth of the liner by approximately one-half.

### 3.3 Field Observations on the Processed Sulphur Test Section

The most notable difference in the sulphur liner after one year was a number of cracks through various panels. Figure 6 gives the locations and widths of these cracks, while Plate 27 shows a typical panel. Plate 28 shows one of the wider cracks and Table 6 gives details of cumulative crack lengths and panel areas. These cracks were in the range of 1 to 3 mm (0.05 to 0.1 in) wide and extended through the full depth of the sulphur lining. Some cracks completely crossed a panel, others only did so partially. There seemed to be no clear-cut relationship between panel thickness or size - panel 12, the thickest, had the most cracks and panel 13, the largest, had fewer cracks than panel 10. Very small panels such as 3 and 5, did not appear to be cracked. Disregarding external causes, Table 6 suggests that Types III and IV formulations have a lower propensity to crack than do Types I and II (refer to Table 1 for type formulations).

The two phenomena which may be responsible for the cracking are vertical differential movement of the ground due to thaw settlement or frost heave, or relief of stresses induced by thermal contraction. The thaw settlement explanation seems unlikely for three reasons:

1. There is no evidence of differential settlement of tanks or pipe galleries.
2. The panels themselves do not appear to have sagged or heaved (Plate 29 shows one of the few vertically displaced cracks).
3. According to the Gulf Agent at the site, the cracks first appeared in the early winter, an unlikely time for thaw settlement to be occurring.

TABLE 6 CUMULATIVE LENGTHS OF CRACKS IN SULPHUR LINER

PANEL	PANEL AREA (m <sup>2</sup> )	CUMULATIVE LENGTH OF CRACKS (m)	CRACKS (m/m <sup>2</sup> )
1	19.5	0.5	
2	34.0	11.6	
3	5.0	0	
4	13.0	1.3	
5	7.5	0	
6	6.0	4.0	
7	10.0	0.3	
8	26.0	2.8	
9	55.5	14.3	
10	27.0	10.9	
11	26.0	2.3	
12	58.0	16.9	
13	63.0	8.6	
All Type I	176.5	45.2	0.256
All Type II	85.0	17.4	0.205
All Type III	63.0	8.6	0.137
All Type IV	26.0	2.3	0.088



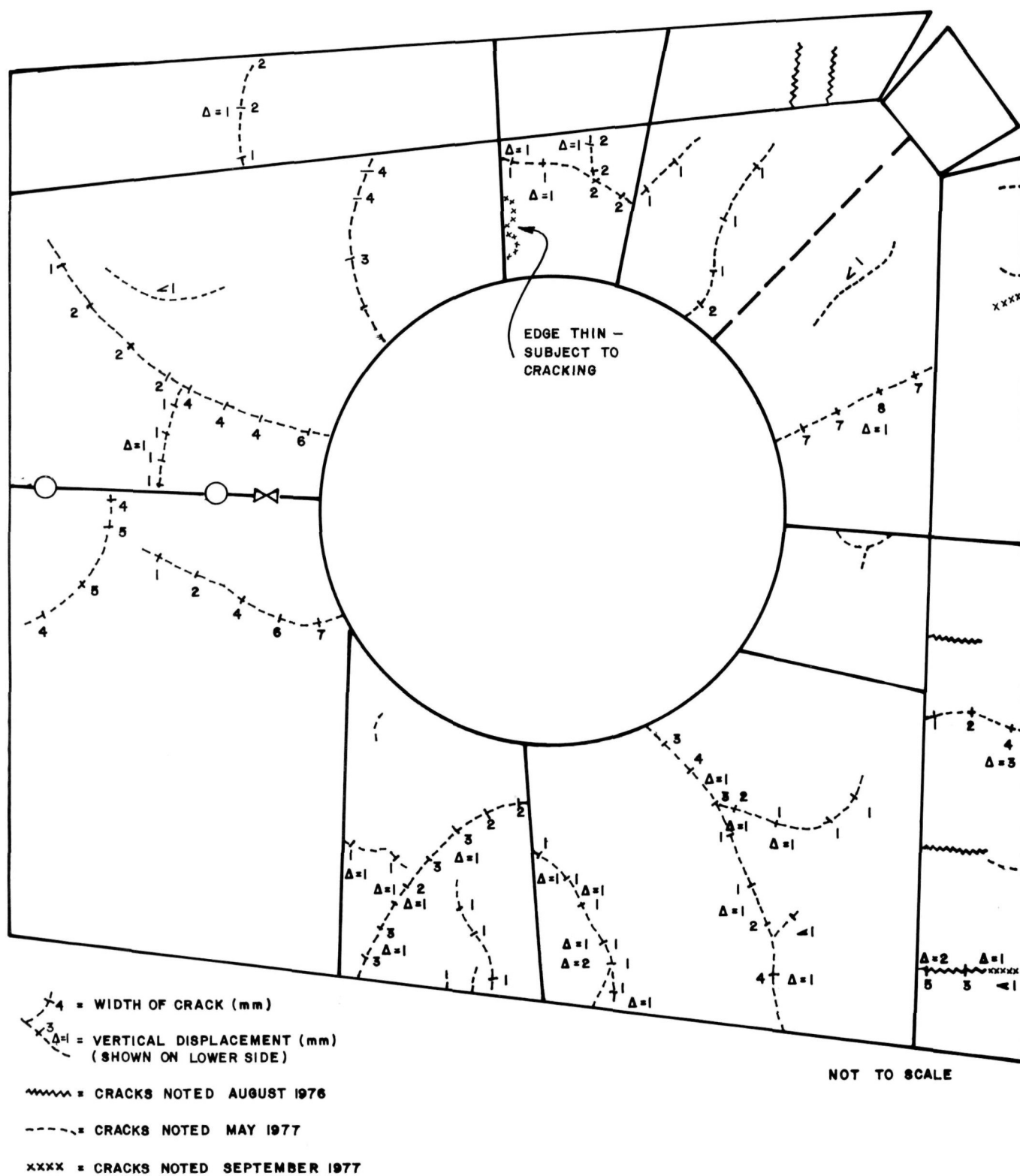


Fig.6 - Crack Configuration in Sulphur Test Section

Plate 27

A typical crack transversing the full width of the panel; width is 1 to 3 mm (0.05 to 0.1 in).



Plate 28

The above crack at 5 to 6 mm (0.15 in) was somewhat wider than average; all cracks penetrated the full depth of the panels.

Frost heaving is more plausible - the early winter timing is right. Although the Gulf Agent did not notice visible heaving of the panels, it would have been possible for the panels to settle back into their original, unheaved position by the fall of 1977. The silty soils underlying the tank farm are frost susceptible, but over a metre of gravel pad between the silt and the sulphur lining would distribute point loading. Differential heaving would be expected between the pad and the tank, creating cracks parallel to the edge of the tank. The actual configuration of the majority of the cracks is radial. The general perpendicularity of the cracks to the long dimension of the panels suggests tensile stress relief. Although the panels are not restrained at the edges, adhesion to the gravel may develop enough resistance to induce significant tensile stresses upon thermal contraction.

Three "permeability" tests were run on representative cracks. The first two were run on a 3.5 mm (0.13 in) crack in panel 9, and the third on a 3.0 mm (0.10 in) crack in panel 12. A bucket 28.5 cm (11.2 in) in diameter was sealed over each crack. In the first test, 16.1 l (3.5 gal) of water drained in four minutes under an average head of 12.5 cm (5 in). The main mechanism appeared to be piping along the crack, exiting onto the surface about 25 cm (10 in) from the bucket, as shown in Plate 30.

In the second test at the same location, the surface of the crack was sealed for 25 cm (10 in) and sealant forced into the crack down to the substrate soil to prevent flow along the crack. A similar amount of water was drained in two minutes, exiting further down the crack: apparently the gravel-sulphur interface provided a channel as accessible as the crack. In the third test, the entire 3.3 m (11 ft) length of the crack was sealed: 82.9 l (18.2 gal) of water drained in 19 minutes under an average 25 cm (10 in) head. These results suggest that losses of 15 l (1 gal/min/ft) of crack are possible under relatively low heads. Given the cracking ratios in Table 6, 1.3 to 3.8 l/min/m<sup>2</sup> (0.1 to 0.3 gal/min/ft<sup>2</sup>) of fluid loss could be expected at least until substrate soils become saturated. Thus, the presence of cracks, whatever the cause, significantly decreases the ability of the liner to retain spilled fluids. Conscientious maintenance on a frequent basis would be necessary to keep such cracks sealed.

The sulphur test sections had been coated with a fire-retarding paint in the spring of 1977, except for a small section which was covered with a few centimetres of 2 cm crush gravel. The surface of the unpainted sulphur section did not appear to have changed colour significantly over the winter and there was no evidence of crazing or spalling, although minor crazing was noted on panels 2 and 10 in May 1977. All of the fire-resistant paints appeared to be 0.1 to 0.2 mm (5 to 10 mils) thick and well bonded to the sulphur. The Albi and Diathon fire-resistant paints are shown in Plate 31. Motorcycle tracks were evident on the surface of the paint, including several areas where the tire was either spun or locked upon braking. No perceivable damage had resulted to either the paints or the sulphur liner. Triathon and Diathon were relatively elastic compared to the Albi system, but none were flexible enough to coat the mastic joint sealant without splitting as joint movement occurred. This is evident in Plate 32.

