



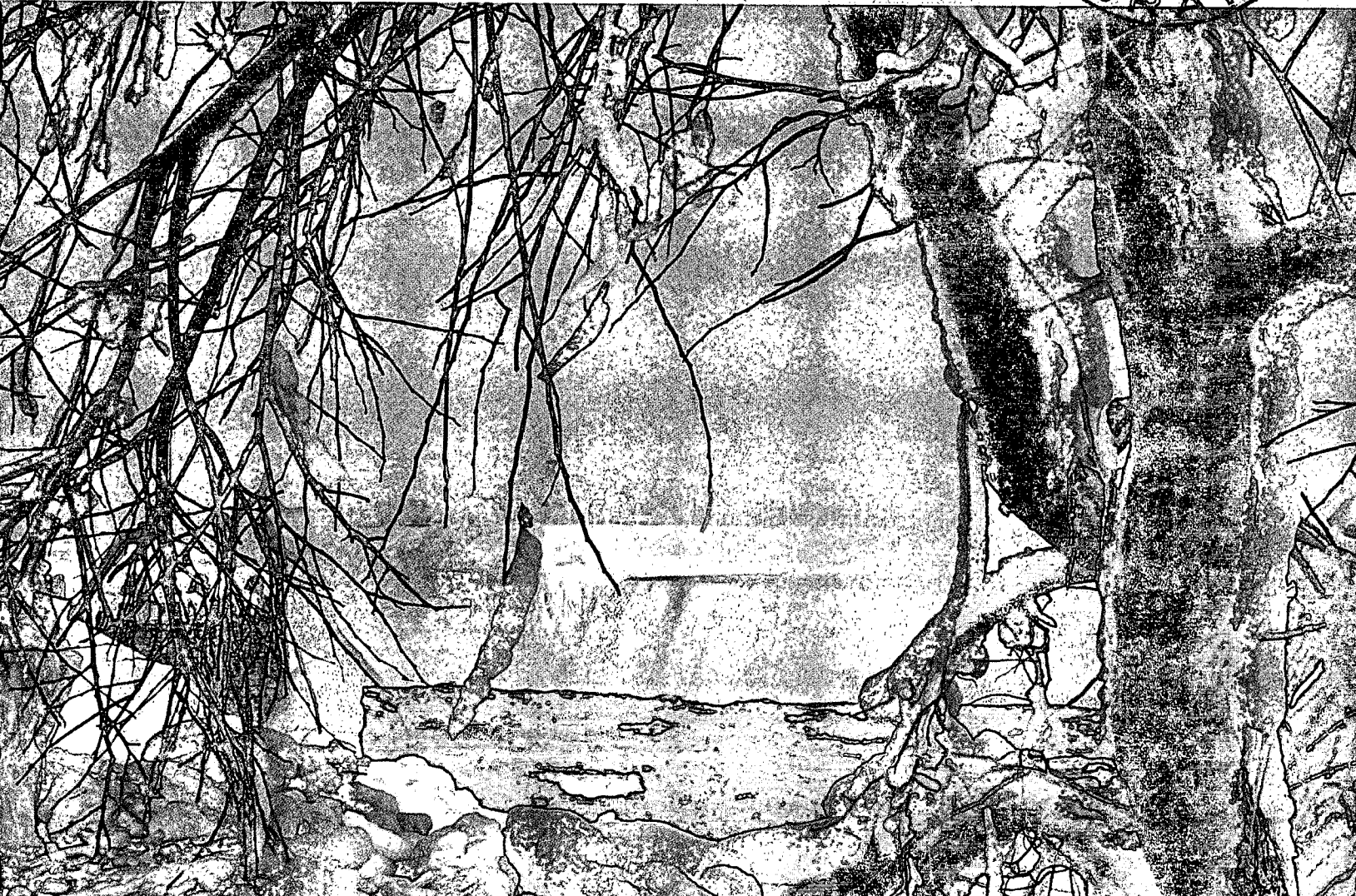
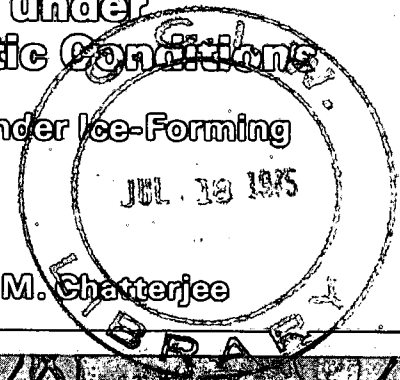
Environment  
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# Behaviour of Oil under Canadian Climatic Conditions

## Part 1. Oil on Water under Ice-Forming Conditions

Brian F. Scott and Robi M. Chatterjee



**SCIENTIFIC SERIES NO. 50**  
*(Résumé en français)*

**INLAND WATERS DIRECTORATE,  
WATER QUALITY BRANCH,  
OTTAWA, CANADA, 1975.**

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Information Canada  
Ottawa, 1975

Cat. No.: En 36-502/50

Contract No. KL327-4-8069  
THORN PRESS LIMITED

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## Abstract

Oil was poured onto a water surface under ice-forming conditions. Weather conditions were monitored continuously, as were the physical properties of the oil and the effect of the oil on its physical environment. Properties of the oil were investigated by gas chromatography and the following forms of spectroscopy: neutron activation ( $\gamma$ -ray), infrared, ultraviolet, visible and fluorescence. The weathering of the oil and its influence on its environment were correlated with the weather parameters. An estimated 50% of the oil had evaporated before the oil was covered with snow, as determined by gas chromatographic analysis and supported by neutron activation analysis. A biological assessment was conducted during the following summer where the effect of the oil on one pond was compared with the control pond. In the oiled pond, the variety of biological species was substantially less than in the control pond.

## Résumé

On a versé du pétrole sur une surface d'eau au point de congélation. On a constamment contrôlé les conditions atmosphériques, de même que les propriétés physiques du pétrole et ses effets sur son environnement physique. On a étudié les propriétés du pétrole par la chromatographie gazeuse et les formes suivantes de spectroscopie: activation neutronique (rayons  $\gamma$ ), infrarouge, ultraviolet, rayonnements visible et fluorescent. L'action des facteurs météorologiques sur le pétrole et l'effet de celui-ci sur son environnement ont été comparés aux paramètres météorologiques. On a estimé que 50% du pétrole s'était évaporé avant qu'il ne soit recouvert par la neige; l'analyse par chromatographie gazeuse a permis d'arriver à ce chiffre qui a été confirmé par l'analyse par activation neutronique. On a effectué au cours de l'été suivant une évaluation biologique où l'on comparait l'effet du pétrole d'un des étangs avec l'étang témoin. La diversité des espèces biologiques était beaucoup plus faible dans l'étang où l'on avait versé le pétrole que dans l'étang témoin.

# Behaviour of Oil under Canadian Climatic Conditions

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### INTRODUCTION

The exploration for oil in Canada's northern frontier has brought into focus the possibilities and dangers of oil spills in the environment. Indeed, the transportation of oil from the present and possible future oil discoveries in the Arctic to heavily populated areas of use in the south, has emphasized the lack of knowledge of the behaviour and influence of oil in cold environments. It is the mission of the Oil Pollution Research Group of the Inland Waters Directorate to provide a comprehensive understanding of the behaviour of oil in ice-water systems. This report describes the results of the initial field studies undertaken by this group.

### BRIEF REVIEW OF SEVERAL ACCIDENTAL AND PLANNED OIL SPILLS IN COLD ENVIRONMENTS

Perhaps the most famous oil spill affecting Canada occurred at Chedabucto Bay in February 1971 (Task Force, 1970). During this mishap 600 tonnes of a no. 6 fuel oil, (Bunker C), were spilled into the cold waters off Nova Scotia. This particular fuel is mainly the residuum of the distillation process carried out at oil refineries. Therefore there were no light ends in the product to lower the viscosity or pour point, and it resembled a well-aged crude oil when it entered the water. The high viscosity, the high pour point and other properties of this product contributed to the difficulties in the subsequent clean-up operations. Its high ignition temperature and its tendency to form water-in-oil emulsions further increased the difficulties.

The second major spill of interest was the spill of 100 tonnes of a no. 2 fuel oil at Deception Bay in the eastern Arctic (Ramseier, Gantcheff and Colby, 1973). This particular fuel is a refinery cut between 150°C and 280°C and contains components which are reasonably volatile. A slush slide into an oil tank farm caused this oil spill. Surface oil

volatilized to some extent, but a considerable amount was trapped under the ice, which resulted in difficulties in calculating the mass balance of the oil and during its eventual clean-up.

In the winter of 1971, a third spill occurred on Lake Champlain, N.Y., as a result of the overfilling of a storage tank. Again snow and ice hindered the clean-up, but eventually removal efforts were considered successful (Lamp'l, 1973).

Human error was again responsible for a spill in the Northwest Territories during the winter of 1972 (Globe and Mail, 1973). Here most of the oil found its way under the shore-fast ice. In these circumstances recovery operations had to be postponed until the break-up.

In Sweden, a technical mishap caused at least 552 tonnes of a no. 2 fuel oil to be released into an ice-infested river (Jerbo, 1973). After using several clean-up techniques, the railway officials concluded that they had recovered most of the oil.

This short list of accidental spills does not completely catalogue oil spills occurring in cold environments.

Owing to the occurrence of oil spills under cold conditions, various programs have been initiated in the North. The most extensive studies have been conducted by the U.S. Coast Guard. Members of the Oil Pollution Research Group have been official observers on both of the U.S. missions which investigated the behaviour of oil on ice and snow.

During the summer of 1971, on the ice-covered Chukchi Sea, refined and crude oils were spilled, their spreading rates determined, ignition tests carried out and the behaviour of oil under the ice observed (Ramseier, 1971). A film produced by the Department of the Environment recorded many of these activities (Ramseier, 1971).



In 1972, at the Port Clarence test area, studies were made of the behaviour of crude oil on ice and snow as well as attempts to burn the oil (Chen, 1972; McMinn, 1972). Samples brought back from this study will be discussed in our next report (Scott *et al*).

In Alaska, a controlled spill occurred in Cook Inlet (Kinney, Button and McScheel, 1969). The investigators examined the residual oil, oil movement, and bacterial action on the oil. This test occurred in open water.

In the Mackenzie Delta area of the Northwest Territories, the Fisheries Research Board of Winnipeg conducted separate test spills on a small lake and a river to determine the effect of oil on the biota (Brunskill *et al*, 1973). Very little was done to determine the behaviour of the oil.

### STUDY BY THE OIL POLLUTION RESEARCH GROUP

The initial spill was conducted by the group to investigate the fate of oil under ice-forming conditions. Understanding the behaviour of this spilled oil should aid in the eventual control of the pollution of waterways by oil. Also this study will aid those involved in the forensic aspects of oil pollution; the federal police force's crime laboratories participated in this and other spills conducted by this group.

