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062 Field Research Spills to Investigate the Physical and Chemical Fate of Oil in Pack Ice

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FIELD RESEARCH SPILLS TO INVESTIGATE THE PHYSICAL AND CHEMICAL FATE OF OIL IN PACK ICE

S.L. Ross Environmental Research Limited

and

D.F. Dickins Associates Limited

Scientific Advisers: E. Gauthier and M. Fingas

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SUMMARY

Three experimental crude oil spills, of 1 m^3 each were carried out in pack ice offshore of Cape Breton Island, Canada. Ice conditions for the spills ranged from 6/10 dynamic open pack ice to 9+/10 pack ice in a state of moderate compression. Oil spreading was dramatically reduced compared with that on open water; simple ice concentration and oil viscosity correction factors to Fay's (1969) spreading equations adequately model the results. Evaporation of the oil and subsequent property changes were well predicted using the evaporative exposure technique of Stiver and Mackay (1983). No water-in-oil emulsification was observed, even in extremely dynamic conditions. The rocking action of ice floes in a swell did result in temporary natural dispersion of oil near floe edges. Only minor oiling of floes was observed; the significant oil/ice interaction was with brash and slush ice between floes. No pumping of oil between converging ice floes occurred. In situ burning of oil contained by brash in high pack ice concentrations proved to be an effective countermeasure; nothing seemed feasible for the oil in lower concentration, dynamic pack ice conditions.

RESUME

Trois volumes de pétrole brut d'un m^3 chacun ont été déversés à titre expérimental dans la banquise au large de l'Ile du Cap-Breton, Canada. L'englacement variait entre une banquise mouvante de 6/10 et une couverture de 9+/10 modérément comprimée. L'étalement des nappes fut grandement réduit comparé à ce qui se passe en eaux libres; les équations d'étalement de Fay (1969) décrivent assez bien le processus pourvu que l'on introduise des facteurs de correction simples pour la concentration des glaces et la viscosité du pétrole. La technique de Stiver et Mackay (1983) prédit bien l'évaporation du pétrole et les changements de propriétés qui en résultent. Nous n'avons observé aucune émulsion d'eau dans l'huile même sous des conditions très dynamiques. Le balancement des floes par la houle a temporairement dispersé le pétrole près de leurs bords. Nous n'avons observé qu'un recouvrement mineur de pétrole sur les floes; les contacts importants entre le pétrole et la glace avaient lieu parmi les sarrasins et la gadoue entre les floes. Il n'y a pas eu d'épuisement de pétrole entre floes convergents. Le pétrole contenu dans les sarrasins situés dans une banquise dense pouvait être efficacement brûlé in situ; aucune contremesure ne semble efficace dans une banquise plus clairsemée et mouvante.

INTRODUCTION

To make reasonable evaluations of the effects of oil spills and to make decisions on their control, an understanding of their short-term and long-term physical and chemical behaviour and fate is necessary. For oil spilled on water and on or under ice, such an understanding exists because of a decade of study of these situations. However, little is known about the behaviour and fate of oil spilled in pack ice conditions. This was the subject of the study.

BACKGROUND

Previous Spills

Early observations of oil spilled in pack ice include those of the Othello spill (Metge and Telford 1979), a spill of 100 t of No. 2 fuel oil at Deception Bay, N.W.T. (Ramseier et al. 1973), and a spill of 600 t of No. 2 fuel oil in an ice infested river in Sweden in 1972 (Jerbo 1973). More recently, two spills in pack ice conditions have been more thoroughly reported: the Bouchard #65 spill in Buzzards Bay (Deslaurier et al. 1977) and the Ethel H. spill in the Hudson River (Deslaurier 1979). Observations from these spills are generally sparse and, even for the last two incidents, largely qualitative or anecdotal in nature. The Kurdistan spill in Cabot Strait in March 1979 (C-CORE 1980; Vandermeulen and Buckley 1985) was the most significant event leading to field observations of oiled pack ice offshore of eastern Canada. Unfortunately, most of the direct observations of ice oiled from the Kurdistan were made weeks after the spill occurred. Without details of the oil/ice interaction immediately post-spill, quantitative conclusions of oil fate cannot be made.

A recent incident involving oil in pack ice under freezing conditions occurred at Matane, Quebec, in December 1986 (Wilson and Mackay 1986). As was observed after the Kurdistan disaster, the Bunker C oil was often found as particles incorporated into the slush/brash ice. Following the

Matane spill, the main effort was directed at mechanical recovery, and few quantitative observations were made concerning the interaction of oil with the ice immediately post-spill (Rivet 1986).

Tank Studies

A number of tank studies of oil behaviour in pack ice have been undertaken, the first of which involved the determination of the equilibrium thickness of No. 2 fuel oil and Prudhoe Bay crude oil in a static broken ice field (Getman and Schultz 1976). At the same time, tests of the behaviour of Prudhoe Bay crude oil spilled under simulated sea ice in a wave field were undertaken (Martin 1976).

The next series of tests involved three largely qualitative laboratory tests in an agitated tank to investigate oil/pack ice interactions under dynamic conditions (Metge and Telford 1979). This was followed by an intensive flume testing and modelling effort to characterize the spreading of oil amongst ice pieces (Free et al. 1982). More recently, larger tank trials have been conducted to investigate oil spreading and thickness in both static and dynamic pack ice conditions (S.L. Ross 1983), and to research the phenomenon of lead pumping (MacNeill and Goodman 1985). Studies of oil burning in leads have also been conducted (Brown and Goodman 1986). Finally, a recent study (Tebeau et al. 1984) was undertaken of the spreading rate of oil amongst pack ice, something still not well understood.

Ice Information

One of the major drawbacks of all of these tests has been the dearth of information on actual pack ice conditions in northern regions. Ice charts provide a general picture of concentrations in broad categories of floe size, but the resolution at a scale of 1:4,000,000 is clearly inadequate for predicting oil behaviour. Synthetic aperture radar (SAR) imagery and aerial photographs do exist in certain areas, but have not been analysed to describe quantitatively the broken ice environment in terms of individual floe geometry and floe motions needed as input to the oil spill problem. A study of lead and pack ice dynamics in Canadian Arctic waters has just been completed which provides many data on these processes (Dickins et al. 1986).