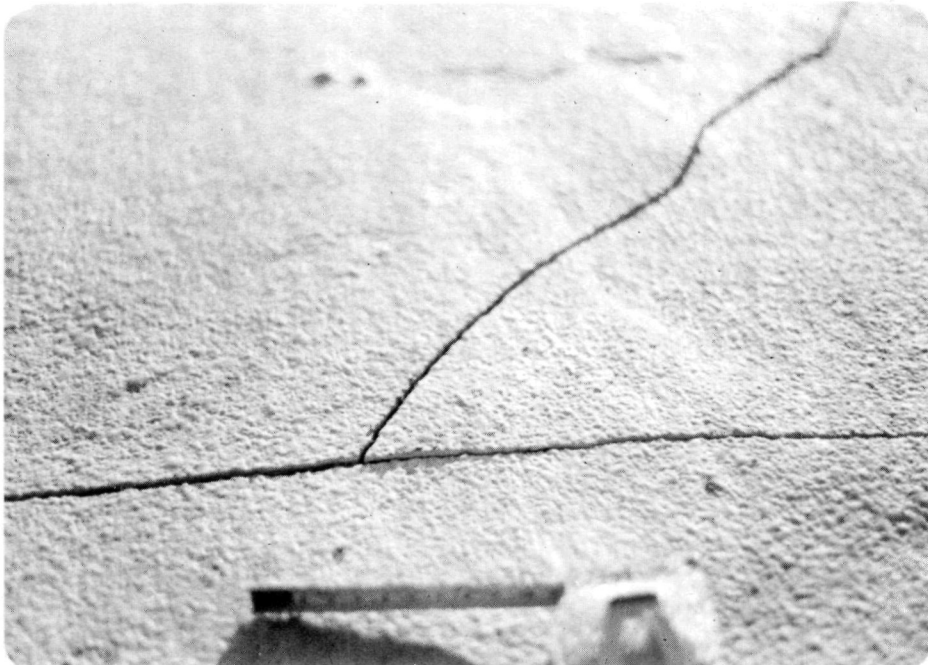


Plate 29

In general, no vertical displacement across cracks existed, and where differential movement was noted, magnitudes were very small. The above shows the most extreme example of displacement, approximately 3 mm (0.1 in).



Plate 30

Field permeability tests demonstrated that water flowed along the crack, existing with sufficient velocity to carry sand and smaller soil particles. A second test on a completely sealed crack indicated that water would escape almost as quickly along the liner-soil interface when no surface exit was available.



Plate 31      The fire-resistant paints appeared to be 0.1-0.2 mm (5-10 mils) thick and well bonded to the sulphur. At left is the Albi 107X/144 system, at right the Diathon system.

The mastic sealants themselves were not flexible enough to withstand joint movements. As Table 7 and Plates 32 to 34 illustrate, over half of the joints had one or more flaws, although the joints seemed to be in good condition in May 1977. The usual configuration of these flaws was loss of adhesion between the mastic sealant and one panel; in some cases the mastic sealant itself separated. The Domtar Fibregum Plastic Cement was stiff to the touch and only somewhat elastic. Both the DAP sealants were much softer and more pliable. The Architectural Grade Caulking Compound exhibited loss of adhesion to the sulphur in several locations. The Butyl Gutter and Lap sealer did not lose adhesion - it was still tacky when the fire-resistant paint was peeled back. Because this sealant was only used over a very short length, however, little may be inferred from its performance. It was noted that joint sealants were pliable under finger pressure at extremely cold temperatures in mid-winter.

During construction of panel 2, boards were placed intermittently to form a line of weakness in the panel. It was expected that cracking would occur in a controlled direction along this quasi-joint. Although several cracks had formed in this panel, however, (one crack was within a metre and parallel to the quasi-joint) none formed along the quasi-joint itself. This indicates that thickness variations and other anomalies were more influential than the artificially induced line of weakness along the quasi-joint. Plate 35 shows such an anomaly where a sample was removed for laboratory testing.

TABLE 7 FLAWS IN JOINTS BETWEEN PANELS OF SULPHUR LINER

JOINT BETWEEN PANELS	TYPICAL FLAW LENGTH (mm)	TYPICAL FLAW WIDTH (mm)	COMMENTS
1 & 2			No visible flaws
1 & 3	120	15	Loss of cohesion in mastic
1 & 8	30 - 40	5 - 7	Four flaw- loss of adhesion to sulphur
2 & 3			
3 & 4			
4 & 5			No visible flaws
5 & 11	50/50/1000		Three flaws
5 & 6			No visible flaws
6 & 12			No visible flaws - very wide joint (6-7 cm)
7 & 8			No visible flaws
7 & 9			Several flaws - cumulative length 2 m in joint length of 3 m
8 & 9			No visible flaws
9 & 10			Many small flaws- loss of adhesion to sulphur
10 & 13	30 - 100	5 - 10	Five to ten flaws
11 & 12			No visible flaws
12 & 13			No visible flaws
2 & Tank	500	10	
6 & Tank	150	3 - 5	Loss of adhesion to tank
7 & Tank			
9 & Tank			
10 & Tank	30 - 100	5	Five flaws
12 & Tank	200	1	Loss of adhesion to tank
13 & Tank			
2 & 4			DAP Architectural Grade caulking Several flaws - loss of adhesion to sulphur
2 & 6			DAP Butyl Gutter and Lap sealer
2 & 7			Lap joint



Plate 32      Joint failure: note combination of splitting within the sealant and loss of adhesion to the sulphur panel. Note that this splitting had occurred since the fire-resistant paint was applied.

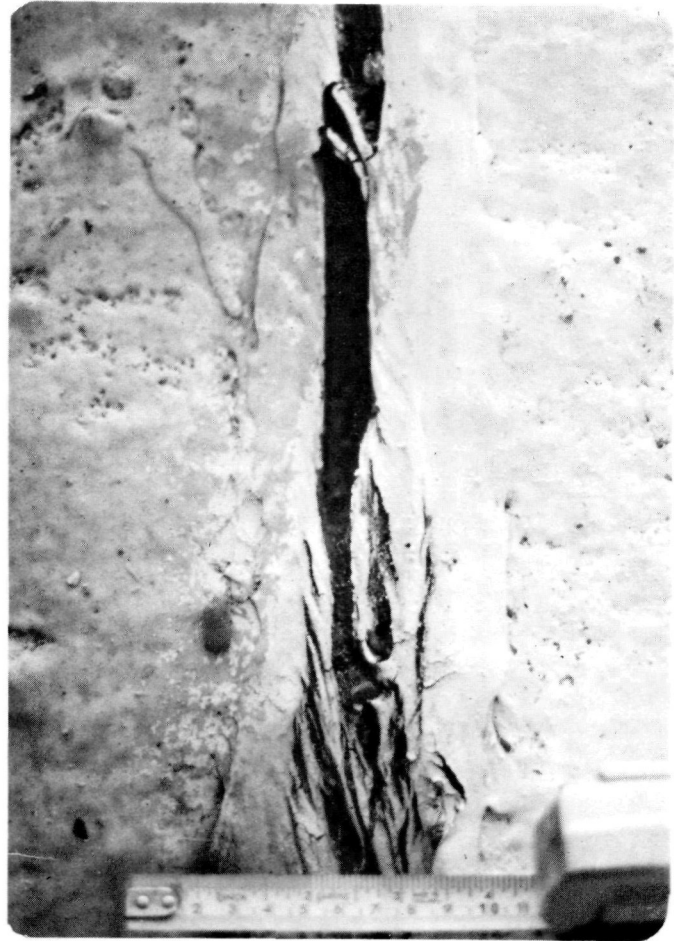


Plate 33      Typical joint failure originated from loss of adhesion to sulphur panel.



Plate 34

The joint at the tank base apparently accommodated some differential movement, but failure of the sealant were evident.



Plate 35

Anomalies in panel thickness may have acted as initiation points for cracking.



The Gulf Agent noted that the sulphur surface was extremely slippery when wet or covered by a skiff of snow.

Samples for laboratory testing were cut out of the edges of various panels. It was noted that the interfaces between layers form definite planes of weakness. Using a thin blade it was possible to delaminate edges on a number of panels, as is illustrated in Plate 36.

### **3.4 Field Observations on the Urethane Coatings Test Sections**

Weathering caused opposite discolouration effects in the two urethane polymers. Carboline had changed from a forest green to a very dark green. Elastuff 504 changed from a dark green to a light greyish green, as is evident by comparing Plates 14 and 37. On both test sections, colouration much closer to the original was retained in areas covered by several centimetres of sand. Also, the colour of the Elastuff 504 had faded much more noticeably where the coating was thinner than average. As expected, these spots succumbed more quickly to the effects of weathering. The Tufton-backing fabric showed no signs of deterioration.

A motorcycle had been ridden and skidded repeatedly on the test sections without any apparent damage, as shown in Plate 38. On the inside face of the dyke, the liner had crept downslope, placing the upper portion in tension; there was no evidence of failure or adverse effects due to this stress, however.

The anchoring system on the exterior of the dyke, keying the liner into a trench backfilled with soil, seemed to have worked very well. Sandbags used to anchor the centre of the liner had been ripped apart by ravens and were no longer effective. There was no evidence, however, of damage to the liner from either ravens or wind flexing.

The seal between the test sections and the tank, shown in Plate 39, seemed to have performed very well: adhesion to both was excellent. The feathered edge of the foam, considered a weak area at the time of installation, showed no signs of loss of integrity. This edge could not be broken under foot pressure.

The transverse double-lap joints appeared to have performed well in both materials, without developing wrinkles or loose edges, as shown in Plate 40. However, Plate 41 shows that in the longitudinal single-lap joint, several wrinkles were evident extending across the joint one-quarter to one-half of the way. Although there was still an effective seal of 10 cm (4 in) the loose edge formed a potential weak point for tearing or damage by wind.