Any crude oil consists of components having a boiling point range of many hundreds of degrees. Therefore to investigate the original and weathered oils, two principal techniques were employed: gas chromatography and

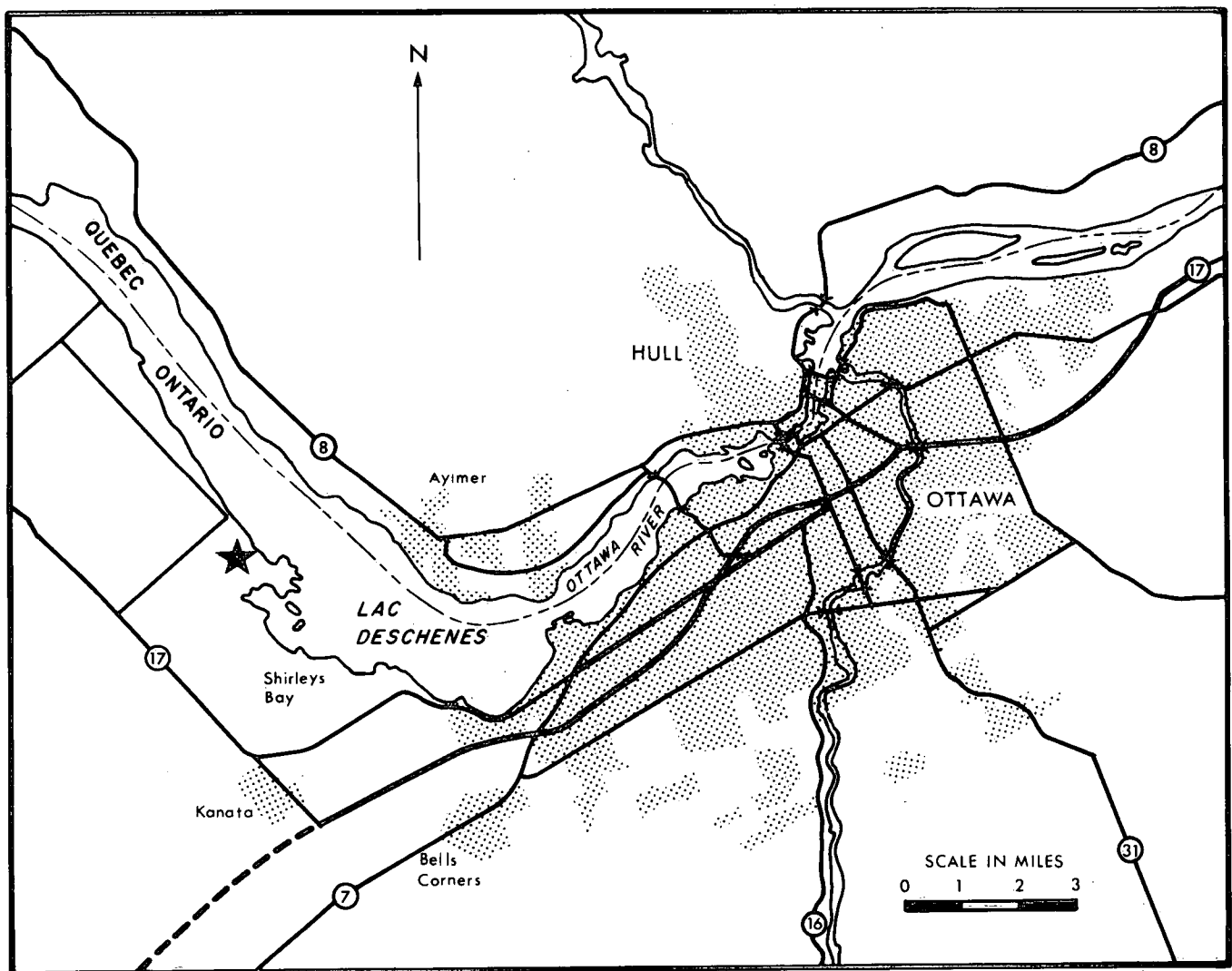


Figure 1. Location of spill site.

neutron activation analysis (NAA). Gas chromatography provides a fingerprint of a great many of the components in an oil. This technique relies on the injected sample or its constituent parts reaching the detector in their vapour states. The higher boiling components of crude or heavy refined oils, however, cannot be vaporized under gas chromatographic conditions. Therefore it is advantageous to use NAA to examine the metal content of oils which is usually associated with the higher boiling fractions. Also the spectroscopic techniques of infrared, ultraviolet and fluorescence spectroscopy were used to examine the oil samples.

The spill was carried out near Ottawa at the Shirleys Bay Quiet Site where four large ponds were constructed. The site was selected because of the following considerations:

- (1) these quiescent ponds simulate typical lakes found in the Mackenzie Delta area,
- (2) better control of the spilled oil is allowed by the ponds to prevent the increase of environmental pollution,

- (3) these ponds are easy to clean up,
- (4) in case of an emergency, service is available from our support personnel since the ponds are close to our laboratories, and
- (5) these ponds, close to Ottawa, experience the severe weather conditions common to Ottawa that can be used to approximate arctic conditions.

## EXPERIMENTAL

### Field

#### Field Site Facilities and Preparation

The location of the ponds is shown in Figure 1 and a plan of the ponds is indicated in Figure 2. Each pond was doubly lined with polyethylene sheets with the ends buried under the earth and with the linings between adjacent ponds overlapping and buried so that the complete filling of the ponds would form one large pond without leaks. This was tested by filling each pond with water and observing

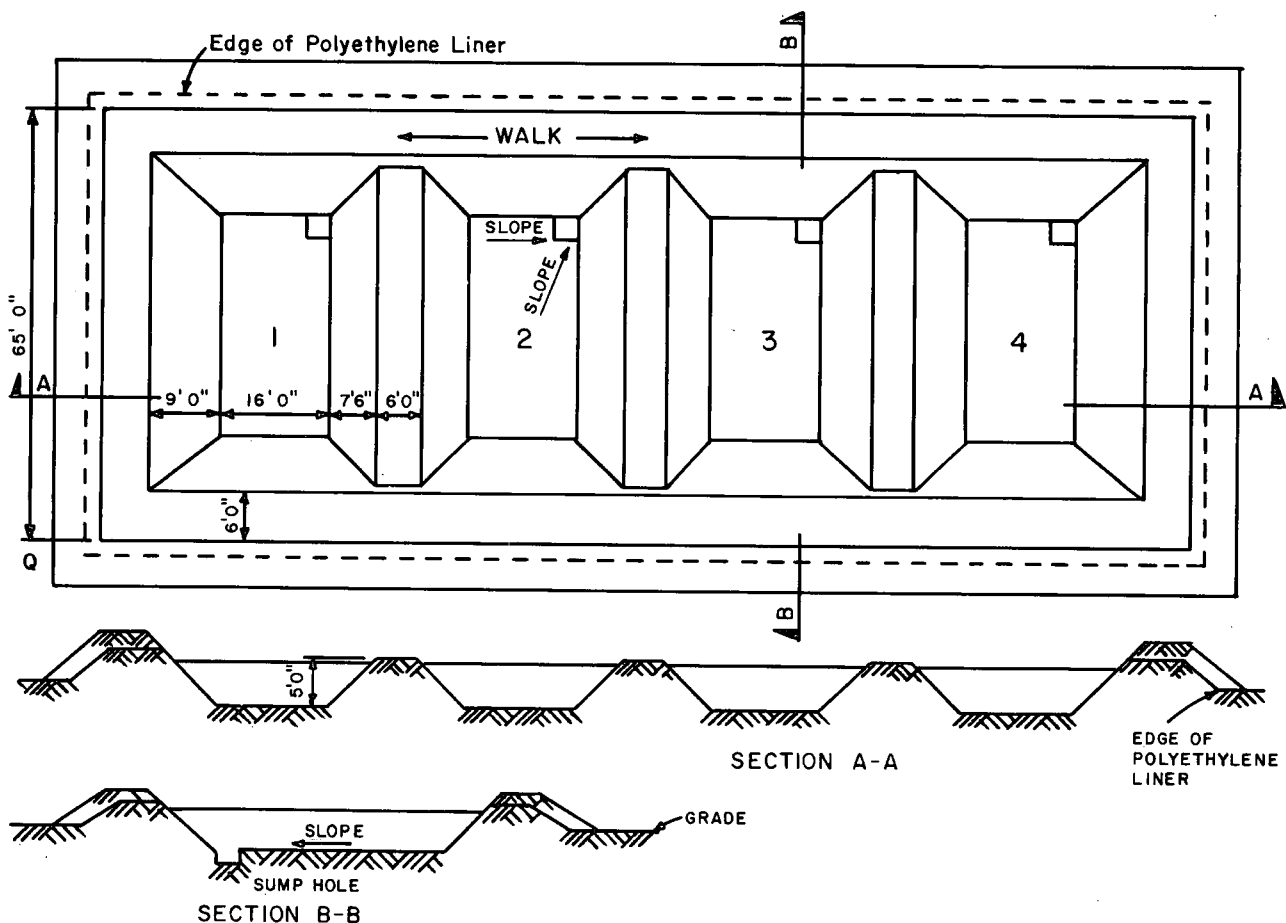


Figure 2. Diagram of experimental oil spill ponds.

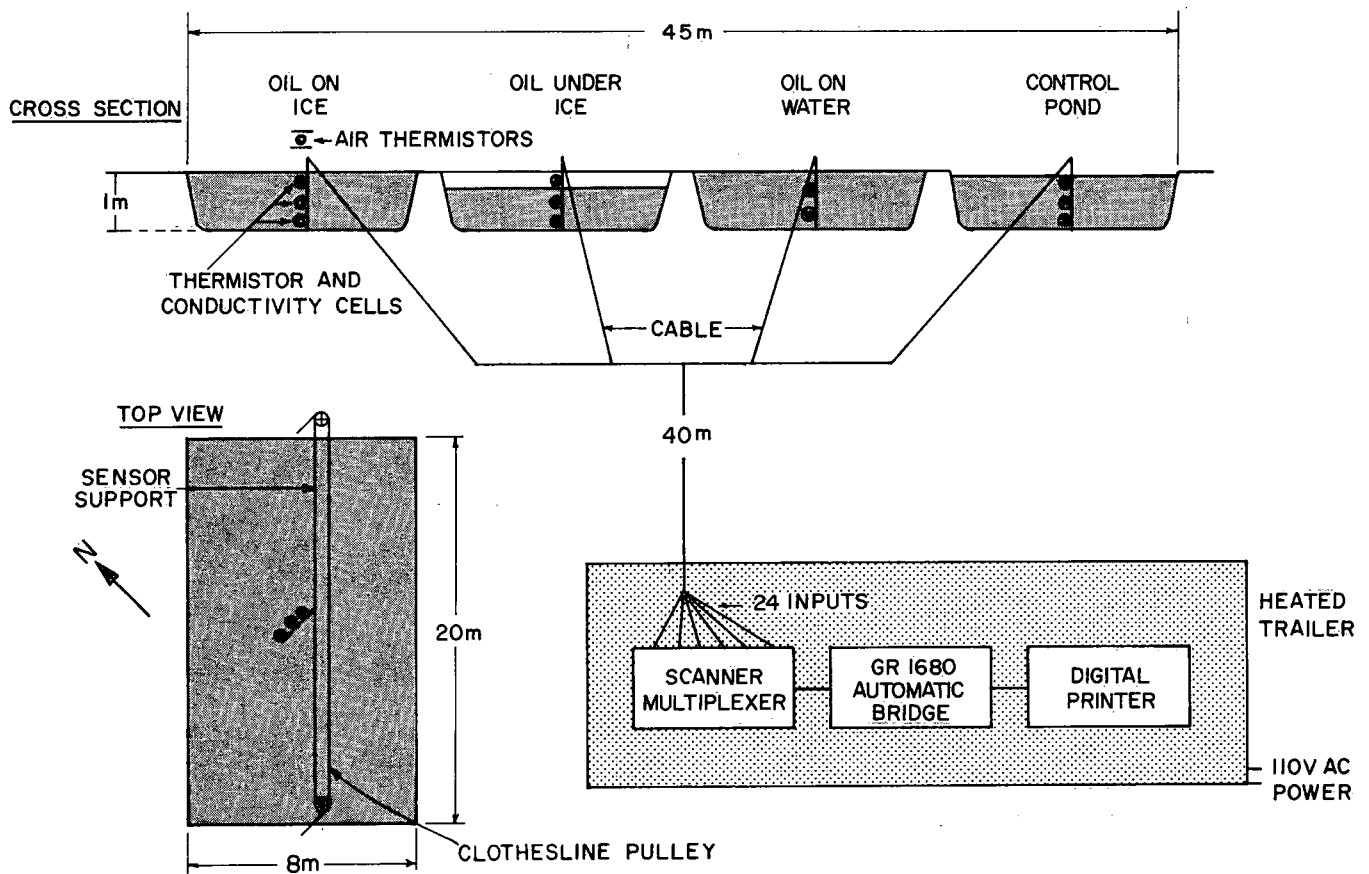


Figure 3. Instrumentation contained in ponds.

that the water levels were constant. A trailer serviced with electricity was located near the ponds to provide a field headquarters.