STUDY RATIONALE

Because tank tests cannot simulate pack ice conditions and because observations of spill incidents tend to be sparse, qualitative, and countermeasures-oriented, there is a need to quantify basic spill processes (oil spreading and weathering) in natural pack ice so that practical countermeasures techniques can be developed for these conditions. This has been concluded by both Environment Canada (AMOP 1979) and the U.S. Coast Guard (Tebeau et al. 1984). In addition, when one considers the logical progression of oil spill behaviour testing for open water and complete ice cover conditions from tank testing to large scale field experiments, it is obvious that field tests in pack ice conditions were long overdue. Though excellent test tank work has been and is being done in this area, it was time for a modest field program to be carried out to validate the results of the laboratory-scale testing. Specifically, a field program was needed to put into perspective past test tank work, to provide realistic spill behaviour data, and to provide a basis for the planning of future tests, both in the laboratory and in the field.

STUDY OBJECTIVE

The objective of the study was to conduct a series of small spills of crude oil in pack ice conditions to observe and document the oil's physical and chemical fate.

More specifically, the spills were designed to:

1. relate oil spreading behaviour to ice conditions in concentrations from 5 to 9/10;
2. evaluate the fate of oil spilled in leads and brash ice according to

processes of evaporation, emulsification, dispersion, and incorporation into or on top of the ice; and

3. identify possible countermeasures strategies for crude oil spills in ice (through observation of the oil behaviour).

REPORT CONTENTS

The next two sections of the report present the location and timing of the research spills and the methods used to carry out the study program. The results and a discussion of the findings are in the subsequent section. The report ends with the conclusions and recommendations arising from the study.

SPILL SETTING

On March 9 and 10, 1986 three spills of 1 m^3 each of Alberta Sweet Mixed Blend crude oil were released in pack ice approximately 140 km east of Chedabucto Bay, Nova Scotia.

SITE SELECTION

The general location for the study was chosen in consultation with the Regional Ocean Dumping Advisory Committee for the Atlantic Region of Environment Canada (see Appendix 1). The Cabot Strait area was eventually chosen because:

- it encompasses a wide range of pack ice conditions over a long time period in spring;
- it is accessible from the open-water port of Mulgrave, N.S., the location of the CCG Emergency Services Centre which could be used as an operations base; and
- it is an environmentally acceptable area: the water is deep, no fishing takes place in the pack ice, and any oil remaining after the spills would drift out to sea rather than ashore.

Figure 1 shows the locations of the three spill sites selected. The first site was chosen to represent loose, dynamic pack ice conditions. The second site was chosen because it contained larger, tightly packed floes in static conditions. The third site was selected originally as an area with an ice concentration between those found in the first and second sites, with minimal brash ice between floes and fairly static conditions.

GENERAL DESCRIPTION OF REGIONAL ICE CLIMATE

Ice Forecasting Central of the Atmospheric Environment Service (AES) provides a sea ice reconnaissance and forecasting service for the Gulf of