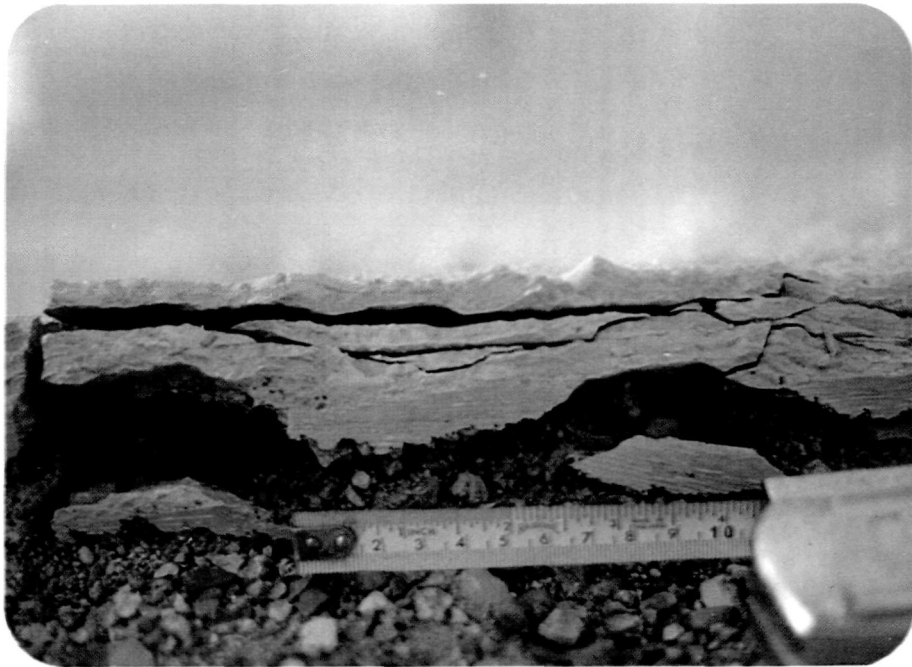


Plate 36 In a number of locations the edges of sulphur panels could be delaminated by forcing a wedge between layers.



Plate 37 Elastuff 504 bleached significantly, but Carboline weathered to a slightly darker shade of green; compare with Plate 14.

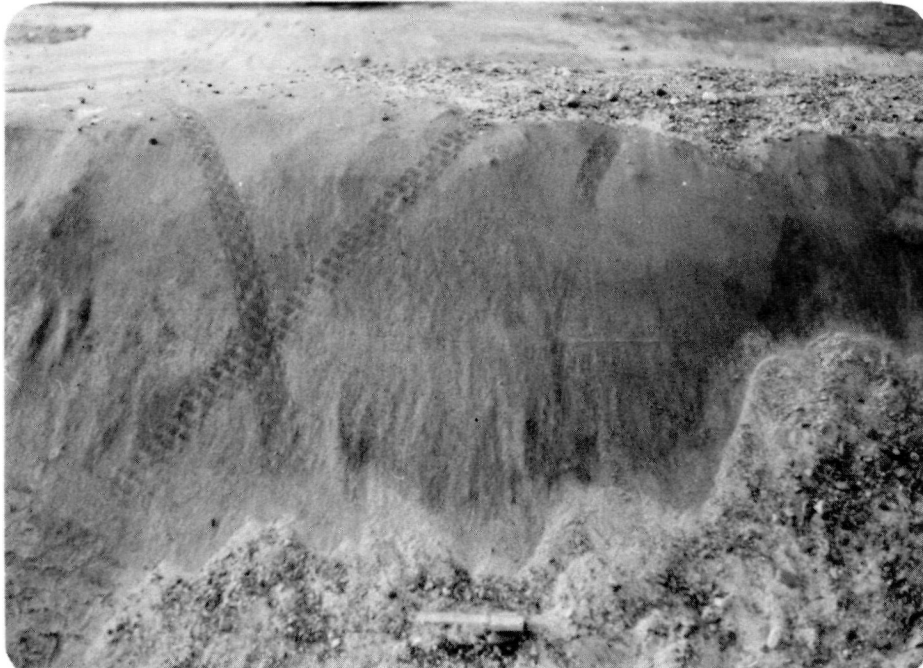


Plate 38 Both urethane coatings withstood damage from motorcycle traffic very well. Note also that this section of liner moved downslope, placing it in tension; no adverse effects were apparent.

The tack coat had peeled away from virtually all of the Carboline test section, and largely away from the Elastuff 504 section. Plate 42 shows that the tack coat was intact and had good adhesion to the original coating in areas protected by several centimetres of sand. There were no signs of cracking or crazing on either test section or any widespread incidence of more puncturing or other damage due to foot traffic. Neither coating was affected by repeated abrasion underfoot: the small punctures noted in Section 2.3 may have occurred while the coatings were still soft after application. There were some instances of small holes (.5 mm (0.2 in) in diameter) through both coatings, the origins of which were not evident. By grasping loose edges, both coatings could be peeled back, as illustrated in Plates 43 and 44. The bond to the Tufton appeared to have weakened slightly over the winter. The Carboline seemed to have become more brittle than the Elastuff 504. The former coating showed signs of fatiguing and cracking after being flexed 5 to 10 times, whereas the latter material showed only a few stretch marks after 10 to 15 flexes. The flexibility of the Tufton backing itself did not appear to be deteriorating.

Traction was good on both test sections, even with most of the sandy tack coat absent. When oily water was sprinkled on the slopes, however, the portions without any grit became slippery to rubber-soled work boots.

When removing samples for laboratory testing, it was noticed that the Carboline scrim system would easily rip perpendicular to the warp of the Tufton. Ripping parallel to the warp required considerable force and frequent assistance with a knife. The Elastuff 504 was difficult to rip in either direction.

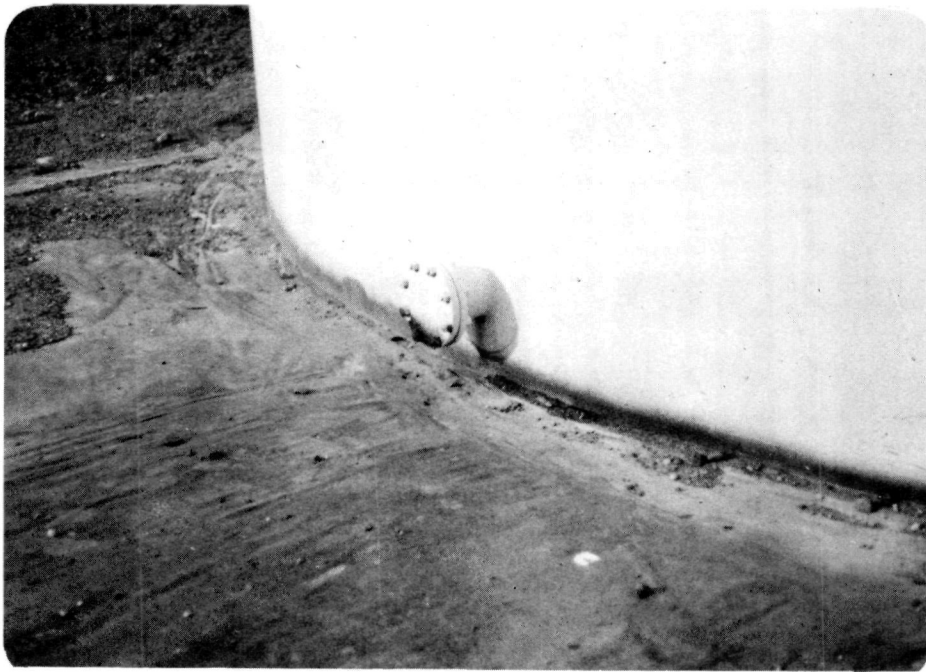


Plate 39      The urethane foam seal between the urethane coating test sections and the tank showed no signs of loss of integrity.



Plate 40      Transverse double-lap joint:  
no wrinkles, loose edges or  
other signs of poor performance.



Plate 41 Several wrinkles and loose edges were present in the longitudinal single-lap joint; these reduced the width of bond in the joint by several centimetres, and created weak points with potential for tearing or wind damage.

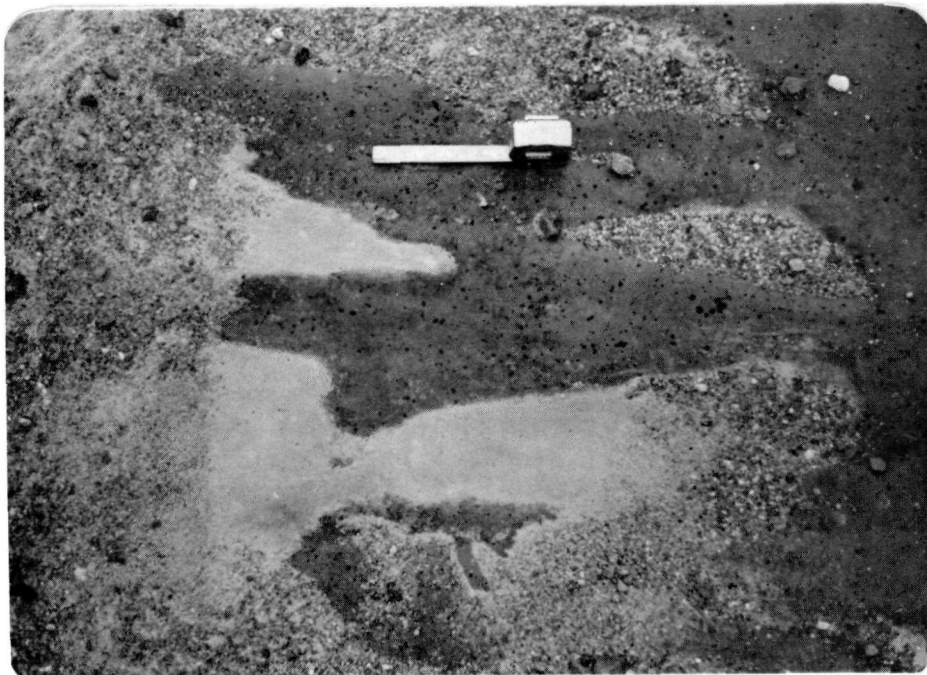


Plate 42 The tack coat and sand course had peeled off both coatings, except where they had been protected against weathering by a layer of sand several centimetres thick.