Three sets of monitoring cells were positioned in each pond. Each set was composed of a calibrated thermistor for temperature readings and a capacitance cell for conduc-

tivity measurements. One set was positioned near the top of each pond, one at mid-depth and the third at the bottom. A schematic diagram of this arrangement is shown in Figure 3. A complete analysis of these measured parameters will be given in a subsequent report (Adams). The pond at the extreme right in Figure 2 was used as the control pond for this and subsequent spills.

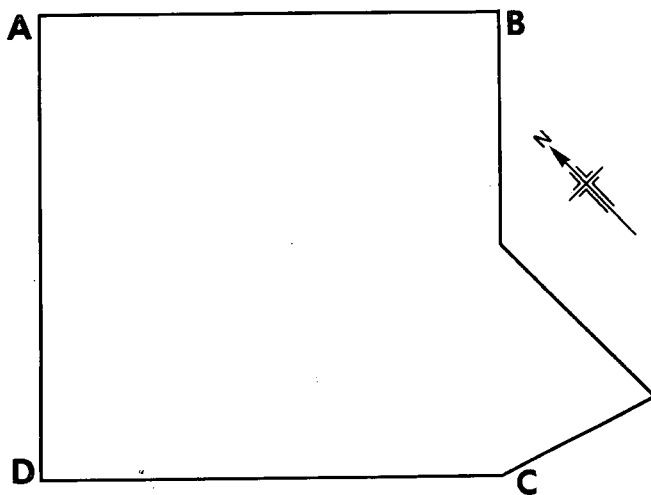


Figure 4. Ice-free area in pond no. 3.

#### Oil Used

Norman Wells crude oil, supplied by Imperial Oil of Canada Limited, was used for this and subsequent spills. This crude oil is found and refined in Canada's Subarctic and used almost exclusively in the North. It has a pour point of  $-51^{\circ}\text{C}$  and a low residuum carbon value (Charbonnier *et al*, 1969). The results of a partial Hempel distillation (United States Bureau of Mines, 1951) are shown in Table 1, and a complete distillation conducted several years ago is shown in Table 2. The low pour point of this oil is similar to that of the oil found at Atkinson Point ( $-43^{\circ}\text{C}$ ), and both of these oils have lower pour points than that of the oil from Prudhoe Bay ( $-9^{\circ}\text{C}$ ) (Parker, 1968). These three oils are found in the Arctic or Subarctic.

Table 1. Partial Analysis of Norman Wells Crude Oil  
Used in This Work (United States Bureau of Mines, 1951)

Fraction cut at °C	Percent (volume)	Cumulative percent (volume)	Specific gravity	Percent (weight)	Cumulative percent (weight)
50	2.7	2.7	0.635	2.12	2.1
75	2.8	5.5	0.664	2.3	4.4
100	5.8	11.3	0.710	5.0	9.4
125	8.2	19.5	0.738	7.3	16.7
150	5.9	25.4	0.759	5.4	22.1
175	5.2	30.6	0.779	4.9	27.0
200	4.9	35.5	0.795	5.2	32.2
225	5.4	40.9	0.811	5.3	37.5
250	5.2	46.1	0.824	5.2	42.7
275	6.2	52.3	0.838	6.3	49.0

### Weather Monitoring

A Rimco 5-inch (123-millimetre) cup contact anemometer and a wind vane attached to a Summer Mark III recorder were installed at position Q shown in Figure 2. Temperature readings were taken daily and correlated with those at the Ottawa Weather Station located at the airport, and with those recorded at the Central Experimental Farm. It was found that the temperature readings taken at the site agreed to within 1°C with those at the other two federal installations.

Table 2. Complete Distillation Analysis  
of Norman Wells Crude Oil

(Charbonnier *et al.*, 1969; United States Bureau of Mines, 1951)

Fraction cut at °C	Percent cut	Cumulative percent	Specific gravity cut
50	2.7	2.7	0.657
75	3.1	5.8	0.673
100	4.7	10.5	0.712
125	7.9	18.4	0.742
150	5.7	24.1	0.764
175	6.1	30.2	0.781
200	5.4	35.6	0.801
225	5.7	41.3	0.815
250	5.4	46.7	0.828
275	6.2	52.9	0.842
Distillation continued at 40-millimetre Hg pressure			
200	4.6	57.5	0.856
225	6.0	63.5	0.865
250	5.0	68.5	0.880
275	3.8	72.3	0.894
300	5.2	77.5	0.902
Residuum	21.5	99.0	0.948

Carbon residue of residuum—6.5%; carbon residue of crude — 1.4%

### Spills

On November 20, 1972, we made our first spill on pond no. 3. This spill simulated oil on water under ice-forming conditions. At this time, freeze-up had commenced in the Ottawa area and 40 mm of ice covered each pond. An approximate 3.6 m by 3.6 m area of ice was removed from the centres of ponds no. 3 and no. 4, but on pond no. 3 an additional area was removed from the southeast side of the pond (Fig. 4). The barrel containing the oil was shaken. Homogenized by the agitation, 23 gallons of the oil were then delivered to the exposed water area of pond no. 3 by a mechanical pump and hose. Pumping commenced at 1500 hours and ended at 1530 hours. Figure 5 shows the oil being pumped onto the water.

### Sample Collection and Treatment

All of the samples were identified by the date, time and location of sampling. Samples of 10 ml were removed daily as shown in Figure 6 and transferred to clean, glass storage bottles previously purged with nitrogen. These samples, which were transported in the dark and stored in refrigerators at -5°C in our laboratories, were used for gas chromatographic, infrared, visible and ultraviolet, and fluorescent spectroscopic analyses. No special pretreatment was given to these samples other than to prevent any water collected with the sample from being withdrawn with the oil prior to analysis.

Less frequently, additional samples of about 20 ml were removed for neutron activation analysis. Surface samples were collected by a polyethylene scoop and transferred to Teflon-gasketed, Nalgene sample bottles for storage under nitrogen in the refrigerator.

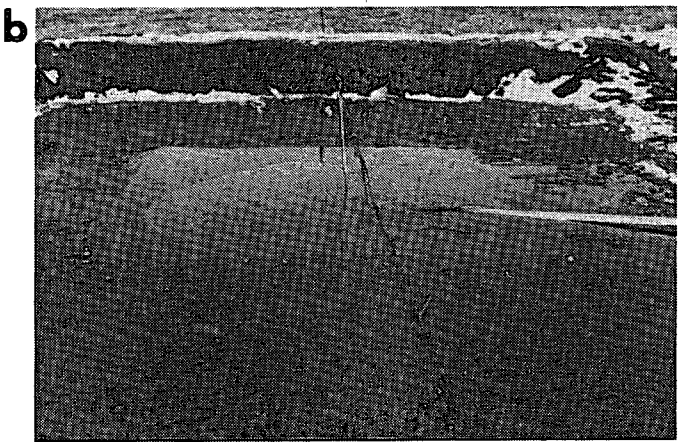


Figure 5. Preparation of pond no. 3 (a) removal of ice from pond to create water surface and (b) pumping oil onto water surface.

## Laboratory

### Neutron Activation Analysis

**Sample Treatment**—Samples were transferred from the Nalgene bottles and washed individually with deionized doubly distilled water. Each sample was then centrifuged to separate the water from the oil. The choice of the material of the centrifuge tubes was restricted to polyethylene that had been cleaned with detergent and thoroughly washed with deionized water. No heating of the centrifuge tubes, of their shielding or of the oil samples was necessary, since the viscosity of the Norman Wells crude oil and the weathered oil samples did not cause any special problems. After a few minutes of centrifugation, the denser water phase in the tube was removed by a disposable syringe. After centrifuging for an additional few minutes, any residual water was withdrawn, and the oil was poured directly into tared polyethylene snap-top irradiation vials. After capping and before heat-sealing, the vials were weighed.

**Irradiation and Counting Procedures**—The samples were irradiated in the sealed polyethylene vials for 1 hour at a thermal neutron flux of  $2.5 \times 10^{12}$  neutrons  $\text{cm}^{-2} \text{sec}^{-1}$ , in the SLOWPOKE nuclear reactor facility at the Atomic Energy of Canada Limited (AECL), Commercial Products Division, Ottawa. Following irradiation, the samples were transferred from the irradiation vials and counted after a decay period such that  $^{24}\text{Na}$  activity had sufficiently diminished. The counting facility used was a  $35 \text{ cm}^3$  Ge(Li) detector coupled to an 800-channel pulse-height analyzer. Standards were irradiated and counted using the same technique. An Au-Al flux-monitor wire was employed with each irradiation to monitor the actual neutron dose.

For  $^{51}\text{V}$ , a short-lived isotope ( $t_{1/2} = 3.8 \text{ min}$ ), a short irradiation of 1 minute followed by a radioactivity measurement was carried out. Vanadium was detected in all of the samples and its abundance masked the detection of other short-lived isotopes. Aluminum ( $^{28}\text{Al}$ ,  $t_{1/2} = 2.3 \text{ min}$ ) was detected in all of the samples. For this short-lived isotope, it was necessary to delay its measurement in order for the  $^{51}\text{V}$  activity to decay. The levels, however, were too low for quantitative determination. For the other elements, the standard procedure was then followed.



Figure 6. Collecting oil sample.

Some samples were also irradiated in the NRX and NRU high-flux research reactors (maximum flux =  $5 \times 10^{14}$  neutrons  $\text{cm}^{-2} \text{sec}^{-1}$  and  $10^{14}$  neutrons  $\text{cm}^{-2} \text{sec}^{-1}$ , respectively) at the Chalk River AECL Nuclear Laboratories. A neutron flux of  $5 \times 10^{12}$  neutron  $\text{cm}^{-2} \text{sec}^{-1}$  was used and the samples irradiated for 75 hours. For certain irradiations the concentration level of desired elements producing relatively long-lived isotopes made it necessary to use quartz capsules as irradiation containers. A number of the samples were irradiated together in the reactor, and the irradiated samples were transported to Ottawa for counting measurements. The total activity had a large contribution from the  $^{24}\text{Na}$  isotope, and therefore it was necessary to wait for this activity to decay before counting for the other isotopes.

### Gas Chromatography

Chromatographic conditions are shown in Table 3. To protect the SCOT column, an empty 1.8-metre precolumn was placed in front of it. Heavier ends of the oil, which would not pass through the column, remained in the precolumn. This arrangement with its resulting dead-space did not seriously affect retention times.