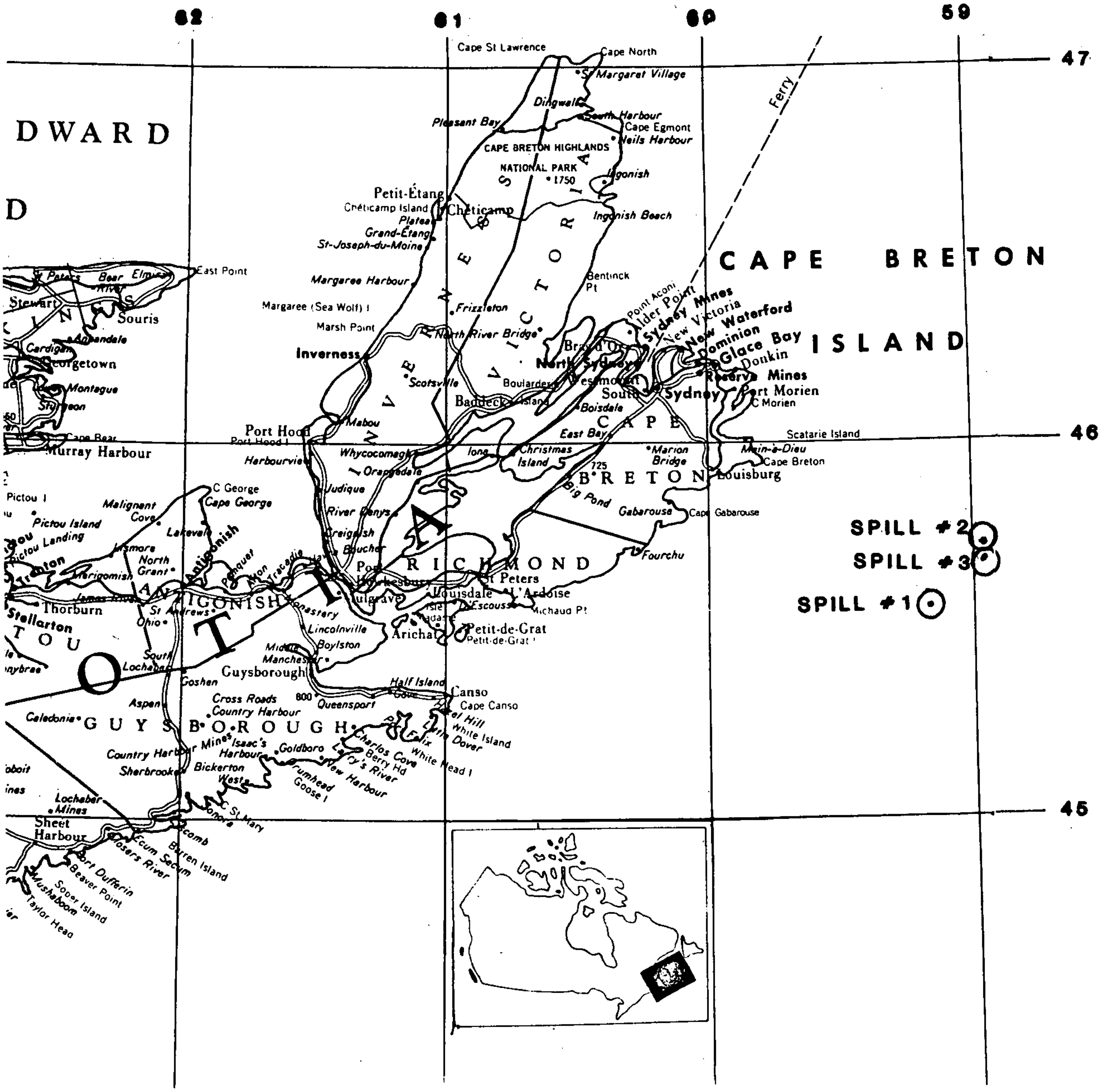


FIGURE 1 - SPILL LOCATIONS

St. Lawrence and eastern Canadian waters. Historical AES ice charts for February and March, 1974 - 85 were compared with the 1986 winter conditions. Maps summarizing median ice concentrations, minimum and maximum ice limits, and the frequency of ice occurrence are presented in Markham (1980) using data for the years 1963 - 73. In addition, Trites and Drinkwater (1985) show historical data on the presence and duration of ice for specific offshore points, based on data for the years 1971 - 83.

The following description of the typical annual ice regime is derived from Markham (1980). Ice formation starts in December in the St. Lawrence River and in shallow areas along the northern New Brunswick coast. In January, the ice cover spreads throughout the Gulf of St. Lawrence and begins to flow into the Atlantic Ocean through Cabot Strait. Ice concentrations in mid-January increase from 1-3/10 at the ice edge to 4-5/10 in the centre of the Gulf. Ice continues to thicken in February and drift through Cabot Strait. By mid-February, the median ice edge (5/10 total ice concentration) extends to Scatarie Island east of Cape Breton Island (Figure 2). The ice cover is usually near its maximum thickness and extent from the end of February until mid-March. The maximum southerly extension of the median ice edge occurs in early March, when it reaches as far south as 46°30'N latitude, and as far east as 58°30'W longitude.

The study area (Figure 2) is contained within the median ice edge boundary defined by Markham (1980) for early March. Within the study area, at a location due east of Scatarie Island, ice was found to be present during 12 of 13 years studied over the period 1971-83 (Trites and Drinkwater 1985). Ice duration was highly variable from year to year, ranging from one to 12 weeks, with a mean of seven weeks. Ice appeared as early as January 15 and stayed as late as April 30. On average, ice was present from February 5 to March 2.

There is no long-term analysis of ice age once it has passed through Cabot Strait. Markham (1980) gives average age categories for ice in the Gulf in March at 50% white, 30% grey, and 10% new ice. These proportions would be expected to shift towards younger ice forms as the ice extends