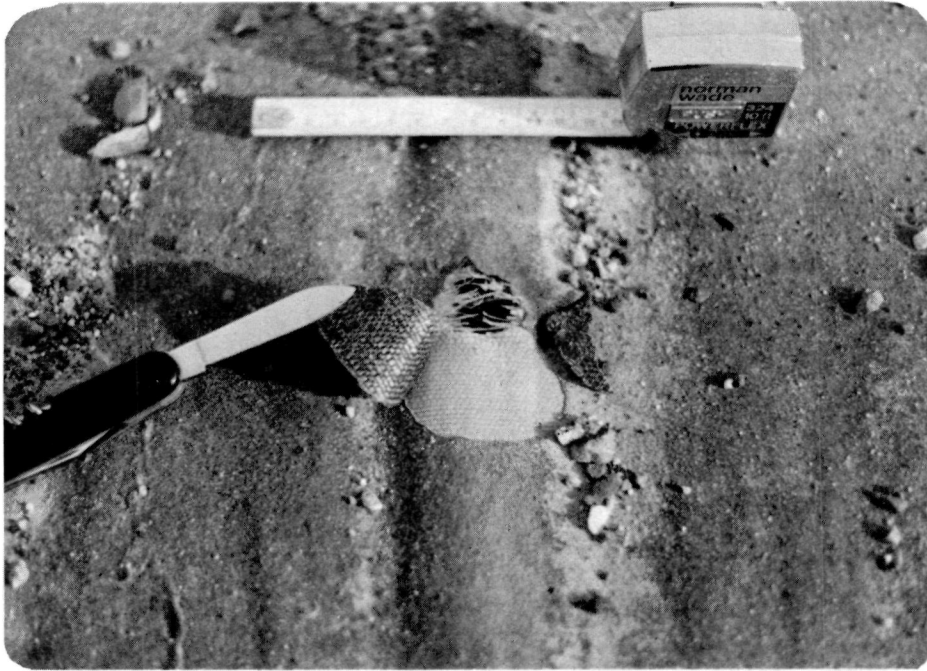


Plate 43 It was possible to peel the Carboline film back from a puncture in the liner (puncture was of indeterminate origin).

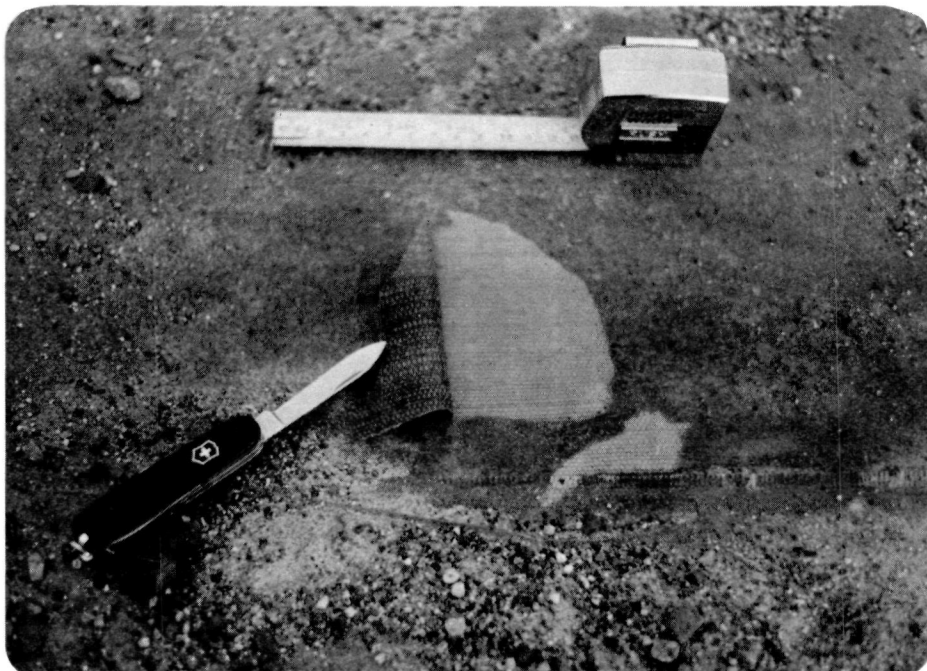


Plate 44 It was possible to peel the Elastuff 504 away from the backing fabric; thus, even small anomalies in the liner have the potential of developing into larger flaws.

### 3.5 Field Observations on the Urethane Foam Test Sections

Weathering affected the surface of the urethane foam - exposed test sections had weathered to a deep orange colour. This discolouration was present in approximately the top 1 mm (0.05 in) as illustrated in Plate 45, except where the foam was protected by several centimetres of sand. The weathered layer was brittle and could be powdered on the normal foam by rubbing under finger pressure. More vigorous rubbing was required to abrade the denser slow foam. Once the orange powder was brushed away, there was no sign of discolouration in the foam below. As long as it was not disturbed, the top opaque layer apparently protected the foam beneath from ultraviolet light. However, the cycle of weathering-abrasion-weathering would result in high attrition rates; this could be avoided by the use of walkways in high-traffic areas. No weathering had taken place below test sections protected by the Carboline polymer coating. The bond between coating and foam was still excellent. Plate 46 shows a cross-section through the Carboline-covered foam.

There was no evidence of damage to any of the foam sections due to foot traffic, but such traffic was undoubtedly light. It was possible to walk on, jump on and scuff the slow foam without leaving a mark, whereas it was possible to make some shallow impressions (2 to 3 mm (0.1 in)) on the normal foam. Comparative scuff marks are shown in Plates 47 and 48. A motorcycle had been ridden over various sections. Tire marks were left in several locations, and where the tire had been spun on one spot on normal foam the upper 1 to 2 cm (0.5 in) of foam had crumbled. The slow foam appeared to be more resistant to such damage. The tire had also been spun on the Carboline-coated section without visible damage. Plate 49 shows the tire marks across the 2 cm crush, normal foam test section.

There were numerous signs of both fresh and old pecking activity by ravens on the Carboline-covered section (Plate 45). More pecking damage was done to the lower density normal foam than the slow foam. In excess of 20 marks were evident, of which several were 2 to 3 cm (1 in) deep. At least one peck hole penetrated entirely through the liner. One or two peck marks were evident on the foam with no coating, but the sand tack coat on the remainder of the test sections apparently discouraged the curiosity of the ravens.

Adhesion between layers of foam was still excellent. The interface between layers was occasionally marked by a slight weathering discolouration, but these did not form planes of weakness.

Bonding to the base aggregate did not appear to have deteriorated at all and still exceeded foam cohesion in all cases. No signs of weathering or discolouration were present on any of the bottom surfaces of the foam test pads, as is evident in Plate 50.

The weight of the underlying aggregate held the foam pads down firmly, except on beach sand. Both the normal and slow foam test sections over the beach sand bowed up slightly. No surficial signs of stress from repeated flexing could be detected, however.

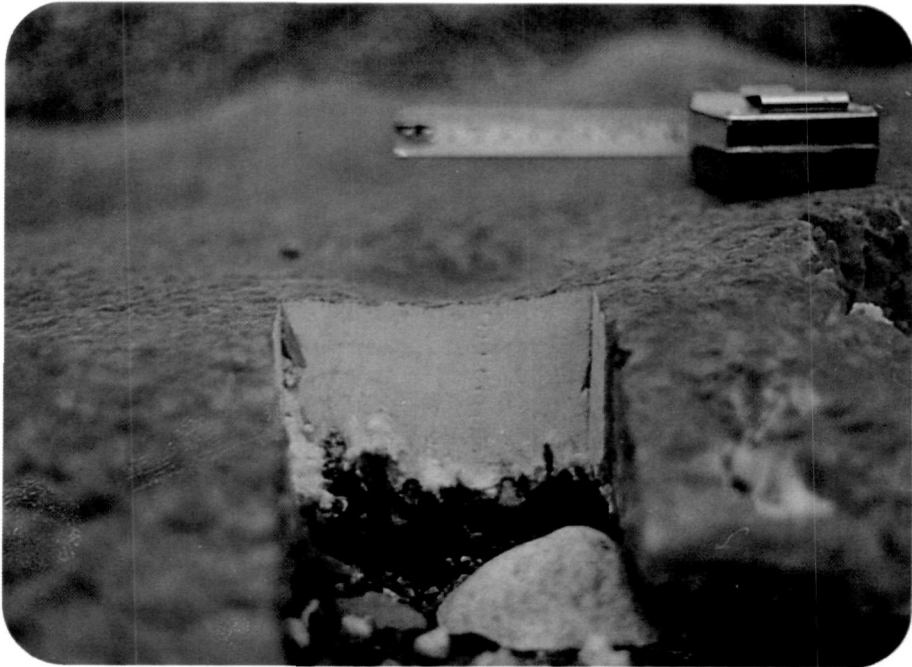


Plate 45

Foam had weathered to an orange colour, but only to a depth of 1 mm (0.05 in). Note recent raven peck marks in lower right corner of picture and old peck marks by the tape measure.



Plate 46

No signs of weathering in the urethane foam were apparent beneath the opaque urethane coating.



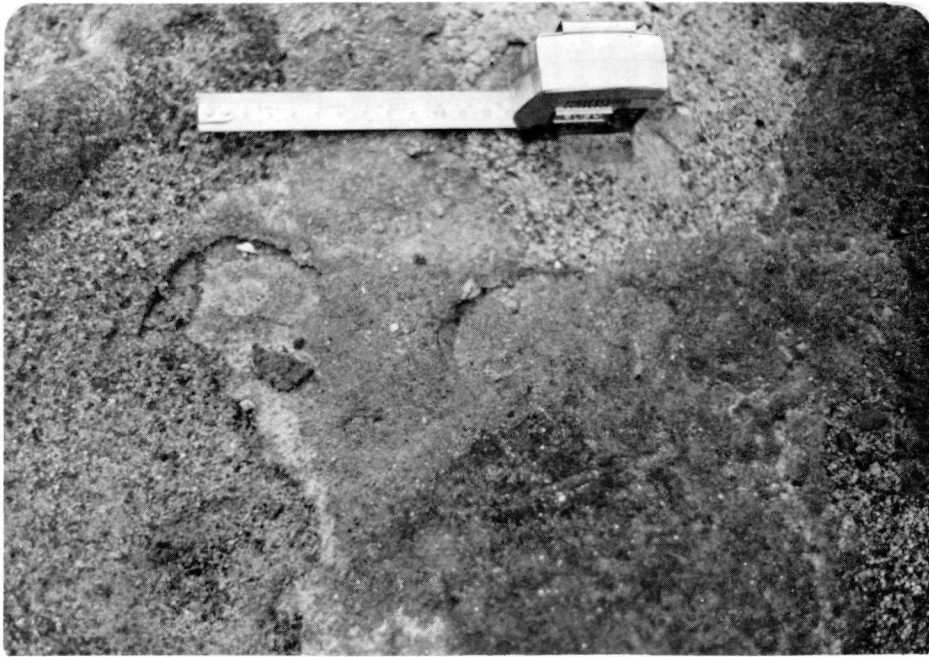


Plate 47 By stamping a heel on the normal foam, it was possible to create localized shear failures in the surface of the foam.