Table 3. Chromatographic Conditions for Oil Analysis on Perkin-Elmer 900

Parameter	Dexsil-300 SCOT column	OV-1 SCOT column
Sample size ( $\mu\text{l}$ )	0.45	0.45
Injector temperature ( $^{\circ}\text{C}$ )	350	300
Split ratio	10:1	10:1
Carrier gas	He	He
Flow rate (ml/min)	10	10
Initial temperature ( $^{\circ}\text{C}$ )	60	35
Initial temperature hold (min)	0	6
Final temperature ( $^{\circ}\text{C}$ )	300	210
Final temperature hold (min)	32	32
Program rate ( $^{\circ}\text{C}/\text{min}$ )	4	4
Detector	FID	FID
Detector temperature ( $^{\circ}\text{C}$ )	350	300
Hydrogen pressure ( $\text{kg}/\text{cm}^2$ )	1.8	1.8
Air pressure ( $\text{kg}/\text{cm}^2$ )	2.1	2.1
Column diameter(mm) (internal)	0.5	0.5
Column length (m)	15.6	15.6
Precolumn length (m)	1.9	1.9
Coating of precolumn	empty	empty

### Infrared Spectroscopy

A Perkin-Elmer (Model 357) grating infrared spectrophotometer was employed for these measurements. Cavity cells were used to hold the samples and chloroform or carbon disulphide was used as solvent.

### Visible and Ultraviolet Spectroscopy

A recording Beckman DBG, double-beam, grating spectrophotometer was used to record the spectra, and occasional replicate samples were run on a Cary Model 14 spectrophotometer. Fused quartz, 10-millimetre cells were employed. Oil samples ( $0.02 \mu\text{l}$ ) were diluted to 10 ml by n-hexane.

### Fluorescence Spectroscopy

A Perkin-Elmer MPF 2A recording fluorescence spectrophotometer was used. The solvent of choice was spectro-analyzed n-hexane. Samples in the 1-microlitre size range were added to 10-millilitre volumetric flasks and these solutions were analyzed by first determining maximum absorption regions in the ultraviolet (ca  $256 \text{ m}\mu$ ) and then using this wavelength as the excitation line. A calibration was performed each day. Efforts were made to resolve the spectra obtained from the fluorometer by a Dupont Model 310 curve resolver.

## RESULTS AND DISCUSSION

### Field

#### Weather Data

Pertinent weather factors influencing the behaviour of the oil are wind speed, temperature, sunlight or cloud conditions and precipitation. These are shown in Tables 4, 5 and 6, respectively. As noted in Table 4, the wind speed is

Table 4. Wind Conditions at the Shirleys Bay Site during the First Spill

Date (1972)	Average wind speed		Direction
	(mph)	( $\text{km h}^{-1}$ )	
November 20	4.5	7.2	NE
November 21	5.9	9.5	E to N to E
November 22	5.7	9.1	NE to N to E
November 23	4.4	7.1	NE to N to W
November 24	4.0	6.4	NW to N
November 25	4.2	6.7	NE to N to E to N
November 26	3.8	6.1	N to W
November 27	10.4	16.7	W to N to NW to N
November 28	7.1	11.4	N to NW
November 29	3.1	5.0	NW to N to NE
November 30	3.6	5.8	NE to N to NW to W
December 1	5.4	8.7	W to NW to N
December 2	5.7	9.1	E to ENE to NE to N to W
December 3	4.9	7.9	W to NE to N to NE
December 4	4.3	6.9	NE to N to SE
December 5	6.9	11.1	SE to W to S to E to N
December 6	5.1	8.2	N to W to NW
December 7	8.1	13.0	E to NE
December 8	4.7	7.1	NE to W

Table 5. Hourly Air Temperatures for Duration of First Spill

Date (1972)	Hourly temperatures (0°C)																							
	00	01	02	03	04	05	06	07	08	09	10	11	12	13	14	15	16	17	18	19	20	21	22	23
November 20	-0.6	-1.1	-1.1	-1.1	-1.1	-0.6	-0.6	-0.6	-0.6	-0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0	-1.7	-1.7	-2.8	-3.3	-4.4	-3.3	-4.4
November 21	-4.4	-3.9	-4.4	-3.3	-3.9	-5.0	-6.1	-6.1	-7.2	-6.7	-6.7	-6.1	-5.6	-5.0	-4.4	-4.4	-5.0	-6.7	-7.2	-7.2	-7.2	-8.3	-7.8	-8.3
November 22	-8.3	-8.9	-11.1	-10.6	-10.0	-11.1	-11.7	-11.7	-11.7	-11.7	-10.6	-9.4	-8.3	-7.2	-6.7	-5.6	-6.1	-7.2	-7.2	-9.4	-9.4	-10.0	-10.6	-10.6
November 23	-12.2	-12.8	-13.3	-13.9	-13.9	-14.4	-14.4	-14.4	-13.9	-10.0	-9.4	-7.2	-5.6	-4.4	-2.2	-1.1	-0.6	0.0	0.0	0.0	0.0	0.0	0.0	0.0
November 24	0.0	0.0	0.6	0.6	0.6	1.1	1.1	1.7	1.7	1.7	2.2	2.2	2.8	2.8	2.2	2.2	2.2	2.2	2.2	2.2	1.7	1.7	1.7	1.7
November 25	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	1.7	2.2	2.2	2.2	2.8	2.8	2.8	2.2	2.2	2.2	1.7	1.7	1.7	1.1	1.1
November 26	1.1	0.6	0.6	0.6	0.6	0.6	0.6	1.1	1.1	2.2	2.2	1.7	1.7	2.2	1.7	2.2	2.8	3.3	3.9	3.9	3.3	3.3	3.3	2.8
November 27	2.8	2.2	2.2	2.2	2.2	1.7	1.7	1.7	1.7	2.8	3.3	3.9	3.3	3.3	3.3	3.3	3.3	2.8	2.8	2.8	2.2	2.2	1.7	1.7
November 28	1.1	1.1	1.1	0.6	0.6	1.1	0.0	0.6	2.2	2.2	2.8	3.3	2.8	2.8	2.2	2.2	1.7	1.7	1.7	1.1	1.1	1.1	0.6	0.6
November 29	1.7	1.1	0.0	-0.6	-1.7	-0.6	-0.6	-1.1	-1.7	-1.7	-1.7	-1.1	-1.1	-0.6	-0.6	-0.6	-0.6	-1.7	-2.8	-2.8	-5.0	-4.4	-3.9	-4.4
November 30	-3.3	-2.8	-2.8	-2.8	-4.4	-3.3	-3.3	-2.8	-2.8	-1.7	-1.1	-0.0	-1.1	2.2	1.7	1.1	1.1	-0.6	-1.1	-1.7	-6.7	-2.2	-1.7	-1.7
December 1	0.0	0.0	-2.2	-2.2	-2.2	-2.8	-2.8	-2.8	-2.8	-2.8	-2.2	-1.7	-1.1	-0.6	0.6	1.1	-1.1	-2.8	-5.6	-7.8	-8.9	-9.4	-11.1	-12.2
December 2	-13.3	-13.9	-14.4	-16.1	-16.1	-17.2	-17.2	-17.8	-17.8	-16.1	-15.6	-14.4	-12.8	-11.7	-10.6	-11.1	-11.7	-11.1	-11.7	-11.7	-11.7	-11.7	-11.1	-10.6
December 3	-10.0	-9.4	-8.9	-8.3	-8.3	-8.3	-8.3	-8.3	-8.3	-8.9	-8.9	-8.9	-8.9	-8.3	-8.3	-7.8	-8.9	-10.0	-10.6	-10.6	-12.2	-12.8	-12.2	-13.9
December 4	-13.9	-14.4	-15.6	-15.6	-16.7	-17.8	-17.8	-17.8	-17.8	-17.8	-16.1	-16.1	-15.6	-15.0	-15.0	-15.0	-15.0	-15.0	-14.4	-14.4	-13.9	-14.4	-14.4	-13.9
December 5	-13.3	-13.3	-13.3	-12.8	-12.2	-11.7	-11.1	-10.6	-10.0	-9.4	-9.4	-8.3	-7.8	-7.8	-7.2	-7.8	-7.8	-7.8	-7.8	-7.2	-7.2	-7.2	-7.2	-7.2

Table 6. Cloud Conditions and Precipitation

Date (1972)	Sunlight	Precipitation
November 20	Sunny during afternoon	Snow in morning
November 21	No cloud cover	
November 22	Intermittent clouds	Trace of snow
November 23	Overcast	Trace of snow
November 24	Overcast	
November 25	Overcast	Wet snow during evening and night
November 26	Overcast	Snow and rain (3 in.)
November 27	Overcast	Freezing rain and snow (trace)
November 28	Overcast	
November 29	Intermittent clouds	
November 30	Overcast	Snow in afternoon (1 in.)
December 1	Overcast	Snow (4 in.)
December 2	Sunny in morning Cloudy in afternoon	Snow in afternoon (4 in.)
December 3	Cloudy in morning Clear during afternoon	Snow in morning (4 in.)
December 4	Sunny	Snow in evening (trace)
December 5	Overcast	Freezing rain and snow (trace)
December 6	Overcast	Freezing rain and snow (trace)
December 7	Clear	
December 8	Overcast	Snow (1 in.)

generally constant at 2.0 m/sec, but the wind direction continually changes. Temperatures generally were about the freezing point of water up to November 28, 1972, when the weather turned colder. The cold weather persisted until December 6, 1972, when the temperature again reached 0°C, but then went back down to seasonable averages. There were approximately 12 hours of sunlight from November 20 to December 2. From December 2 to December 8, there were about 8 hours of sunlight at the field site. A summary of the weather conditions is shown in Figure 7.

Field Observations

To facilitate the presentation of these observations, they are presented in diary form:

- November 20—spill commenced at 1500 hours and ended at 1530 hours
  - 23 gallons of Norman Wells crude oil were poured onto the opening
  - uniform depth of about 5 mm of oil over exposed water (Fig. 8a)
  - clear skies and temperature about freezing
- November 21—sampling times at 1000 hours and 1530 hours