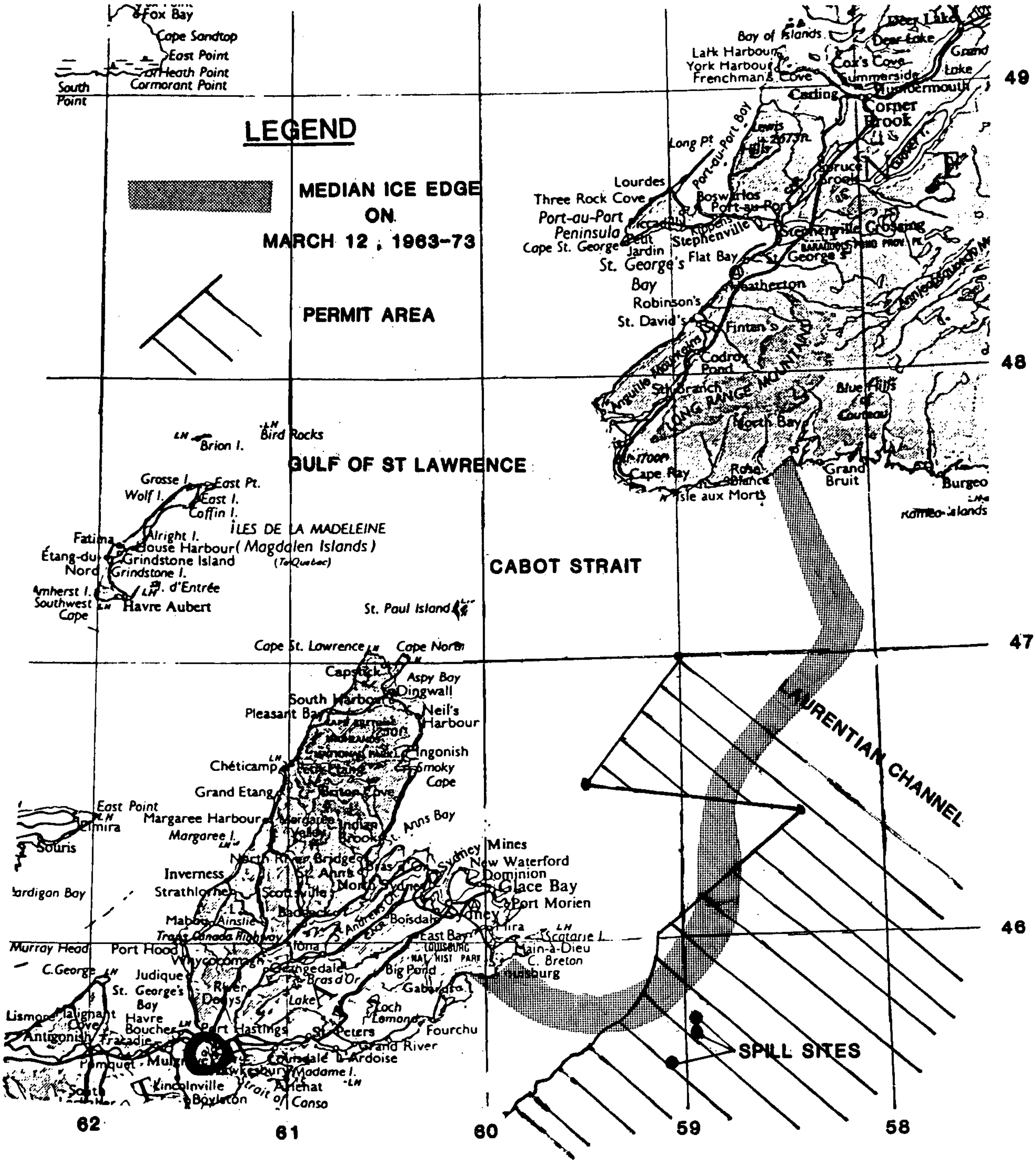


FIGURE 2 - MEDIAN ICE EDGE AND PERMIT AREA

further south. Maximum level ice thickness reached in March is in the range of 60 - 90 cm. Significantly greater thicknesses may occur as a result of due to local rafting.

Ice motion through the study area is generally towards the southwest with the Scotian Shelf current. However, the presence of a strong clockwise eddy moving ice to the northeast along the Cape Breton shore at speeds up to 1 kt has been inferred by a number of observers (Ingram 1972; Vandermeulen and Buckley 1985). Mean drift rates of oiled ice in this area following the Kurdistan spill were in the range 13-16 km/day between March 23 and 25, 1979. Currents are known to exceed 22 km/day near Cape North at the entrance to Cabot Strait.

On a local scale of several kilometres, the ice can move in a complex pattern. Isolated strips and patches often extend tens of kilometres away from the main pack as shown in Figure 3.

The maximum southerly and easterly limits of ice extent are highly variable from year to year, depending on ice production rates and prevailing winds. In extreme years, pack ice can reach as far south as Halifax and as far east as St. Pierre and Miquelon.

Ice dispersal begins in early March in the Gulf of St. Lawrence, but is usually delayed until early April around Cape Breton Island. By late April, ice is found east of Sydney in only about one in five years. Complete melting of ice in the southern Gulf and along the west coast of Cape Breton Island usually occurs by early to mid-May.

Pack ice along the east coast of Nova Scotia can be quickly dispersed seaward to be broken up by wave action or driven into the coast to pile up along shore, depending on local winds. Surface puddling on the ice in the spring is limited. The ice tends to melt from below as the water temperature rises. This is very different from the process of pack ice deterioration in the Beaufort Sea, where the ice melts almost entirely from above through solar heating.

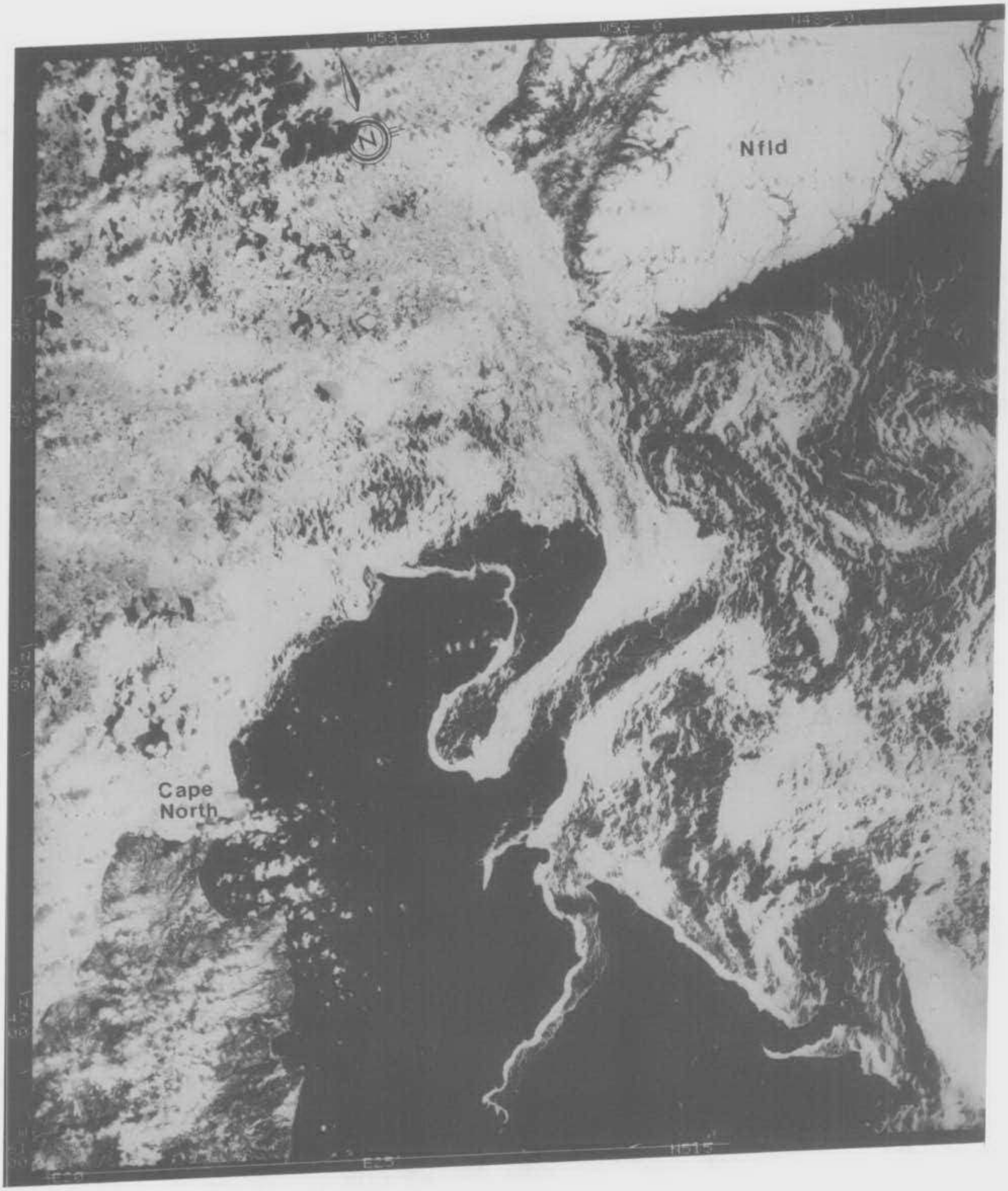


FIGURE 3 - Landsat image received March 25, 1974, showing the Gulf pack ice streaming through Cabot Strait and breaking into a complex series of ice belts and patches.