Plate 48 Similar "heel tests" yielded much smaller shear failures in the higher density slow foam - the crescent-shaped mark is barely visible in the centre of the above picture. The higher density foams are more resistant to damage and are thus more suitable for the surface layer.

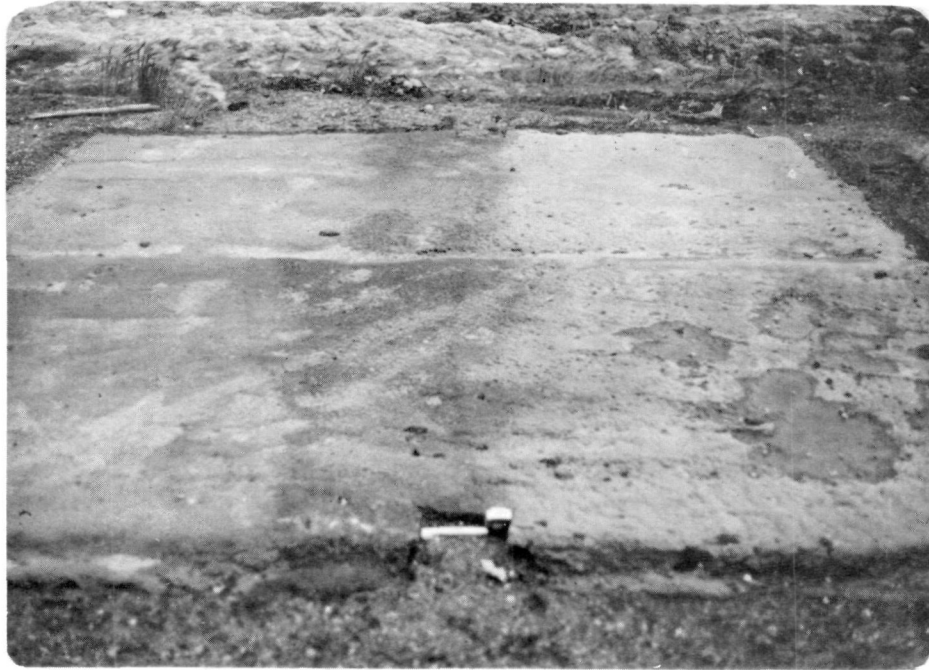


Plate 49 Where a motorcycle tire had been spun on normal foam, the upper 1-2 cm (0.5 in) of foam had crumbled. The Carboline-covered section and the slow foam appeared to be more resistant to such damage.

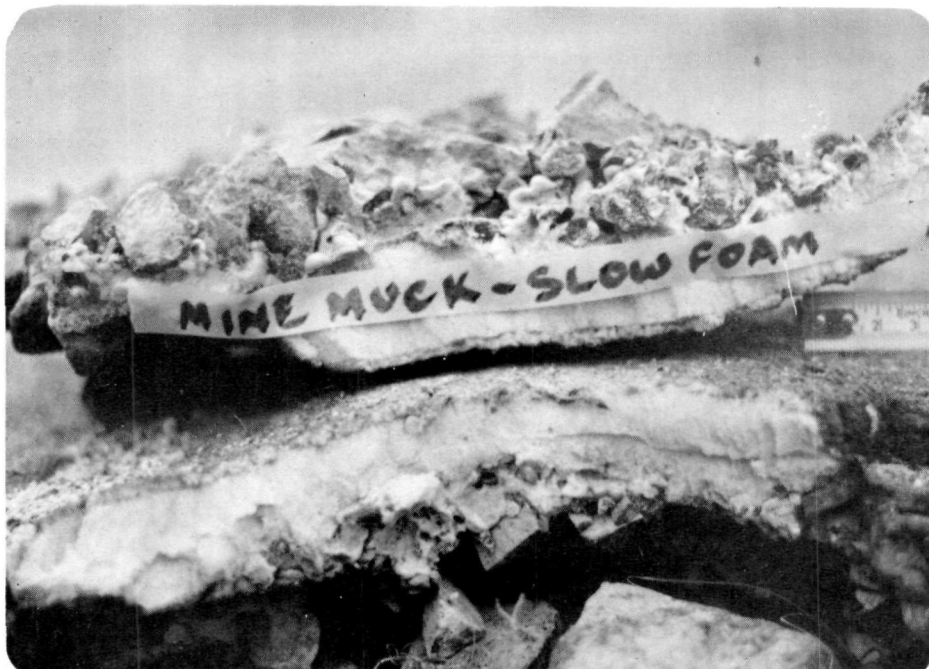


Plate 50 Adhesion of foam to the substrate aggregate was excellent. Also, no signs of weathering or discolouration were visible on the bottom surfaces of the test pads.

The soils beneath the foam pads were damp but not saturated. Differentials between air temperature and the ground temperature immediately below the foam seemed to be in the range of 1 to 2°C (2 to 3°F). No evidence could be found of weeds or other vegetation having penetrated through even the thinnest edges of the foam test sections.

### 3.6 Discussion of Field Observations

One of the initial concerns with the bentonite liner was that desiccation cracking would cause loss of seal integrity. It is apparent that the opposite situation is also of concern: excessive moisture makes the bentonite layer soft and subject to puncturing. Either traffic must be controlled or a thicker gravel protective cover must be used in order to prevent damage to the liner. Several weeds were noted in the test cells, with roots penetrating into the bentonite layer. If the vegetative population becomes substantial, biological desiccation could compound ordinary drying. Most significant, however, was the variation in thickness of the bentonite layer. In the worst cases, "pipes" of pervious soil without bentonite penetrated completely through the liner. Theoretical analysis and field permeability tests demonstrate that such anomalies may substantially reduce the retention capabilities of the liner system. This emphasizes the need for proper mixing equipment and stringent quality control with this system.

Cracking is the major source of concern with respect to the sulphur liner. Fluid losses through open cracks are potentially high. Although not obvious, the cause of this cracking is likely the result of frost heaving or thermal contraction. These factors are apt to exist to some degree at virtually every tank farm in northern Canada. Furthermore, cracking will likely result if ground movement occurs for any reason, such as consolidation or thaw settlement. Care should be taken not to place the sulphur liner on a newly constructed or reshaped base unless it is stable and well compacted. Because cracking will likely occur in this rigid liner in any case, conscientious maintenance would be required to maintain liner integrity. Crack location is inclined to be more dependent on specific anomalies rather than panel size or thickness; there is some evidence, however, that differences in formulation can reduce the incidence of cracking.

Some areas of preferential weakness may exist between layers of sulphur, making these prone to delamination under thermal or other imposed loads. Close quality control is therefore necessary during application. After one summer season, the fire-resistant paints appeared to have remained well bonded to the surface of the sulphur. The joint sealants, however, were not performing satisfactorily due to splits and loss of adhesion to the sulphur. Sealants used in future installations must have better elastic adhesion qualities. For safety reasons, a surface traction coating on the liner should be included.

Weathering of the urethane coatings appears to have affected colouration, strength of bond to the Tufton, and flexibility of the two polymers. Weathering is more pronounced in areas of thin coating and therefore demands closer control over uniformity of coating. A few centimetres of soil cover appeared to have provided a

protection against weathering; the joints and the foam seal at the tank also appeared to have performed satisfactorily. No damage due to wind flexing or raven attack on the liner itself was noted, although the ravens had torn the sandbags apart. The technique of anchoring the liner edge in a trench worked well. No further puncturing due to foot traffic was found - it is likely that the previous punctures occurred before the coatings were fully cured. The tack coat had peeled away from exposed areas of the liner, probably as a result of moisture and dust contamination between the coats. In future applications, time lapse between coats should be minimized to reduce the chance of such contamination.

Weathering of the urethane foams, evidenced by orange colouration, was surficial only. As with the urethane coatings, a few centimetres of soil cover was sufficient to protect the foam from weathering. The higher density foam sections would appear to have more resistance to wear and tear than the normal foam sections - regardless of whether the wear was caused by motorcycles or ravens. Adhesion to substrate aggregate and between layers remained very good. Although a thermal insulator, foam in small isolated sections did not appear to have any profound effect on ground temperature. However, appropriate thermal analyses should be undertaken before large-scale utilization in permafrost areas so as to ensure that thermal equilibrium is not adversely affected. The Carboline-coated sections of foam continued to attract the attention of ravens, resulting in consequent pecking activity. The use of such a brightly coloured coating is not recommended for future applications.

### **3.7 Laboratory Testing**

Samples of each of the materials were then laboratory tested. As base data existed for the urethane coatings from the time of installation, the tests were performed using identical techniques so as to yield comparable data. Specific base data was not available for bentonite, sulphur and urethane foam materials, so tests of a more general nature were conducted.

**3.7.1 Processed Bentonite.** Grain size analyses were performed on samples from the three bentonite test cells. Comparison of particle size distributions from these samples and blank samples of substrate soils indicate that beach sand and 2 cm crush contain approximately 18% bentonite, while the 4 cm crush contains 24% bentonite. Comparative grain size distribution curves are shown in Figures 7 to 9.