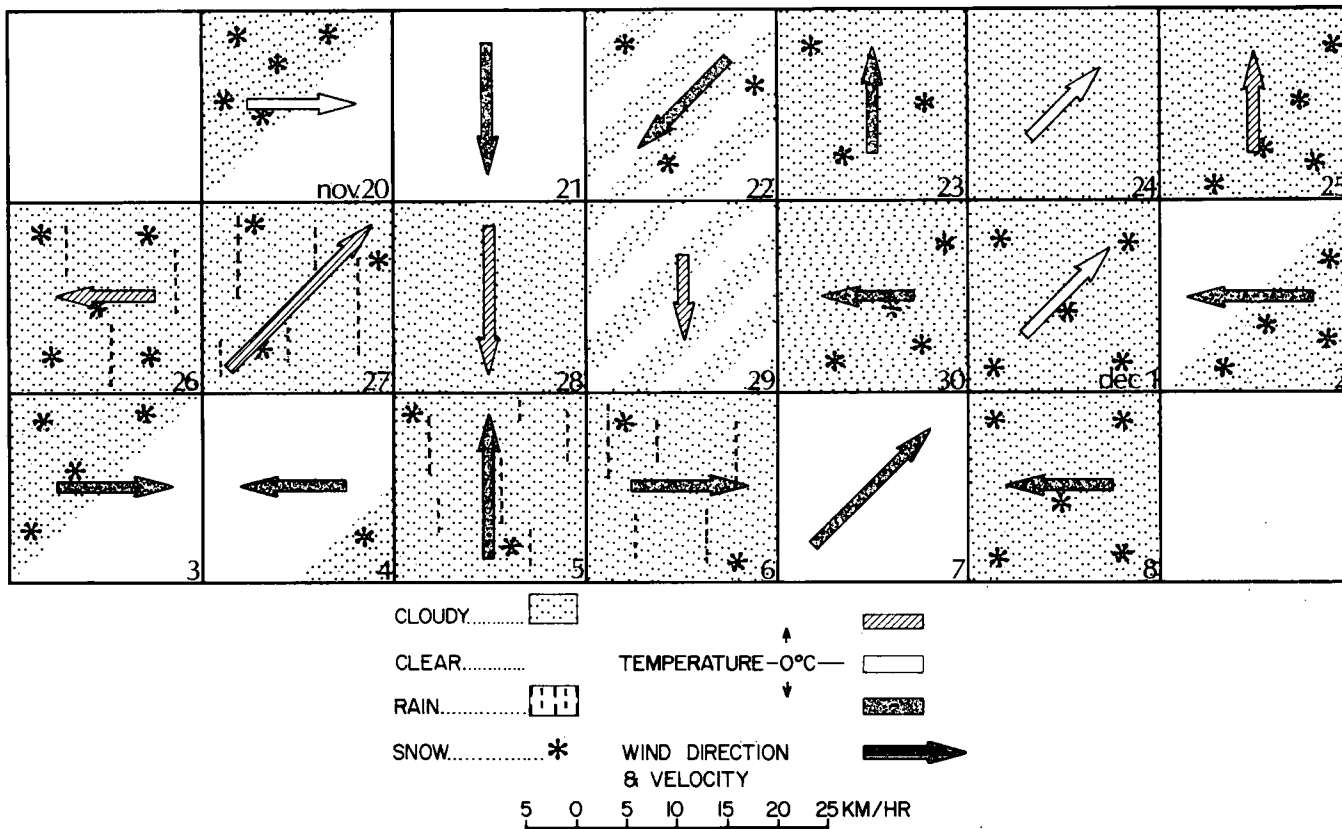
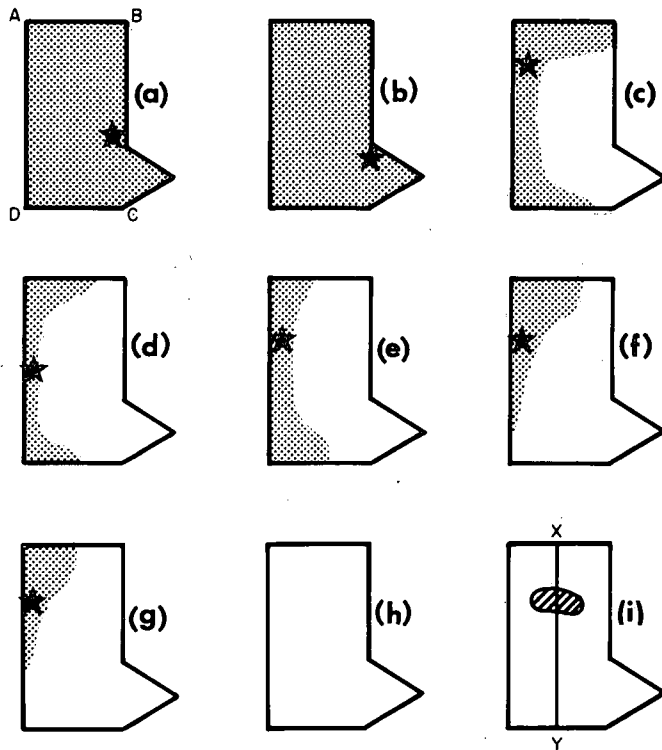


Figure 7. Weather conditions during spill.



- in morning some water under oil layer which became more noticeable during the afternoon
- ice had formed under the oil layer, but oil remained in the original cut, although at a level lower than the original ice surface (Fig. 8b)
- weather was bright and clear with wind velocity at 2.7 m/sec from NE to N



★— INDICATES SAMPLING POSITION

Figure 8. Movement of oil on pond surface.

- November 22—sampling time at 1245 hours
- water under oil layer
  - area C (Fig. 8b) has oil, with small ridges having been formed and oil in furrows
  - sunny in morning and flurries during afternoon
- November 23—sampling time at 1000 hours
- water under oil layer
  - ridges in area C are better defined and begin to lose definition of ice boundary on right-hand side of spill area (Fig. 9)
  - relative position of oil (Fig. 8b)
  - overcast with snow flurries; temperature  $-4^{\circ}\text{C}$
  - wind velocity of 2.0 m/sec from E to N



Figure 9. Small ice trees formed by action of oil.

- November 24—sampling time 1135 hours
- water collected with oil samples
  - overcast; temperature about  $3.5^{\circ}\text{C}$
  - melting conditions on pond surface
  - wind velocity 1.8 m/sec from N
  - more loss of boundary definition on right-hand side of pond (Fig. 8c)
- November 25—sampling time 1500 hours
- water under oil surface
  - level of oil almost at surface of original ice layer
  - oil had moved about the pond (Fig. 8d)
  - overcast, above freezing temperature
  - wind velocity 1.9 m/sec from N
- November 26—sampling time 1230 hours
- wet snow (approx. 50 mm) and rain (approx. 13 mm)
  - overcast; temperature about  $4.2^{\circ}\text{C}$
  - more movement of oil as recorded in Figure 8e
- November 27—sampling time 1200 hours and some water in sample
- overcast; temperature about  $2^{\circ}\text{C}$
  - light rain and strong winds (4.6 m/sec)
  - oil in same position as observed on previous day (Fig. 8e)
- November 28—sampling time 1120 hours
- overcast; temperature  $3.4^{\circ}\text{C}$
  - wind speed 3.2 m/sec
  - oil mainly along left-hand side of pool (Fig. 8f)
- November 29—sampling time 1135 hours
- weather clear, temperature at freezing
  - position of oil shown in Figure 8g
- November 30—sampling time 1120 hours
- weather overcast; temperature above freezing
  - water collected with sample

- snow started at 1635 hours
- December 1—sampling time 1335 hours
  - overcast and snow covering oil
  - oil-water-snow mixture in sample
  - little oil on surface (Fig. 8g)
- December 2—sampling time 1515 hours
  - weather overcast with snow; temperature  $-10^{\circ}\text{C}$
  - position of oil not altered from previous day
  - scarcity of surface oil
- December 3-5—oil covered by snow (25 cm)
- December 6—sampling time 1400 hours
  - overcast with freezing rain; temperature  $8^{\circ}\text{C}$
  - slush layer on ponds (4 cm)
  - very little surface oil, the oil being embedded in the slush (oiled area shown in Figure 8h)
- December 7—sampling time 1335 hours
  - clear, but temperature had turned colder  $-10^{\circ}\text{C}$
  - little surface oil, but oil visible under ice surface
- December 8—sampling time 1100 hours
  - overcast; temperature  $-9^{\circ}\text{C}$
  - very little oil on surface
  - photographs taken along line designated as XY shown in Figure 8i
- December 9 to January 7—new snowfall with new upper ice surfaces being formed
- January 8—all pools inspected carefully in preparation for new spills; no oil visible, but pressure from observers walking on ice surfaces caused fissures to appear in the ice
- January 9—oil appeared on ice surface at fissures in the ice.

**Behaviour of Surface Oil**—For the first few days after the spill, the oil stayed contained within the area cut out of the ice for this spill, as denoted by the illustrations mentioned in the previous section. Small ridges formed on the exposed ice near point C along side BC (Fig. 4) within two days after the spill. At their maximum height these ridges were 20 mm high (Fig. 9). By the fifth day after the spill, these ridges began to lose their structure. On November 27, the ridges were no longer visible, but there were furrows only in the ice as recorded in Figure 10. The disappearance of this structure was aided by the higher air and oil temperatures occurring at that time. No similar structures were noted in the control pond or in other areas of the pond where the spill occurred. This area was originally bounded, in part, by the polyethylene liner.

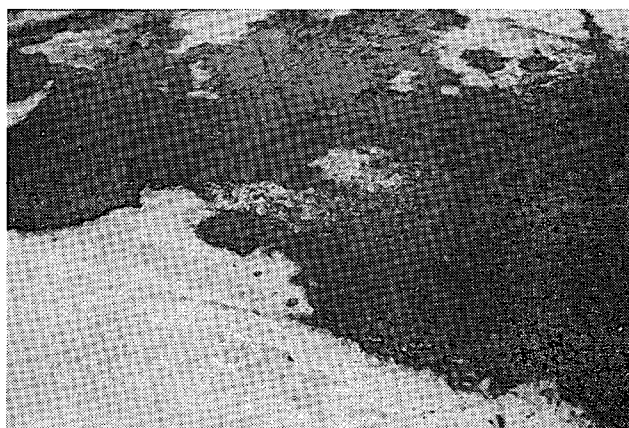


Figure 10. Furrows on ice surface where small ice forms were previously.

By November 24, the ice edge between B and C (Fig. 4) resulting from removing the ice layer for the spill began to lose its sharp definition. It is known that the oil is usually at a higher temperature than its surroundings because of solar radiation (McMinn, 1972; Adams). This is reinforced by the fact that samples collected prior to December 1 contained water that came from a water layer formed between the ice surface and the oil. During this time, no water was visible on the surface of the adjacent control pond. When the oil cooled during the night, the water under the oil layer could solidify if the temperature went below freezing. This effect was the most noticeable between points B and C (Fig. 4). As the new ice layer formed, it appeared preferentially near the sides of the section removed to contain the oil; point C (Fig. 4) was near the edge of the ice surface of the pond. Therefore a thicker ice layer would form causing an uneven surface and the oil flowed to a lower surface. It appeared that the prevailing winds did not affect the position of the oil while it was contained within the original spill area at this time.

On November 25, very little oil was observed on side BD (Fig. 4). The increase in the height of the ice surface at BC and the prevailing winds caused the oil to flow in the direction of AD (Fig. 4). From November 25 to November 29, the oil movement on the pond depended on the wind direction. Prior to the snowfall of December 2, the oil was always exposed to solar radiation and consequently had a temperature higher than that of its surroundings. Before that time, any snow that fell onto the oil was melted by the internal heat of the oil. With the decrease of temperature on December 2, any water under the oil was solidified, and part of the oil became embedded in the ice. A trace of free oil could still be observed on the northeast side of the pond. The snow on December 3 completely covered the oil, and the temperatures on this

day were well below freezing. These conditions prevented further melting of the snow cover by the oil.

On December 6, only a small amount of oil was found on the surface of the slush-like mixture which extended down 50 mm. If the oil was contained only within the snow that covered it, more oil would be expected rather than the small amount that was later found. Therefore the oil must have been embedded in the ice that eventually formed from the melted snow that fell prior to December 3. When the slush layer had frozen the next day (December 7) only a small area near line AB had free oil. On inspection, however, oil was observed beneath the ice surface and was concentrated in the area where oil was observed on December 2. From December 9, 1972 to January 9, 1973, 750 mm of snow fell and the ponds were covered. On January 9, there was an ice cover on the pond as well as the control pond and the ice level had increased by about 200 mm over that observed on December 8. During the visit to the site, the ice surface was inspected. The pressure on the ice caused by walking on it resulted in cracks occurring in the ice. About 2 hours later, a small amount of oil oozed to the top of the ice surface through the cracks as shown in Figure 11. On the following days, very little oil came out of the cracks. The oil was observed in the vicinity of point A.

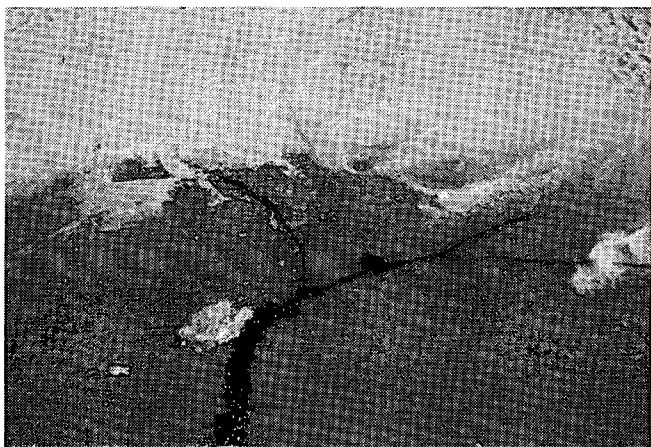


Figure 11. Oil on ice surface after emerging from cracks in the ice.