OIL PROPERTIES

The crude oil used in this study was an Alberta Sweet Mixed Blend (ASMB). The properties of the fresh oil are given in Table 1.

TABLE 1

Properties of Alberta Sweet Mixed Blend Crude Oil

Density at 0°C:	856.6 kg/m^3
Viscosity at 0°C:	43.7 mPas
Interfacial tension	
air/oil:	25.7 mN/m
oil/seawater:	19.0 mN/m
oil/water:	26.2 mN/m
Pour point:	-8°C
Flash point (closed cup):	7°C

Each experimental spill involved the release of 1 m^3 of oil.

STUDY METHODS

OIL DISCHARGE

For the first discharge (denoted as Spill 1) the oil was transferred from drums on the deck of the MV Brandal (Figure 4) to a plastic bladder on a raft (Figure 5). The raft was placed in the centre of the chosen site using the boom on the MV Brandal (Figure 6). The bladder was slit open to release the oil after the ship had moved away and the ice had filled the ship's track (Figure 7).

For the second and third discharges (denoted Spill 2 and Spill 3 respectively), the oil drums were slung over the side of the ship and placed on a suitable floe (Figure 8). Once the ship had moved away and its track had closed, the drums were opened and tipped over the edge of the floe.

REMOTE SENSING

A Bell 206 helicopter was used as a remote sensing platform (Figure 9). Sensors mounted on the helicopter included (Figure 10):

- a Barr and Stroud IR-18 infra-red video camera and recorder;
- a black and white Low Light Level television (L^3TV) camera and recorder;
- a 70-mm Vinten aerial camera with colour film;
- a 70-mm Vinten aerial camera filtered to record in the ultraviolet band on a black and white film; and
- a colour 0.5 inch video system.

Coloured nylon circles were placed around each spill site to aid both aerial video and photo interpretation (Figure 11). Some of these circles included multi-coloured segments to permit analyses of floe rotation. A

Figure 4 - MV Brandal

Figure 5 - Spill raft

Figure 6 - Placement of spill raft

Figure 7 - Oil release, Spill 1

Figure 8 - Placing oil drums on floe, Spill 2

Figure 9 - Remote sensing helicopter

Figure 10 - Sensors mounted on struts

Figure 11 - Coloured nylon floe markers

Figure 12 - Coloured nylon strip for aerial photo scale

10 m x 1 m orange nylon strip was placed on a centrally located floe at each site to provide an accurate scale for video and photo interpretation (Figure 12).

For the first spill, the helicopter hovered directly over the raft during the oil release. As the oil spread it became necessary to fly over the site at different heights to ensure complete coverage. Altitudes ranged from 150 to 1,000 m during these flight lines. For the more stationary second and third spills, all aerial photography was done while hovering.

Positions were determined by LORAN-C receivers on both the ship and the helicopter.

OIL SAMPLING

Sampling of the oil slick during Spill 1 was conducted from inflatable Zodiac boats powered by 10 HP outboard motors. Surface oil samples were taken at predetermined times and locations from both thick and thin portions of the slick using the Belore sampler (Belore and Ross 1982). The sorbent pads were placed in 500 mL glass jars containing 100 mL of hexane, "killed" with mercuric chloride, and tightly sealed with Teflon lined lids. Grab samples (125 mL) of the slick, oiled brash ice and oil on floes were also taken whenever possible and similarly stored. Free water and ice were separated from these samples with a separatory funnel prior to storage.

Grab samples only were taken from Spills 2 and 3 because the oil was too thick for sorbent sampling.

OIL ANALYSES

Evaporative loss for each oil sample was determined by comparing gas chromatographic (GC) traces of the samples to a standard of the same oil weathered by gas sparging (Stiver and Mackay 1983). Oil contents were determined by ultraviolet spectroscopy. Sample density was determined using a Parr densitometer; viscosities were measured using a Brookfield viscometer rotating at 0.3 rpm.

ENVIRONMENTAL MONITORING

A simple low cost environmental monitoring program was developed. It was realized from the outset that sophisticated ice tracking and reconnaissance systems would not be available, and that a rigorous investigation of pack ice driving forces was beyond the study's terms of reference. The reader is referred to the series of continuing ongoing international Marginal Ice Zone Experiments (MISEX; Wadhams 1981-86) for investigations of small-scale air/ice/ocean interactions in different pack ice environments. Meso-scale characteristics of pack ice dynamics in different Canadian offshore areas are presented in terms of interest to oil spill modellers in Dickins et al. (1986).

The environmental documentation associated with the 1986 field spills was planned around three levels of source information as outlined below.

Regional Pre-Spill:

- 30 day ice forecasts issued by the Atmospheric Environment Service (AES)
- satellite imagery (Landsat and NOAA).

Regional Historical:

- weekly composite ice charts issued by AES
- freezing degree-day accumulations for Sydney, N.S. (1953-75)

Figure 13 - View of coring operations during Spill 1

Figure 14 - Deployment of underwater video system

Temperatures were recorded by inserting a thermistor probe into the centre of the ice core immediately on core recovery. Salinity was estimated by taking refractometer readings on melt-water from 5-cm core slices. Sections of cores which contained oil droplets were sliced and placed in 500-mL jars containing mercuric chloride. A hand-held anemometer was used to take periodic wind readings on the ice for comparison with shipboard readings at a standard 10-m elevation.