**3.7.2 Processed Sulphur.** The sulphur samples suffered some damage in transit. The Type III sample was completely delaminated on all layers, making tests impossible. The top layer of Types I and IV partially delaminated; the sample of Type II material remained intact.

Beams were cut from each of the intact samples and loaded at the midpoint until failure occurred. Flexural strengths calculated from these test results appear in Table 8. While the results for each type varied somewhat, it is apparent that Type I was the strongest formulation, while Type IV was the weakest. No delamination was noted in the failed flexural samples.

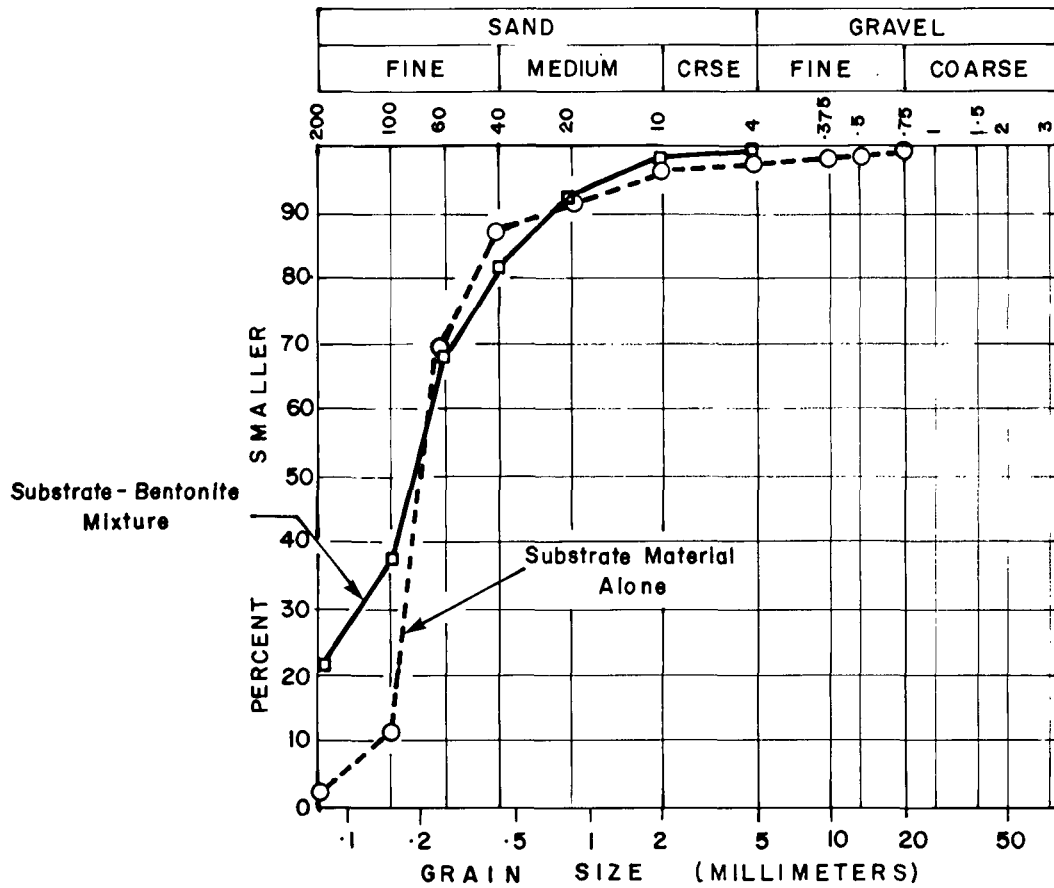


Fig.7 - Grain Size Distribution—Beach Sand

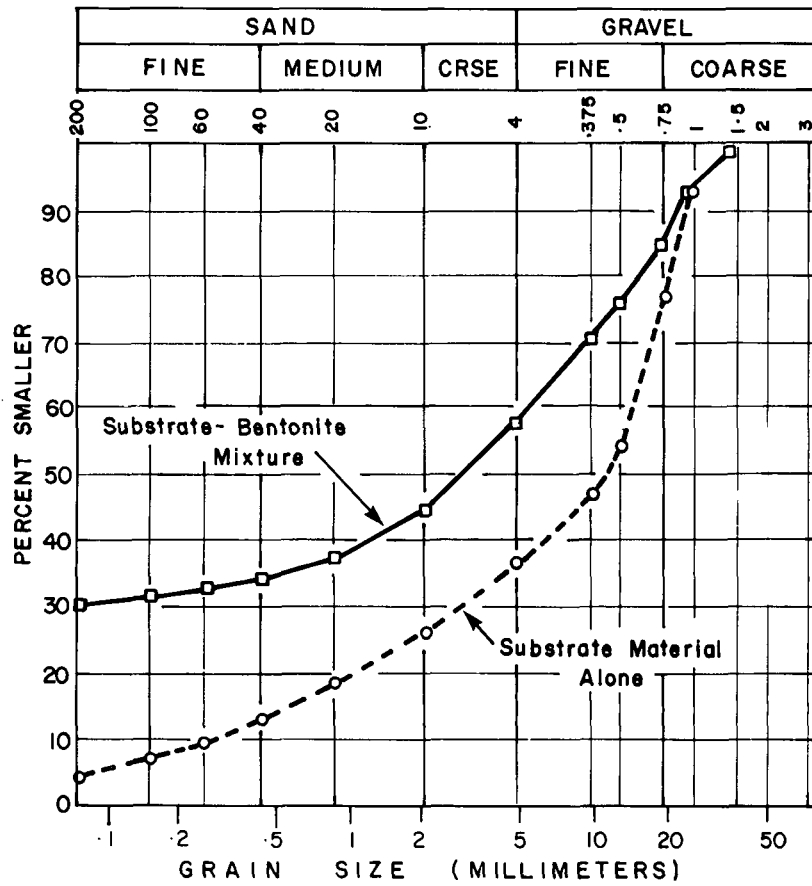


Fig.8 - Grain Size Distribution—4cm Crush

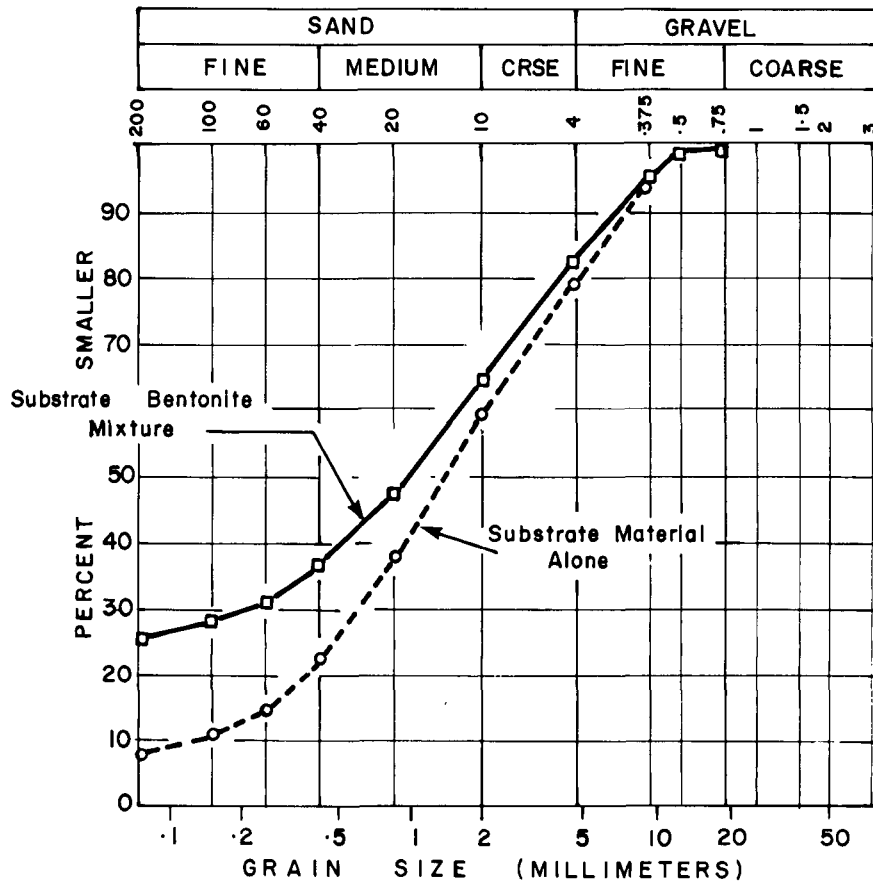


Fig.9 - Grain Size Distribution—2cm Crush

Although standard test methodology was used, strength results were substantially lower than strength values for unweathered samples noted in the Chevron report mentioned in Section 2.2. The Chevron Research Company has carried out accelerated weathering tests and reports a decline in mechanical properties, which appear to level out at 65% of the original values. The extremes of temperature which occur at the Yellowknife test site may have contributed to a more dramatic loss of flexural strength. Also, the laboratory samples were obtained at the edges of the sulphur panels. Poor application techniques, such as long, low-spray patterns that result in cool, thin layers, are more likely to occur along panel edges. Therefore, test samples from the edge of the liner may have somewhat lower flexural strengths than might be found in samples from the centre of the panels. It is important to note that, through the combination of circumstances outlined above, low strengths may be found in at least some areas of the sulphur liner.

Results of impact testing at room temperature, shown in Table 9, correspond with flexural strengths. At -30°C, Type I showed no indications of cracking under impact. Type II apparently became more brittle, exhibiting a higher degree of cracking. Type IV showed a lower tendency to crack, possibly because of the increased plasticizer component.