### Laboratory Studies

By applying the techniques outlined in the experimental section, the composition of the oil remaining from the spill was monitored. Some of the methods employed yield more information than others.

#### Gas Chromatography

This technique involves the separation of the components of a sample by a simulated distillation. This

distillation occurs in columns contained in a programmable heating chamber. The length and internal coating of the column determine the degree of separation of the components in the sample of interest. For the present investigations, SCOT columns, 50 ft x 0.02 in. (15 m x 0.5 mm) i.d., were used, as they give a better separation of components relative to shorter and thicker columns. Since the technique is essentially a distillation, only those components that are in their vapour state in the column can be detected. In addition the type of material used as the liquid phase in the columns defines the upper temperatures that may be used. For this investigation, two types of SCOT columns were used. One contained Dexsil 300, a material that allows high temperatures to be used (+400°C), but at temperatures below 125°C it is a solid. Accordingly below this temperature solid vapour chromatography was being performed and the peaks under these conditions were not too well resolved (typical of this type of chromatography). These columns were used to monitor the higher boiling fractions of the weathered oils. A second type of SCOT column with OV-1 liquid phase was used to investigate the lighter ends.

Chromatograms of the original crude oil, run on the two types of columns, are shown in Figure 12. As can be seen from these two chromatograms, there is a distinct difference in the resolving power of the two columns, but both columns indicate there is an abundance of high vapour-pressure components. A sample, taken from the aqueous surface just after the spill, had a slightly different pattern of peaks at the beginning of the chromatogram relative to the original oil. This resulted from the evaporation of the extremely volatile fraction.

The sample taken on the morning of November 21 did not contain those components with vapour pressures greater than that of n-heptane. Significant changes were noted in the chromatogram of the afternoon sample of the same day, but some octane was still present. The sample collected on November 24 showed that all of the octane had disappeared and the amount of nonane was low. The sample removed on November 28 contained no nonane; decane was greatly depleted in the sample of November 30 (Fig. 13). The amount of decane in the sample taken on December 1 was about the same as that in the sample of November 30, and the concentration of undecane was also low. Analysis of the sample collected on December 8 did not differ greatly from that taken on December 1 nor did the chromatogram of the sample taken on January 9, 1973. All of the samples had similar chromatographic traces between tetradecane and hentricosane. This indicates that very little alteration of this fraction of the oil occurred.

In Table 7, the boiling points of the n-alkanes between C<sub>6</sub> and C<sub>20</sub> are listed. As can be seen, the boiling points

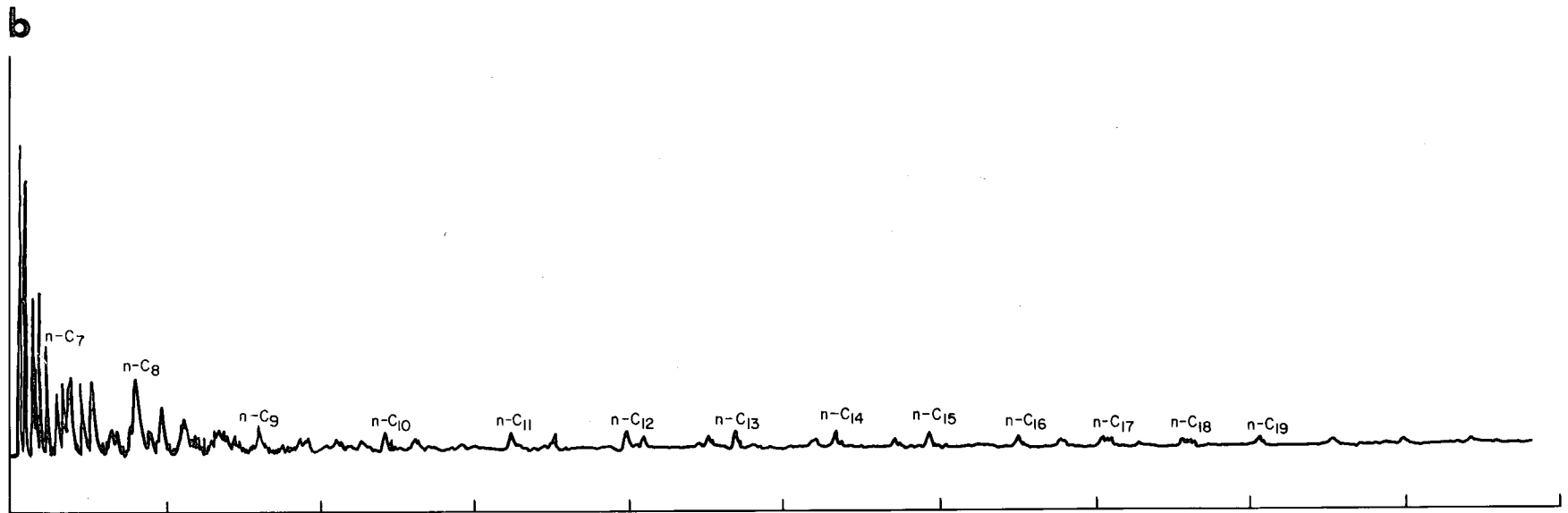
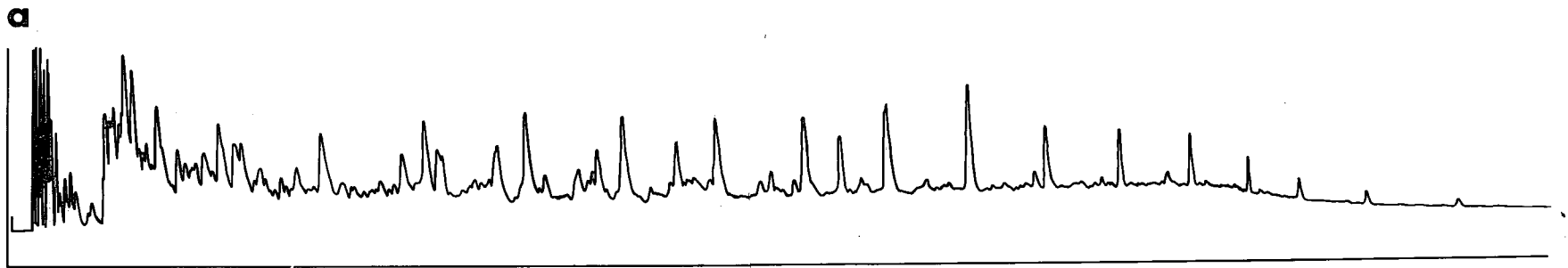


Figure 12. Chromatogram of Norman Wells crude oil using (a) Dexsil-300 SCOT column and (b) OV-1 SCOT column.

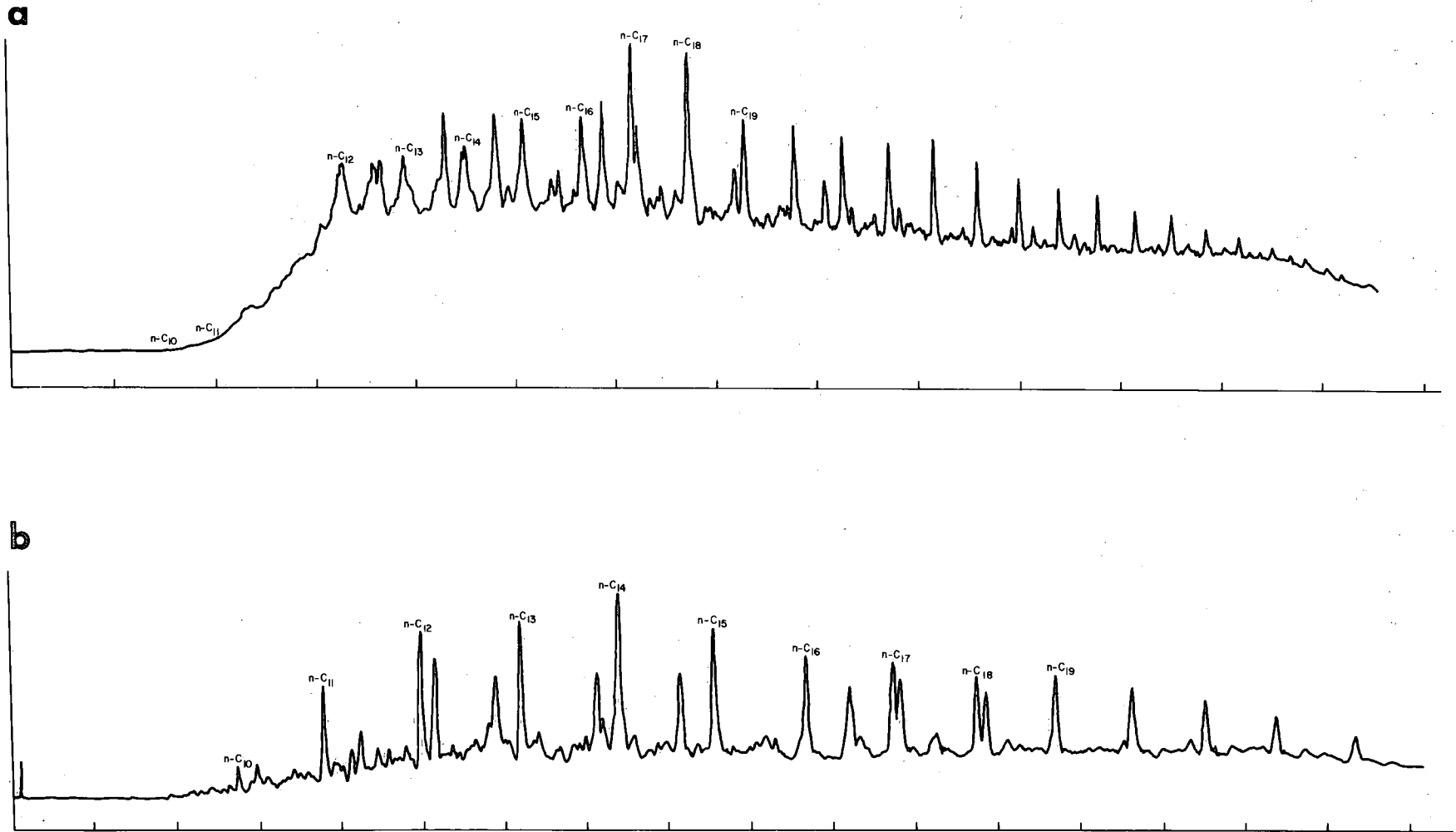


Figure 13. Chromatogram of weathered oil sample taken November 30 by (a) Dexsil-300 SCOT column and (b) OV-1 SCOT column.

have a range of 350°C. Table 1 records an abbreviated Hempel distillation report of the crude oil used in the spills (United States Bureau of Mines, 1951). The information obtained from this and similar distillations is helpful in refinery operations. Each fraction of this distillation was chromatographed on both types of SCOT columns. These chromatograms showed that many constituents were present in consecutive fractional cuts; for example, heptane was found in the first four cuts.