A Cushing electromagnetic current meter was obtained from the Department of Fisheries and Oceans, Institute of Ocean Sciences, with the intention of measuring relative currents from the ice. These measurements were impossible to complete because of a malfunction in the meter. As it turned out, such measurements would have been of questionable value during Spill 1, as the floes were alternately accelerating and decelerating through the crests and troughs of the large ocean swell propagating through the pack. An underwater video system was used to document oil/ice interactions (Figure 14).

Ship records during the spills made use of LORAN C for position fixing, and a weather station (wind speed/direction, temperature and pressure) mounted above the bridge at a 10-m elevation (above sea level).

COUNTERMEASURES

In-situ burning was evaluated by igniting the oil with oil-soaked sorbent pads and measuring the area of the slick on fire versus time. A Morris MI-30 skimmer and pumps were on board the MV Brandal. Manual recovery was accomplished using shovels and sorbent pads.

RESULTS AND DISCUSSION

SUMMARY OF 1986 REGIONAL ICE CONDITIONS

Two major climatic factors work to determine the severity of the ice conditions in the study area in any particular year. First, mean air temperatures in the area are generally close to freezing for much of the winter. As a result, small shifts in winter climate significantly affect the ice production rate. Secondly, winter winds determine the location of areas of ice dispersal and congestion.

The AES forecast for the 1985-86 winter was for a worse-than-average ice year because of below-normal temperatures in December and January, i.e., an increase in freezing degree-day FDD accumulations. Freezing degree-days provide an important index of ice severity in terms of ice growth rates. Table 2 lists the normal (FDD) accumulations at Sydney for the period 1953-75, compared with those for the 1985-86 winter. By January 1, 1986, the number of FDD accumulated was double the average. By the end of March 1986, the total number of FDD throughout the winter was 159 greater than normal. Ice conditions along the east coast of Cape Breton Island reflected the severity of climate as the pack ice edge advanced well south of the median position.

Ice conditions in the study area were monitored using the bi-weekly ice charts produced by AES, Ice Forecasting Central. The following description outlines the chronological development of ice conditions in the study region as shown on the ice charts.

January 15, 1986:

A tongue of 4/10 new ice was present north of Cape North. Ice conditions appeared to be one to two weeks ahead of median conditions. Ice has been present north of Cape North in mid-January in only three out of 11 years.

TABLE 2

Freezing degree day accumulations for Sydney, N.S.

	1953-75	1985-86
1st FDD	Dec 2	Nov 23
1st MDD*	April 4	Mar 28
ACCUMULATED FDD		
Dec 18	35	84
Jan 1	75	151
Jan 29	205	282
Feb 26	375	507
Mar 26	485	672
TOTALS	515	674
MAXIMUM FDD	1961	845
MINIMUM FDD	1958	85

* MDD indicates melting degree day

January 26, 1986:

The 3/10 ice edge, composed of 1/10 thin first-year ice and 2/10 grey-white ice, extended as far south as Scatarie Island. Ice concentrations within Cabot Strait were 9/10 grey to grey-white in strips. Air temperatures from mid-to late January alternated between much above normal and much below normal, with the mean being 2°C above normal.

February 2, 1986:

In late January, the ice edge retreated north to between Cape North and Port aux Basques, Nfld. By February 2, the ice edge had re-established in Cabot Strait, and the study area contained 5/10 new ice in strips and patches. The northeast coast of Cape Breton Island, between Cape North and Scatarie Island, was still ice-free. February air temperatures averaged 3 - 4°C below normal.

February 12-26, 1986:

Rapid expansion of the ice edge occurred during early February. Major storms tracking through the Gulf caused variability in wind strength offshore. Cold spells between storm fronts contributed to ice consolidation and expansion. By mid-February, close pack ice composed of first-year and grey-white ice spread south as far as 45°30'N. This central tongue of 9/10 ice was surrounded by 6/10 new ice which filled Chedabucto Bay. Ice occurrence this far south during February is only a one-in-ten-year event. The ice edge reached its maximum southern extent by the end of February, with 4/10 grey and grey-white ice as far south as Halifax, though further offshore. Figure 15 shows an unusually clear Landsat image acquired on February 8, 1986, showing large first-year floes up to 5 km in extent off Scatarie Island. Polynyas are frequent within the main ice field. New ice is seen forming between the offshore pack and the Cape Breton Shore.

March 2-5, 1986:

In the first half of March, temperatures averaged 2 - 4°C below normal. Winds were predominantly from the northwest. While ice concentrations within the pack increased to 8-9/10, the areal extent of the ice cover was reduced from its February maximum. Chedabucto Bay became