TABLE 8 FLEXURAL STRENGTH OF SULPHUR SAMPLES\*

SUCCOAT TYPE	FLEXURAL STRENGTH	
	kPa	(lb/in <sup>2</sup> )
I	14288	2072
	10373	1504
	9003	1306
II	5382	781
	6459	937
	8025	1164
III	5774	837
	2349	341
	5382	781

\* Note: Values shown are for individual tests

TABLE 9 IMPACT RESISTANCE OF SULPHUR SAMPLES

SULPHUR TYPE	REMARKS	
	+20°C	-30°C
I	Marked surface only	Marked surface only
II	Small cracks	Shattered
IV	Shattered	Cracked



A sample of the sulphur liner surfaced with the Albi 107X/144 fire-resistant paint was immersed in gasoline for 15 days; no discolouration or softening of the paint was noted.

Tensile tests across a joint containing the Domtar Fibregum Plastic Cement indicated that the ultimate strength of this joint in tension is approximately 15 N/cm (8 lb/in) of joint length. In a 5 cm (2 in) wide joint, elongation at failure was approximately 1 cm (0.4 in); the material appears to be elastic at room temperatures. A 5 x 2 x 2 cm (2 x 1 x 1 in) sample of this material completely dissolved after being immersed in gasoline for 12 hours.

**3.7.3 Urethane Coatings.** Both samples of the urethane coatings were free of pinholes. The Carboline was slightly less flexible than the Elastuff 504, primarily because the former had a slightly thicker coating. The coating-scrim bond was subjectively evaluated as "good" for the Carboline and "fair to good" for the Elastuff 504. As in the original testing, immersion in gasoline for 15 days did not appear to affect coating-scrim bond.

Tensile and tear strengths of the two coating-scrim systems are given in Table 10. Comparison with results from similar testing at the time of application indicates that strength of these samples has not deteriorated. It is also significant that, in general, specimens containing joints were as strong or stronger than the rest of the liner. Thus, the joints are not locations of weakness in the overall liner. Weathered samples were soaked in gasoline for 15 days. A marked reduction in tensile strength resulted - approximately 25%, compared to a strength reduction of about 10% for unweathered samples. This indicates that weathered urethane coatings are more susceptible to attack by gasoline than unweathered coatings. That gasoline immersion did not affect tear strengths indicates that the weakness induced by the nick in the tearing specimens is the controlling factor for strength, rather than the coating-scrim bond or other factors affected by gasoline.

Table 11 shows the relative change in dimensions of samples of the two coating-scrim systems after having been soaked in gasoline for 15 days. Dimensional changes induced in the Elastuff 504 are no higher than immediately after application. Conversely, the width and length changes in Carboline were double the original values, indicating that susceptibility to attack by gasoline increases with time. Both Elastuff 504 and Carboline exhibit equal tensile strength losses after short-term immersion in gasoline.

Cold-temperature flexibility of Elastuff 504 had not changed materially after one year; no signs of stress were evident at -55°C. The Carboline previously cracked at -55°C; in the present tests even the -25° sample fractured. Thus, Carboline has suffered some deterioration in low-temperature flexibility.

TABLE 10 TENSILE AND TEAR STRENGTHS OF URETHANE COATING-SCRIM SYSTEMS

TENSILE STRENGTH* Newtons (Pounds)		
Elastuff 504	Unsoaked	Soaked 15 days
Across lap joint	2001 (450)	1246 (280)
Parallel to warp	1623 (365)	1423 (320)
Perpendicular to warp	1068 (240)	890 (200)
Carboline		
Across lap joint	2669 (600)	2001 (450)
Parallel to warp	2091 (470)	1557 (350)
Perpendicular to warp	1646 (370)	1423 (320)
TEAR STRENGTH* Newtons (Pounds)		
Elastuff 504	Unsoaked	Soaked 15 days
Across lap joint	1357 (305)	1423 (320)
Parallel to warp	1379 (310)	1379 (310)
Perpendicular to warp	912 (205)	934 (210)
Carboline		
Across lap joint	1690 (380)	1913 (430)
Parallel to warp	1246 (280)	1512 (340)
Perpendicular to warp	1146 (325)	1512 (340)

\* Note: Values shown are for individual tests

TABLE 11 PHYSICAL EFFECTS OF IMMERSION IN GASOLINE FOR 15 DAYS

	% CHANGE	
	Carboline	Elastuff
Length	+ 4.1	+5.6
Width	+ 5.5	+4.3
Thickness	+16.0	+7.5

Flammability tests carried out on the two coating-scrim systems showed that the burn rates did not change significantly over the one-year period. Flame advanced over Elastuff 504 at a rate of 0.3 mm/sec (0.01 in/sec), emitting a greyish smoke. This material self-extinguished when the external heat source was removed. The Carboline, however, burned completely, emitting a black smoke, at a rate of 0.4 mm/sec (0.01 in/sec). It was also noted that both samples ignited immediately with the application of a flame to an edge; when flame was applied to the sand-covered surface, however, 15 to 20 seconds elapsed before ignition.

Permeability values determined at the time of application, were 1100  $\text{cm}^3/\text{m}^2/24 \text{ hr}$  (3.6 fl. oz/ft<sup>2</sup>/24 hr) for Elastuff 504, and 500  $\text{cm}^3/\text{m}^2/24 \text{ hr}$  (1.6 fl.oz/ft<sup>2</sup>/24 hr) for Carboline. Values determined during the tests under this program were approximately half of the above figures. It is not likely that permeabilities declined so substantially after a year of exposure to the elements. Conditions for this particular test are extremely difficult to duplicate, so the above variance is probably due to procedural anomalies. It is reasonable to infer, however, that permeability values have not risen substantially over previously reported values.

**3.7.4 Urethane Foams.** Table 12 reports flexural strengths for urethane foam samples. The denser slow foam has substantially more strength than the normal foam. In general, adhesion to substrate aggregate is good, but anomalies may cause lower strengths. For example, the last specimen tested from the 2 cm crush section contained a large pebble which reduced the depth of foam by one-third to one-half. Failure occurred in proximity to the reduced section, yielding a lower strength.

TABLE 12 FLEXURAL STRENGTH OF URETHANE FOAM SAMPLES\*

SUBSTRATE TYPE	FOAM TYPE	FLEXURAL STRENGTH	
		kPa	(lb/in <sup>2</sup> )
Mine Muck	Slow	1028	149
	Normal	538	78
2 cm Crush	Normal	568	82
		460	67
		509	74
2 cm Crush	Slow	1752	254
		1487	216
		783	114

\* Note: Values shown are for individual tests

For observations on flammability, a small propane torch was used in applying a flame to both foams; as soon as this external flame was removed, both foams self-extinguished.

Because urethane foam is essentially impermeable, "permeability" testing was carried out by slicing the foam into thin wafers, which were then placed in a pressure cell containing coloured water. Penetration of this water into the surface of the wafers ranged from 0.3 to 0.5 mm (0.01 to 0.02 in); volumetric absorption inferred from weight gain is summarized in Table 13. The upper layer of the foam covered with a urethane coating absorbed less than the lower layers, as one surface was effectively sealed. The upper layer of the normal foam absorbed more water than the lower layers because of higher open cell content due to weathering. The higher density slow foam does not appear to be as greatly affected by weathering as the lower density foam. Also, the denser foam has a more durable "curing skin" on the surface, which resists penetration by water.

**3.7.5 Summary of Laboratory Tests.** Comparison of grain size distribution curves of pure substrate soils and those mixed with bentonite showed that the beach sand and 2 cm crush contained approximately 18% bentonite, while the 4 cm crush contained about 24% bentonite.

Some problems were encountered in shipping the sulphur test sections. The sample of the Type III panel delaminated almost completely. Samples from other panels suffered minor delamination only. Laboratory testing indicated relatively low flexural strengths. These results are probably due to a combination of strength loss from weathering and the utilization of samples from panel edges where application procedures might have been poor.

TABLE 13 WATER ABSORPTION BY URETHANE FOAM SAMPLES

FOAM TYPE	LAYER*	ABSORPTION (% by Volume)	REMARKS
Normal	1	7.5	Surface coated with urethane polymer
	2	8.9	
	3	8.8	
	4	8.6	
Normal	1	10.7	
	2	9.1	
	3	7.2	
	4	8.4	
Slow	1	5.8	
	2	7.0	
	3	6.3	
*Layer	1	Surface - 5 mm	
	2	5 - 10 mm	
	3	10 - 15 mm	
	4	15 - 20 mm	

While higher strengths might be expected in the interior of the panels, the low strengths at the edges underline the need for stringent quality control during application. Results of flexural testing indicate that Type I is considerably stronger than Types II and IV. Whether this is a result of differences in formulation or application is not clear. Similarly, Type I exhibited a lower propensity to crack under

impact at both normal and low temperatures than did Types II or IV. The mastic sealant used in joints between sulphur panels is inappropriate because it dissolves rapidly in gasoline.

Tensile and tear strengths of the two urethane coatings had not deteriorated radically after a year of exposure. However, short-term immersion in gasoline produced a more marked reduction in tensile strengths than that which occurred in fresh samples. This indicates that these materials are more susceptible to attack by gasoline after exposure. Dimensional changes induced by short-term soaking in gasoline doubled for Carboline after a year's exposure, but did not increase for Elastuff 504. Fresh Carboline cracked at -55°C, but weathered Carboline cracked upon flexing at -25°C. Flammabilities and permeabilities did not change significantly over the past year.

Weathering appears to have had only a surficial effect on either the normal or slow foam. Adhesion of the urethane foam to base aggregates is still good. Anomalies, such as protruding aggregate reducing the thickness of the section, may cause relatively low strength at specific locations. Flammability does not appear to have increased radically as a result of weathering, and the foam has remained relatively impervious, even at the weathered surface.

## **4 DISCUSSION**

### **4.1 General**

All four of the liner systems studied require summer conditions for application. Urethane coatings and urethane foams should not be installed below 15°C (60°F); the sulphur and bentonite liners are somewhat more tolerant to cool temperatures. None of the liners are to be installed during rainfall or onto an excessively wet base.