Table 7. Boiling Points of N-Alkanes

Compound	Boiling point (°C)
n-hexane	67.0
n-heptane	98.4
n-octane	125.7
n-nonane	150.8
n-decane	174.1
n-undecane	195.9
n-dodecane	216.3
n-tridecane	235.4
n-tetradecane	253.7
n-pentadecane	270.6
n-hexadecane	287.0
n-heptadecane	301.8
n-octadecane	316.1
n-nonadecane	329.7
n-eicosane	343.0

Some caution must be exercised in correlating the results of chromatograms of the aged oil with the data of the Hempel distillation. Generally there is a loss recorded in the Hempel distillation, in this instance, 3.1%, and this is usually explained as very light ends that did not condense. Accordingly values may be 3.1% higher by volume. Also the Hempel distillation conditions may not replicate the manner in which components evaporated from the crude oil used in this spill. The two modes of "distillation," however, are correlated, since it is realized that it is best to obtain a reasonable estimate of the residual oil. Chromatograms of several distillation cuts are shown in Figure 14.

As apparent from the chromatograms, approximately 30% by volume or 27% by weight of the crude oil had evaporated within the first 24 hours because of the loss of the very volatile fractions, and by November 24 (93 hours), 41% by volume or 37% by weight of the oil had disappeared. On November 26, it was estimated that 46% by volume or 42% by weight had volatilized. By November 28, 48% by weight of the oil had gone. With only nominal differences of November 28, 29, and 30, it can be assumed that approximately 50% by weight of the oil had evaporated as determined by gas chromatography. The residue of the abbreviated Hempel distillation could still be poured at -5°C (United States Bureau of Mines, 1951).

### Neutron Activation Analysis

Neutron activation analysis is a technique that can be used to determine the concentration of heavy metals in an oil matrix. These metals are usually associated with components comprising the heavier ends of the oil, for example, the metal porphyrin complexes. In most systems, the metals in the complexes may exchange with other metals present in the vicinity. In the present experimental conditions such an exchange was not observed. This is not unexpected, since the water in the pond had low concentrations of other metals. Therefore any increase in the metal concentration of the oil primarily results from the evaporation losses of the lighter components.

Table 8 lists the concentration of four metals initially present in the oil and their concentrations after definite periods of aging. Generally there is a concentrating effect. Three of the elements, Mn, Cu, and Al, however, do not exhibit definite trends on aging. The variations in the values of these elements, given in Table 8, are considered to reflect the experimental difficulties because of the interferences of other trace metals present in small quantities. The spurious reactions of neutrons affecting Fe and Co nuclei give a higher reading for Mn. Similarly Zn interferes with Cu determination by undergoing the  $(^{64}\text{Zn} + ^1_0\text{n} \rightarrow ^{64}\text{Cu} + ^1_0\text{p})$  reaction. In light of the possible interferences and also because of the large statistical error during counting of the low activities, the values for Al, Cu, and Mn were not found to give any definite trends on weathering. The fourth element, vanadium, exhibits a well-defined behaviour. Indeed, in characterizing oils, vanadium and nickel are used extensively. From the vanadium values in Table 8, it is calculated that after 24 hours approximately 30% by weight of the oil had evaporated. After 11 days of exposure to the weather, the vanadium concentration indicates that 35% of the oil had disappeared. These neutron activation analyses confirm the estimate of the evaporative loss of the aged oil obtained from gas chromatographic techniques.

Table 8. Neutron Activation Analysis of Weathered Oil on Water under Ice-Forming Conditions

Sample	V (ppm)	Mn (ppb)	Cu (ppb)	Al (ppb)
Original	6.5	19	570	90
Aged 1 hour	7.6	30	260	90
Aged 19 hours	10.2	42	320	300
Aged 24 hours	8.4	14	370	200
Aged 45 hours	8.4	12	180	80
Aged 71 hours	8.5	56	460	100
Aged 5 days	7.8	23	1,900	400
Aged 6 days	7.3	55	560	4,900
Aged 7 days	8.6	31	300	100
Aged 8 days	8.0	260	630	400
Aged 9 days	8.6	50	530	900
Aged 10 days	8.7	150	1,020	6,000

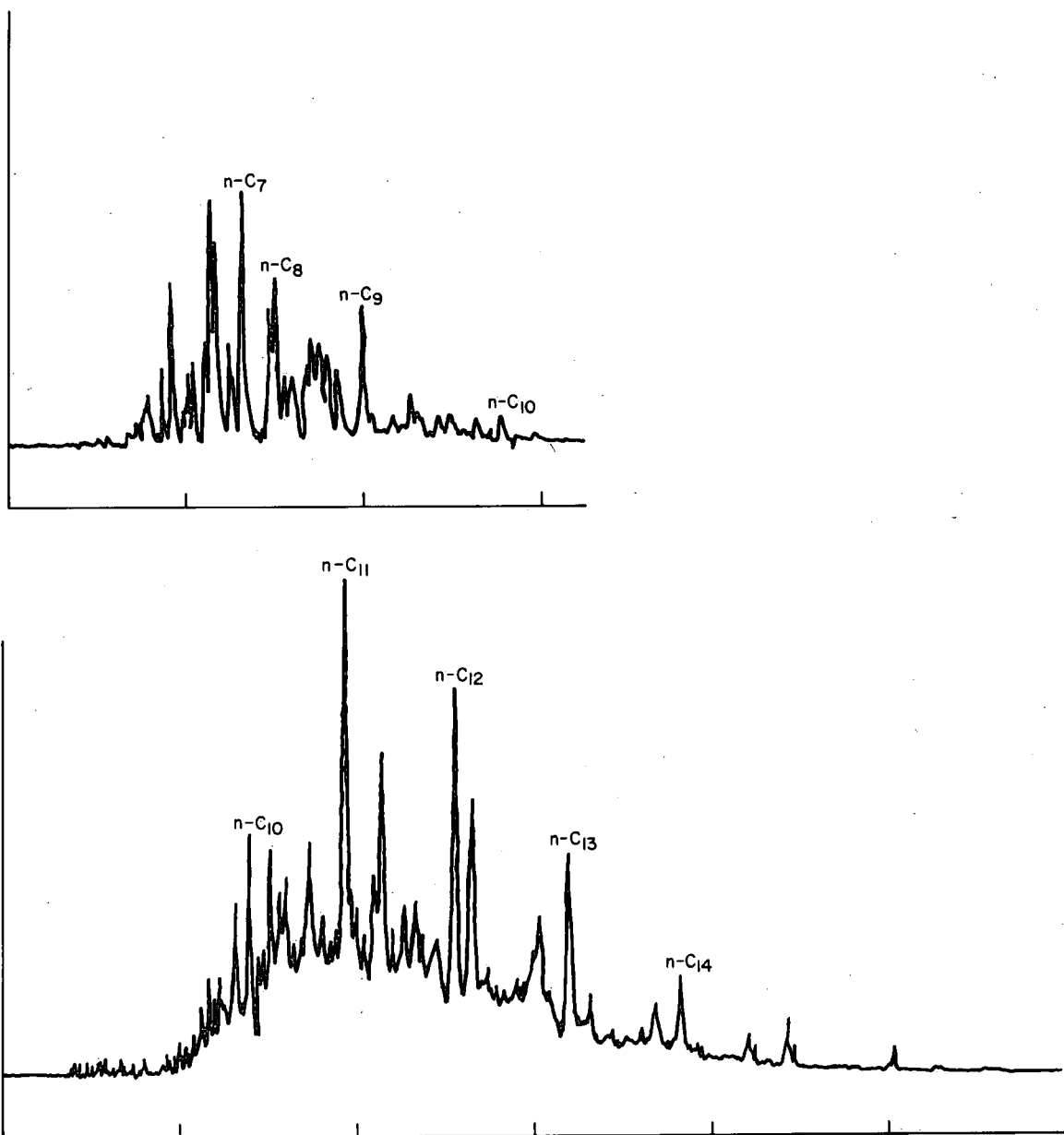


Figure 14. Chromatograms of fractions (a) no. 5 and (b) no. 8 of a Hempel distillation of Norman Wells crude oil.

#### *Ultraviolet Spectroscopy*

It was not possible to obtain any specific information from the UV/VIS spectra. It helped, however, in selecting the excitation wavelengths for the fluorescence measurements.

#### *Infrared Spectroscopy*

The samples were dissolved in chloroform, although this solvent has many interfering bands. It proved difficult to extract any valuable information, since very little difference could be seen in the spectra of samples of successive days.

#### *Fluorescence Spectroscopy*

Considerable effort was put into this method, as it is often used as an ancillary technique for determining the source of oil spills. The sensitivity of the technique, however, resulted in difficulties in comparing spectra. Samples were obtained below quenching concentrations (Parker, 1968), and Beer-Lambert plots were obtained using the unaged oil. Since this plot changed on successive days, calibration curves were determined daily and samples were run on the same day. No concentrating effect was found for this oil despite the loss of lighter components as indicated by other techniques. A typical fluorescence spectrum is shown in Figure 15.

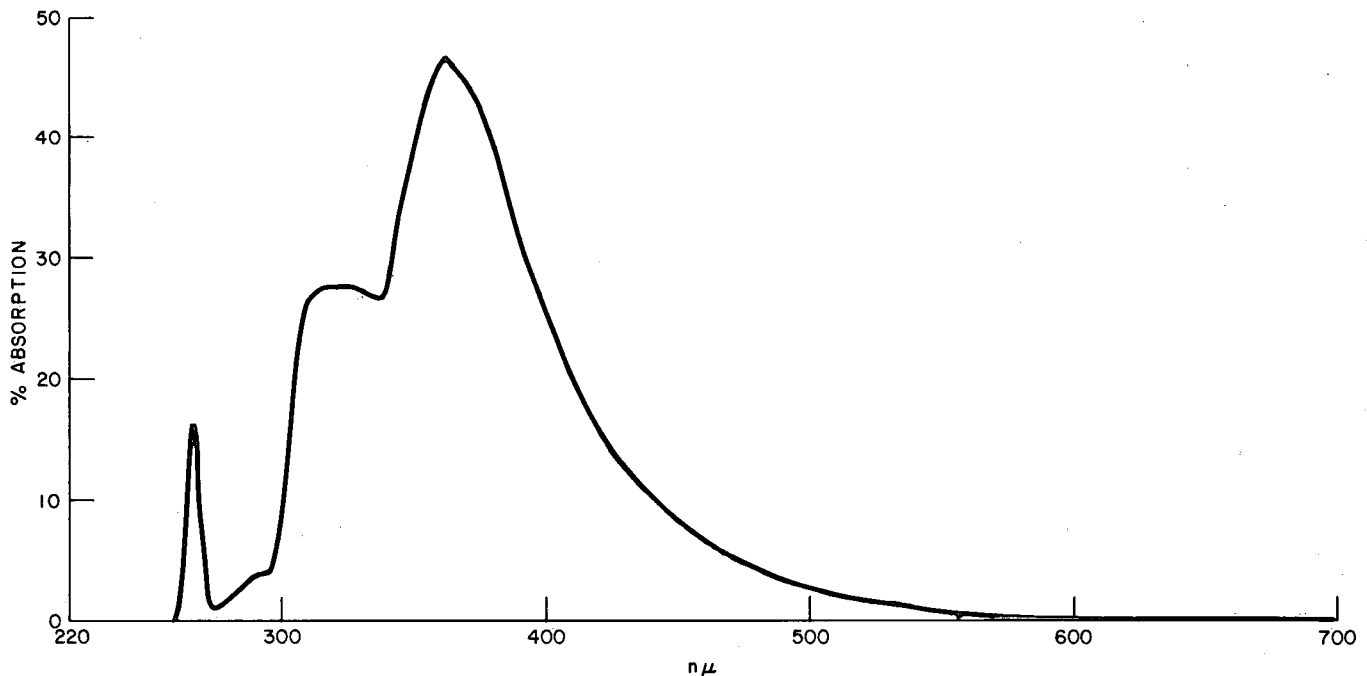


Figure 15. Fluorescence spectrum of Normal Wells crude oil.