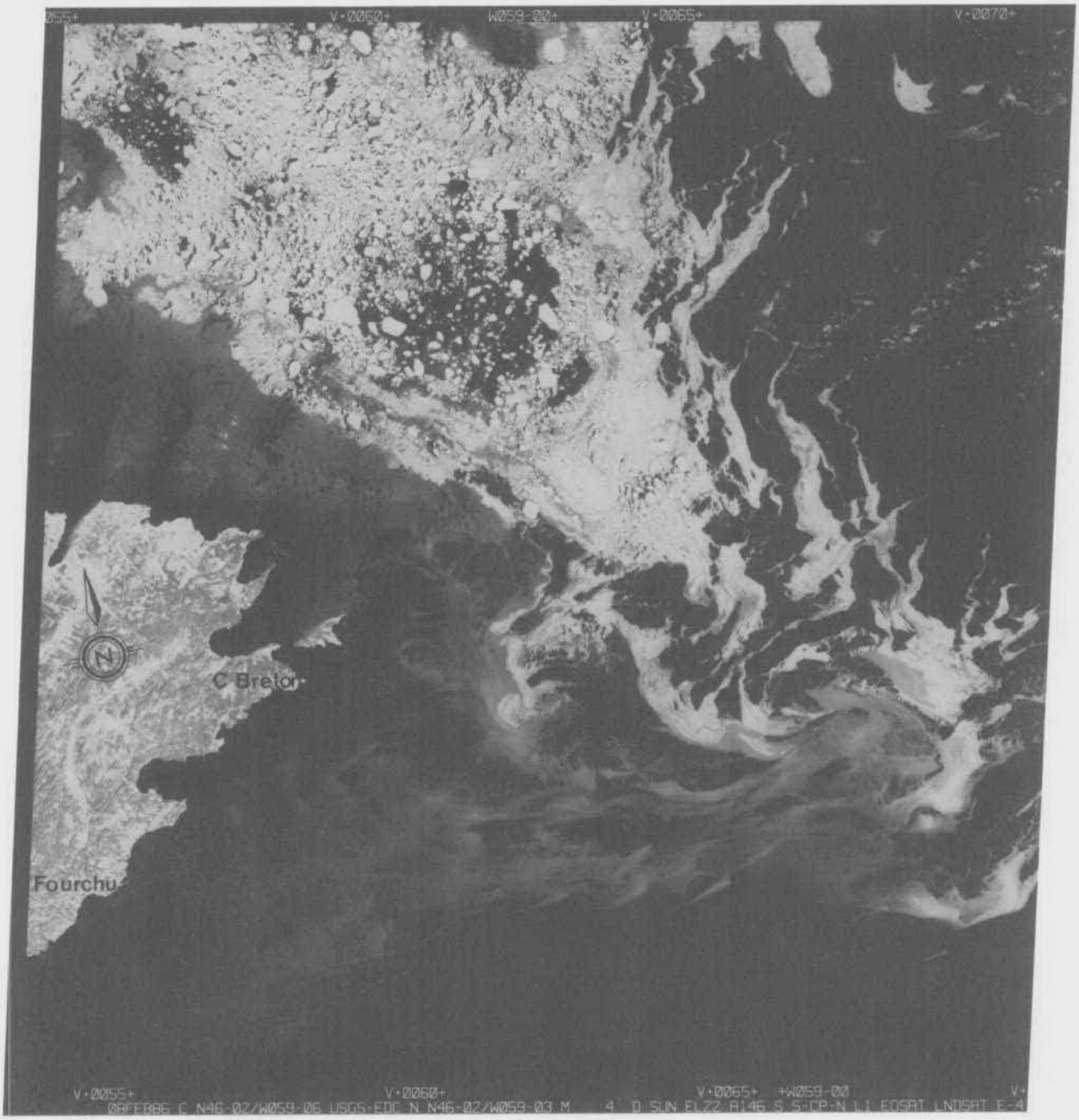


Figure 15 - Landsat image showing pack ice conditions east of Scatarie Island on February 8, 1986.

ice-free, and open water extended north to Scatarie, separating the south Cape Breton shore from the main pack further offshore.

March 9, 1986: Spill 1

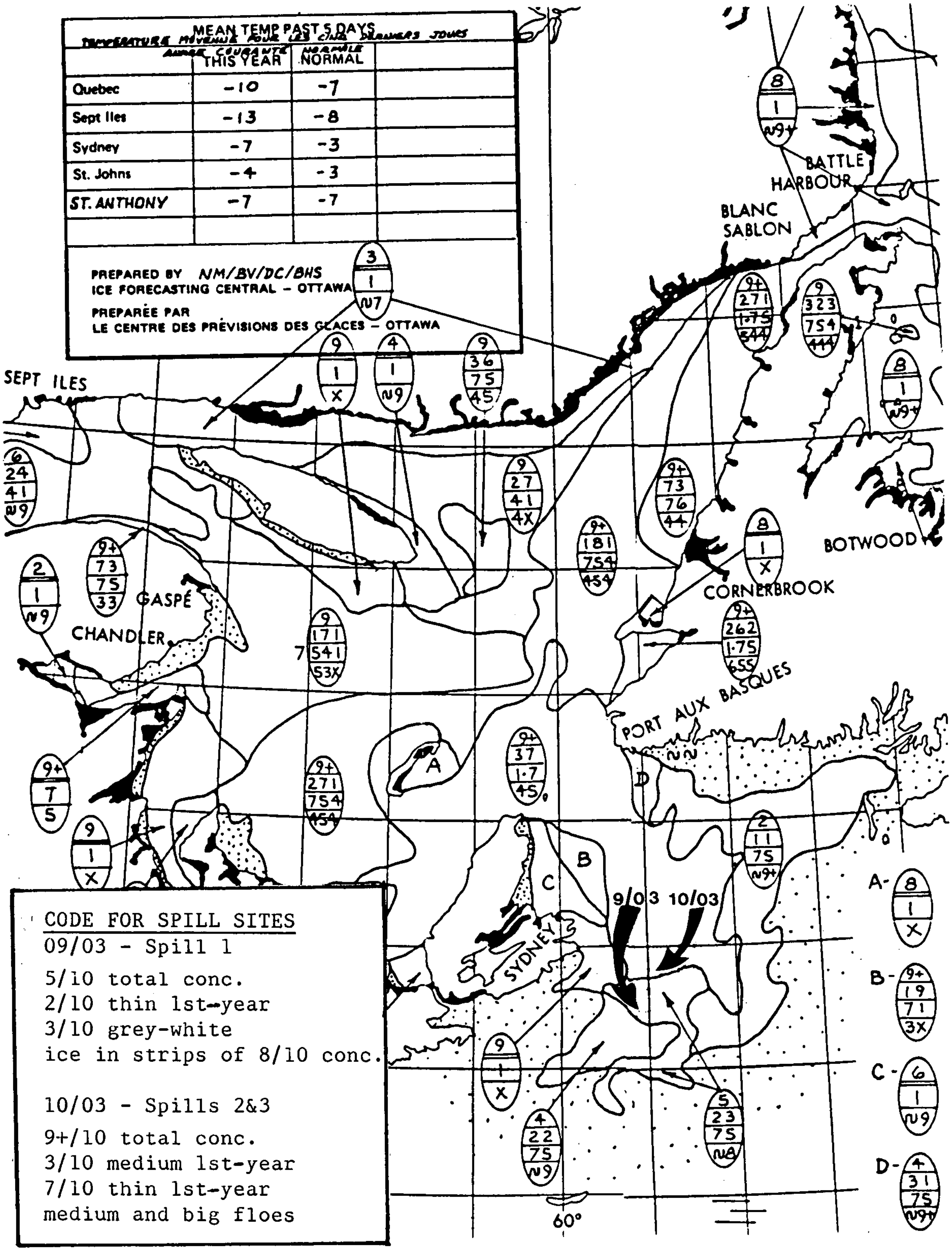
The 9/10 first-year ice edge retreated north to 45°50'N. Ice concentrations ranging between 4 and 5/10 thin first-year and grey-white ice still extended south to near 44°50'N. New ice was forming along the northeast coast of Cape Breton Island. Figure 16 shows a copy of the March 9 AES composite ice chart.