The three spray-applied liner systems are suited for use in existing tank farms. Minor difficulties with application of the sulphur arose because the melt-mix apparatus used was a prototype. The bentonite system appears to be more appropriate for open areas than for congested tank farms. To use equipment to achieve uniform mixing and compacting, adequate room for maneuverability is required.

The bentonite may be mixed with the base soil with no preparation other than removal of debris. Similarly, urethane foam may be applied over bases with virtually any degree of roughness. Urethane coatings and sulphur liners require somewhat more preparation. The base must be smoothed, then a backing fabric placed for the former liner system. Wooden forms, as well as a smoothed base, are necessary to separate the panels of the sulphur liner.

The bentonite and sulphur liners do not require any anchoring. The urethane foam should be placed over a granular rather than a fine-grained base so that sufficient aggregate will adhere to the foam to weight it down. The edges of urethane coating liners may be keyed into shallow trenches for anchoring purposes. The interior should be held down by round stones or concrete weights with mass over 20 kg (45 lb) placed on a 5 m (17 ft) grid.

Of the four liner systems, sulphur is the only one that is jointed. These joints present a weak point in the liner system unless the joint sealant is as good or better than the liner material. The other three liner systems are monolithic, requiring joints only where they meet tanks or other fixtures. Sealing at these locations may be characterized as "adhesive" for urethane coatings and urethane foams, and "contact" for the bentonite liner.

It should be stressed that all of the spray-applied liner systems require expert and experienced applicators if liner quality and longevity are to be achieved.

A fire rating has not been established for sulphur or urethane products in horizontal configurations on the ground within petroleum product storage areas. Both may be made fire resistant, however, through the addition of fire retardants to their respective formulations. The acceptability of these materials for use as exposed liners in petroleum product storage areas should be confirmed with appropriate fire authorities before large-scale installations are undertaken. The alternative of covering liners with an earth blanket is undesirable because they may become punctured while the blanket is being placed. The earth blanket obscures flaws which may develop and hinders repairs. Placement of the blanket adds substantially to liner costs.

For safety reasons, the three spray-applied liner systems should be coated with a traction surfacing. Local sand adhering to a tack coat has worked well on the urethane coating and urethane foam liners.

In remote locations in northern Canada, transportation costs are a significant factor in the total cost of installing a liner. Equipment sizes and material weights summarized in Section 2.5 indicate that the urethane coatings and urethane foams have a substantial advantage over the other two liners in terms of logistics.

Because base conditions, labour costs and productivity, and transportation costs vary widely from site to site, no cost analysis has been undertaken for the liner systems mentioned in this report. Obtaining firm quotations for specific projects from the respective suppliers is the only practical basis for making accurate cost comparisons.

#### **4.2 Processed Bentonite**

Observations indicated that after one year the bentonite layer had not dessicated, even where a protective soil cover did not exist. The opposite situation appears to be of more concern: an excessively moist bentonite layer was unable to support foot traffic, and promoted weed growth, which could add biological desiccation to other drying mechanisms. Further observations revealed that manual mixing produced a liner of variable thickness, with some areas where material was not mixed. These areas increase the permeability of the overall liner by several orders of magnitude, even if they constitute only a minor percentage of the total area.

Bentonite liner systems should be installed with the use of proper grading, mixing and compacting equipment only, in areas where room for maneuverability is adequate. Because of maneuverability constraints, design thickness of the bentonite layer should be doubled where manual installation is necessary.

Stringent quality control over uniformity of the bentonite-base soil mixture is essential for liner quality.

A granular protective cover should be provided, having thickness sufficient to support expected traffic without damaging the underlying bentonite layer.

Vegetation growth on bentonite liners should be kept to a minimum.

#### **4.3 Processed Sulphur**

The most significant observation on the sulphur liner was that substantial cracking had occurred over the winter. These cracks likely resulted from thermally induced shrinkage stresses or frost heaving of substrate soils. Such conditions are apt to exist at most tank farms in northern Canada. As soil movement for any reason would likely bring about cracking, this type of liner should not be placed on uncompacted or unstable bases. Furthermore, field tests indicate that these cracks allow a relatively high rate of flow, thereby reducing the retention capability of the liner.

The use of certain sulphur formulations appears to reduce the incidence of cracking; one way to avoid cracking altogether would be to use very small panel sizes. This, however, requires an unacceptably high degree of foaming and joint preparation. The most viable alternative appears to be the use of intermediate panel thicknesses and sizes, which is accompanied by the necessary degree of maintenance to keep the cracks sealed. Cracking may either stabilize after a few years or continue over a long period, depending on the mechanisms of crack development.

The choice of sealants was inappropriate in that the mastic material dissolved somewhat quickly in gasoline. Other sealant problems were the development of splits and the loss of adhesion to the sulphur panels. An ideal joint sealant must have suitable elasticity, good adhesion to sulphur, and resistance to detrimental effects of petroleum products.

Incorporation of fire retardants into the liner formulation is a less troublesome approach towards achieving inflammability than the use of fire-resistant paints.

Delamination of samples from the sulphur liner and relatively low flexural strengths obtained during laboratory tests likely resulted from strength loss upon weathering and poor application procedures at sample locations. These results indicate that actual liner strength may be somewhat lower than strengths determined by tests on unweathered laboratory samples. Quality control at the time of application is necessary to achieve uniform liner quality.

Sulphur liner systems should be installed only when owners and authorities are prepared to accept a high degree of maintenance as a trade-off against other desirable properties of this rigid liner, such as good load-bearing characteristics or ability to withstand foot traffic.

#### 4.4 Urethane Coatings

Only minor problems were encountered in the installation of the urethane coating test sections and, as noted in Section 2.5, minor modifications to methodology and materials should overcome these. The use of urethane material as a joint adhesive appears to have been satisfactory, but required extra effort at the time of installation. The scrim backing should be joined with a proper adhesive. The method of joining the backing to tanks and pipe galleries using urethane foam also appears to have worked well. The use of a backing fabric which is slightly more open than the closely woven Tufton may allow a greater penetration of the coating between the fibres of the fabric, leading to a stronger coating-fabric bond. Prohibiting foot traffic from the liner until the coatings are fully cured would likely eliminate the incidence of small punctures. A method other than sandbagging should be used for anchoring, as ravs tore the sandbags, rendering them ineffective.

Design coating thickness should be 0.3 mm (20 mils) or greater. Close quality control should be exercised during application to ensure uniformity of coating in general and that thicknesses are above this minimum.

Work should be planned such that lining a given area starts and finishes within one work day; delay allows contamination between layers and potential loss of adhesion.

High-traffic areas should be protected with a walkway to prevent localized wear.

Although there were no pinholes in either system, the Elastuff 504 material was very thin in some areas. These areas, which experienced greater weathering than thicker areas, were caused by flow of the low viscosity material at the time of application.

Laboratory tests indicated that tensile and tear strengths, flammability and permeability had not deteriorated radically from the time of application. After short-term immersion in gasoline, however, dimensional changes and the relative loss of tensile strength were greater, indicating that the weathered urethane coating liners are more subject to attack by gasoline. These trends cast some doubt on the length of useful service life of Elastuff 504 liner.

With good performance for one year, the urethane coatings show potential for two to three year usage if left exposed. It may be possible to extend liner life by thickening the urethane coating slightly or by covering the liner with soil for protection from sunlight; service life in the latter case could very well be five years. Use in temporary storage sites is feasible as there is a relatively low volume of material to be disposed of when the temporary areas are disassembled.

Performance of liners in such medium-term installations should be critically evaluated in order to determine whether expected service life can be realistically extended.



## **4.5 Urethane Foams**

No difficulties were encountered during the installation of the urethane foam test sections. After one year of exposure to the elements, the urethane foams seemed to be in good condition, aside from surficial weathering.

The Carboline-surfaced areas continued to attract ravens even though the coating had weathered to a dull green: deep gouges were evident in several places. Adjoining sections with no coating and with a sand coating had few peck marks. The higher density foam withstood damage from ravens and vandals better than the lower density foam.

Laboratory testing showed that while weathering had increased open-cell content of the foams at the surface, the foam liners remained virtually impervious. Flammability of the foams had not changed since application, and adhesion to aggregate was still good.

The optimal configuration for a foam liner is an initial layer of low-density foam, then a surface layer of higher density foam to resist impact and abrasion. It is also anticipated that higher density foam would be somewhat more resistant to weathering.

Urethane foam is only surficially affected by weathering and other deleterious forces. Excellent performance through one year suggests that a service life of about five years might be expected with a very low level of maintenance. Although the level of maintenance would increase beyond that time, it is likely that several more years would elapse before maintenance reaches an unacceptable level or replacement becomes necessary.

The surface layer should be a higher density foam to act as a wearing surface and walkways should be placed along high-traffic routes.

Coating with a brightly coloured material is not recommended.

## **5 CONCLUSIONS**

Initial laboratory assessment programs provided a useful screening process to indicate suitable lining materials. The field test sections have provided additional valuable information on performance trends.

Of the four liner systems studied, urethane foams appear to be the most suitable for installation in existing northern petroleum storage areas.

Urethane coatings appear to hold sufficient potential to proceed with installation in temporary sites. Satisfactory performance could lead to applications where longer service lives are required.

Sulphur linings are strong, but are likely to lose integrity due to cracking. This system would be only suitable in instances where the owner and regulatory authorities are willing to accept a high degree of maintenance.

The bentonite liner system is not appropriate for use in congested locations such as existing petroleum storage areas, because of the difficulty in achieving uniform mixing with substrate soils without mechanical assistance.

In addition to good performance, the first two liner systems offer significant advantages over the latter two in terms of weights of raw materials to be transported to remote sites.

Acceptability of sulphur and urethane materials in exposed liners should be confirmed with appropriate fire authorities before large-scale application is undertaken.

Continued general observation on the Yellowknife test sections is warranted, with particular attention to equilibrium of cracking in the sulphur liner, evidence of delamination of the sulphur liner, further weathering and loss or resistance to attack by gasoline by the urethane polymer liners, and further weathering of the urethane foams.

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