#### Effect of Climatic Conditions on the Aging of Oil

A general description of the field observations, the weather, and the analysis of the oil have been documented. A correlation between these parameters is now presented.

The spill was made on water under freezing conditions, and during the period that it was possible to take samples, the oil remained on the water-ice surface. The weather conditions for the first 24 hours after the spill were low temperature, low wind speed and generally clear skies, as can be seen in Tables 4, 5 and 6. Under these conditions the spilled oil lost approximately 29% by weight of its components during the first day. This value includes the very volatile fractions of the oil, some of which had evaporated within an hour after the spill occurred. As can be seen from the chromatogram of the original oil (Figs. 11 & 12), the light ends represent a substantial portion of the total oil. The evaporation of this fraction under cold and clear conditions is reasonable. Once this fraction is removed, however, loss of other components takes longer and depends on the climatic conditions. The following day was colder with intermittent sunshine and constant wind speed. Slight evaporative losses altered the chromatogram of the sample, but not appreciably. The temperature increased to above freezing on November 23 (three days after the spill) and the sample taken on the next day contained no octane. At this point, it is estimated that 40% by volume of the oil had evaporated—a loss of another 10% of the oil. Warm weather (4°C) and cloudy skies persisted

until November 29. On November 26, 46% by volume of the oil had evaporated, characterized by the loss of nonane. Decane was present in the samples until the sampling on November 28 (eight days after the spill). At this time, an estimated 50% of the oil remained. Little change was noticed in the chromatograms of subsequent samples. On November 27, the wind speed averaged 10 m/sec. The wind and moderate air temperatures augmented the evaporation of the oil. Low temperatures that persisted after November 29 retarded the rate of evaporation.

#### Aftermath of This Spill

Little attention was paid to the spill after the snow had completely covered the oil. In April, when the spring break-up occurred, it was observed that all of the ice in the pond melted two weeks before the ice melted in the adjacent control pond. In July, before the clean-up of the ponds, the marked difference of aquatic life existing in the control and oiled ponds prompted a biological examination. This work was contracted primarily to biologists at the University of Ottawa, whose results are shown in the Appendix.

During the clean-up operations, the cleanish water was pumped from the ponds into the Ottawa River, and the contaminated water was pumped into empty oil drums as was the surface oil. The top liner was then removed and the oily residue and small growths were taken out with the liners and discarded. Very little surface oil was observed in



the pond, and an oily slime was in evidence on the bottom of the pond.

The presence of oil inhibited some forms of life in the oiled pond, but increased the abundance of others; larger life forms were not present in the oiled pond.

### ACKNOWLEDGEMENTS

Many agencies and individuals contributed to the success of this undertaking. Imperial Oil of Canada graciously supplied the crude oil for this test. Drs. H. Sawatsky and D.S. Montgomery of the Fuels Research Division of the Department of Energy, Mines and Resources, contributed many helpful suggestions and discussions. Mr. R. Draper of the same Division performed the Hempel distillation and provided many helpful insights into the problem. The help of Dr. W.A. Adams of the Water Science Subdivision and Mr. B. Cartwright of the R.C.M.P. in clearing the ice area just prior to the spill is appreciated, and the aid of the Canadian Oceanographic Identification Centre of the National Museum of Canada in identifying the zooplankton is gratefully acknowledged.

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## APPENDIX

### BIOLOGICAL EXAMINATION OF OILED POND AND ADJACENT CONTROL POND

The principal investigators were Dr. D.B. Carlisle of the Water Science Subdivision, Water Quality Research Division (WQRD), Dr. M. Dickman and Mr. D. Schindler of the Department of Biology at the University of Ottawa and Dr. E. Krelina (consultant). Other investigators were Dr. J.E. Bishop and Dr. B.F. Scott of the Water Science Subdivision, WQRD.

On July 25, 1973, a team of scientists arrived at the pool site. Work commenced at 1030 hours. Physical data relating to the two ponds are listed in Table A. \*

A brief inventory of the attached algae and phytoplankton in the two ponds is compiled in Table B. Table C contains the microbial colony counts in each pond, whereas Table D lists the zooplankton and Table E concerns the diatoms.

From the data listed in these Tables, the following observations were made:

- (1) large amounts of phycomyces were present in the oiled ponds,

- (2) filamentous bacteria were largely confined to the oiled pond,
- (3) diatoms were not observed in the control pond, but occurred in the oiled pond, and
- (4) algal diversity was lower in the oiled pond.

Table D lists the zooplankton found in the two ponds. The control pond had a greater population of zooplankton. Most prevalent in the control pond were oligochaeta (worms), water boatmen, coleoptera (beetles) and midges. Midge larvae were also found in the oiled pond, but at a lower concentration. Two types of frogs, leopard and bull, were observed in the control pond and to a lesser extent in the oiled ponds.

This study is only concerned with the effects of the oil during the first year after the spill and does not attempt to forecast future consequences of the oil on the ecosystems dwelling in these ponds. Also it must be noted that the samplings taken might not truly reflect a statistical average for the ponds, since they represent the findings taken on a single day in summer.

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\*Tables A to E are on pages 20 and 21.

**Table A. Physical Characteristics of Ponds  
Taken on July 25, 1973**

Pond temperatures (°C)	Pond No. 4 (control)	Pond No. 3	Pond No. 2	Pond No. 1
Surface	26.5	27.3		
1 in. under surface	26.0	27.00	31	32
Near bottom	25.75	26.75		
pH	6.28	5.85		
O <sub>2</sub> (ppm)	7.8	8.4		

**Table C. Colony Counts (no. of bacteria per mm<sup>3</sup>)**

Location	Oiled pond		Control pond	
	T medium <sup>1</sup>	KB medium <sup>2</sup>	T medium <sup>1</sup>	KB medium <sup>2</sup>
Surface water	5,300 <sup>3</sup>	11,600	800	4,000
100 mm deep	1,900	2,150	790	850
300 mm deep	1,500	1,600	500	500
Sediment (bacteria/g sediment)	18x10 <sup>6</sup>		19x10 <sup>6</sup>	

Legend: 1—contains (g/l): tryptone, 5; yeast extract, 2.5; glucose, 1; K<sub>2</sub>HPO<sub>4</sub>, 0.5; pH, 7  
2—contains (g/l): peptone, 20; glycerol, 10; K<sub>2</sub>HPO<sub>4</sub>, 1.5; MgSO<sub>4</sub>·7H<sub>2</sub>O, 1.5; pH, 7.2  
3—minimum estimate

**Table D. Zooplankton of Oiled and Control Ponds**

Zooplankton	Number in standard sample	
	Control pond	Oiled pond
Nemata (thread worms)	—	rare
Oligochaeta (worms)		
<i>Vejevskyella comata</i>	1,250	—
<i>Nais variabilis</i>	13	—
Insecta		
Hemiptera (water boatmen)		
<i>Corixidae</i>	9	1
<i>Notonectidae</i>	2	—
Others	6	—
Coleoptera (beetles)		
<i>Dytiscidae</i>	4	—
<i>Helodidae</i>	1	—
<i>Curculionidae</i>	2	—
<i>Hydrophilidae</i>	4	—
Trichoptera (caddis)	1	—
Diptera (midges)		
<i>Chironomidae</i>	2	—
<i>Cricotopus</i>	—	2
Others	5	—
Odonata (dragonflies)	—	1
Collembola (springtails)		
<i>Isotoma</i>	12	—

**Table B. Abundance of Phytoplankton and Periphyton  
in Oiled and Control Ponds at Shirleys Bay**

Type	Abundance	
	Control pond	Oiled pond
Phytoplankton		
<i>Scenedesmus incrassatulus</i>	C	—
<i>Dispora crucigenoides</i>	C	C
<i>Cosmarium depressum</i>	C	—
<i>Cosmarium minutissimum</i>	C	—
<i>Ankistrodesmus falcatus</i>	C	—
<i>Geminella interrupta</i>	C	—
Filamentous bacteria ( <i>Beggiatoa</i> -like)	—	C
Solitary bacteria	—	C
<i>Oedogonium</i> sp.	M	—
<i>Staurastrum alterans</i>	M	—
<i>Coelastrum micropora</i>	M	—
<i>Mougeotia</i> sp.	M	—
<i>Dictyosphaerium pulchellum</i>	M	—
<i>Vorticella</i> sp.	—	M
Solitary <i>Phycomycete</i> sporangia	—	M
<i>Anabaena</i> sp.	R	—
<i>Hapalosiphon hibernicus</i>	R	—
<i>Microcystis limneticum</i>	R	—
<i>Peridinium</i> sp.	R	—
<i>Bodo</i> sp.	R	—
<i>Euglena</i> sp.	FM	—
<i>Pseudoanabaena</i>	—	R
<i>Gonatozygon</i>	—	R
<i>Oscillatoria</i>	—	R
Diatom sp.	—	R
Periphyton		
<i>Dictyosphaerium pulchellum</i>	C	C
<i>Mougeotia</i>	M	C
<i>Scenedesmus incrassatulus</i>	C	P
<i>Cosmarium</i> (depressum)	C	—
<i>Ankistrodesmus falcatus</i>	C	—
<i>Oscillatoria</i> sp.	—	C
<i>Phycomycetes</i>	—	C
Filamentous bacteria ( <i>Beggiatoa</i> -like)	—	C
<i>Staurastrum alterans</i>	M	—
<i>Diffugia</i> ( <i>Urceolata</i> )	M	—
<i>Ulothrix</i> sp.	R	R
<i>Pediastrum boryanum</i>	R	—
<i>Spondylosium planum</i>	R	R
<i>Coelastrum micropora</i>	R	—
<i>Cosmarium</i> —3 spp.	R	—
<i>Anabaena</i>	—	R
<i>Valesneriana</i>	C	R
<i>Gonatozygon</i> sp.	—	R
<i>Trachelomonas</i> sp.	—	R
<i>Oedogonium</i>	P	P
Diatoms (pinnate and centric types)	—	P

Legend: C—common  
M—moderate  
R—rare  
FM—abundant on floating matter only  
P—present but abundance not determined

Table E. Diatoms in Oiled and Control Ponds

Diatom	Pond			
	Control	No. 3	No. 2	No. 1
<i>Achnanthes linearis</i>	1			
<i>A. microcephala</i>	3	1		1
<i>Asterionella formosa</i>			1	
<i>Cocconeis placentula</i>		2		
<i>Cymbella turgida</i>	3		1	
<i>Fragilaria construens</i>	1			
<i>F. virescens</i>	1			
<i>Gomphonema acuminatum</i>	1			
<i>G. angustatum</i>	1			1
<i>G. lanceolatum</i>	1			
<i>G. olivaceum</i>	2			
<i>Navicula cuspidata v. heribaudi</i>	1			
<i>N. gottlandica</i>	1			
<i>N. halophila v. tenuirostris</i>	1			
<i>N. radiosa</i>	1	1		
<i>Nitzschia sp.</i>	1			
<i>N. amphibia</i>	3	1		
<i>N. gracilis</i>	1			
<i>N. recta</i>	3	1		
<i>N. sublinearis</i>	1			
<i>N. thermalis</i>	1			
<i>Pinularia borealis</i>	1	2	1	2
<i>Surirella linearis v. helvetica</i>		1	1	
<i>Synedra ulna</i>	1		1	1
<i>S. rumpens</i>	2			
<i>S. vaucheriae</i>	1			
<i>Tabellaria fenestrata</i>	4		1	1

Legend: 1—indicates presence  
 2—indicates 6 to 10 cells on slide  
 3—indicates 11 to 15 cells on slide  
 4—indicates 16 or more cells on slide

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