March 12-30, 1986:

The areal extent of the pack ice cover in the region of the spills continued to expand during the two days following Spill 1. By March 12, concentrations of 7/10 new ice were present along the southeast coast of Cape Breton Island. Temperatures continued below normal, and, by mid-March, Chedabucto Bay was filled with new ice. Close pack ice remained off Sydney until March 23. By the end of March, the close pack ice in the northern parts of Cabot Strait began drifting southeast as the ice in the Gulf started to clear. An open lead along the eastern Cape Breton shore reached 100 km in width off Scatarie by the end of March.

April 1986:

Temperatures averaged warmer than normal throughout the first half of April in the Gulf. These conditions accelerated the melting and clearing of ice, and, by April 6, the western Gulf of St. Lawrence was mainly open water. Ice concentrations remained in the 8-9/10 range until about April 13. The east shore of Nova Scotia cleared of ice by April 23, about two to three weeks earlier than normal.



MEAN TEMP PAST 5 DAYS
TEMPERATURE MOYENNE POUR LES CINQ DERNIERS JOURS

	ANNÉE COURANTE THIS YEAR	NORMALE NORMAL	
Quebec	-10	-7	
Sept Iles	-13	-8	
Sydney	-7	-3	
St. Johns	-4	-3	
ST. ANTHONY	-7	-7	

PREPARED BY NM/BV/DC/BHS
ICE FORECASTING CENTRAL - OTTAWA
PREPARÉE PAR
LE CENTRE DES PRÉVISIONS DES GLACES - OTTAWA

CODE FOR SPILL SITES
09/03 - Spill 1
5/10 total conc.
2/10 thin 1st-year
3/10 grey-white
ice in strips of 8/10 conc.

10/03 - Spills 2&3
9+/10 total conc.
3/10 medium 1st-year
7/10 thin 1st-year
medium and big floes

Figure 16 - AES composite ice chart for March 9, 1986. Refer to appendix 2 for key to International Sea Ice Symbols, Symbol for spill sites is decoded on the chart

LOCAL ENVIRONMENTAL CONDITIONS, MARCH 9-10, 1986

This section describes ice, sea, and weather conditions during the three test spills on March 9 and 10, 1986. Information sources include weather and position logs maintained on board the ship, on-ice observations and measurements, aerial photography commissioned for the project, weather charts, and significant wave analysis charts (issued by the Canadian Forces Weather Service). Appendix 3 contains a listing of climate observations combined for all sources for the test period. The movements of oiled floes relative to one another are discussed separately in a subsequent section.

Table 3 summarizes the environmental conditions present at the time of the spills.

The following sections describe local ice conditions in the immediate vicinity of the three spills.

TABLE 3

Summary of environmental data

Spill	Ice Conditions	Oceanographic Conditions		Meteorological Conditions		
		Swell	Ice Drift	Air Temp	Wind Speed	Wind
No.	(tenths)	(m)	(km/h @°T)	(°C)	(km/h)	Dir'n (°
1	4-6	3-4*	1.1 @ 140	-8	35-55	270-285
2	6-7	N/A	0.8 @ 195	-14	30-35	310-335
3	3-5**	0.3-0.6	0.7 @ 155	-11	18-22	290-335

* Note: Reported open water swell of 5-6m; swell period ranged from 4 to 9 s; swell direction was ESE (source: Canadian Forces METOC Centre Halifax).

** Note: Concentrations exclude slush, brash, and small pancakes less than 2 m. Total concentration can be misleading because of the presence of new and young ice forms which have a dramatic effect on oil spreading behaviour. See text and photographs for a more accurate description of the pack composition.

Spill 1: March 9, 1986

Ice conditions during this test were extremely dynamic. The combined effects of the wind and of the large ocean swell propagating through the pack led to the pack being divided into strips and patches of high and low concentrations roughly aligned with the wind and swell direction. Local areas quickly contracted and expanded, making any overall estimates of ice concentration very difficult.

At the time of the spill, ice conditions in the immediate vicinity of the spill raft consisted of 2-3/10 thin to medium first-year ice (30-120 cm thick), 1-2/10 grey-white ice (< 30 cm thick), and 3-6/10 pancakes mixed with slush and brash. Floe sizes measured from aerial photographs showed a maximum diameter of 24 m and a mean of 7 m (for floes greater than 3 m in maximum extent). Individual pancakes ranged in size from 1 to 2 m.

Figure 17a is an aerial view of ice conditions in the vicinity of Spill 1 at the time of oil release, showing large variations in ice concentration on a scale of tens of metres. Figure 17b is a close-up view of brash ice and pancakes filling the spaces between thicker floes shown in the previous figure. This comparison shows how the ice appearance is dramatically altered by changes in photographic scale.

Figures 18 and 19 are aerial views showing the ice conditions and oil distribution around the spill raft at 1216 and 1238 (6 and 28 min after oil release). These images show significant changes in floe positions over 22 minutes. Similar pairs of photographs were used to measure the rates of relative floe movements over time scales of up to 329 min (refer to following section, ICE DYNAMICS). Figure 20 is a shipboard view of ice conditions near the spill raft at the time of oil release. Figure 21 shows a corresponding view of ice conditions surrounding the spill raft immediately after oil release. The water between the pancakes and floes is completely covered by a layer of slush and grease ice.

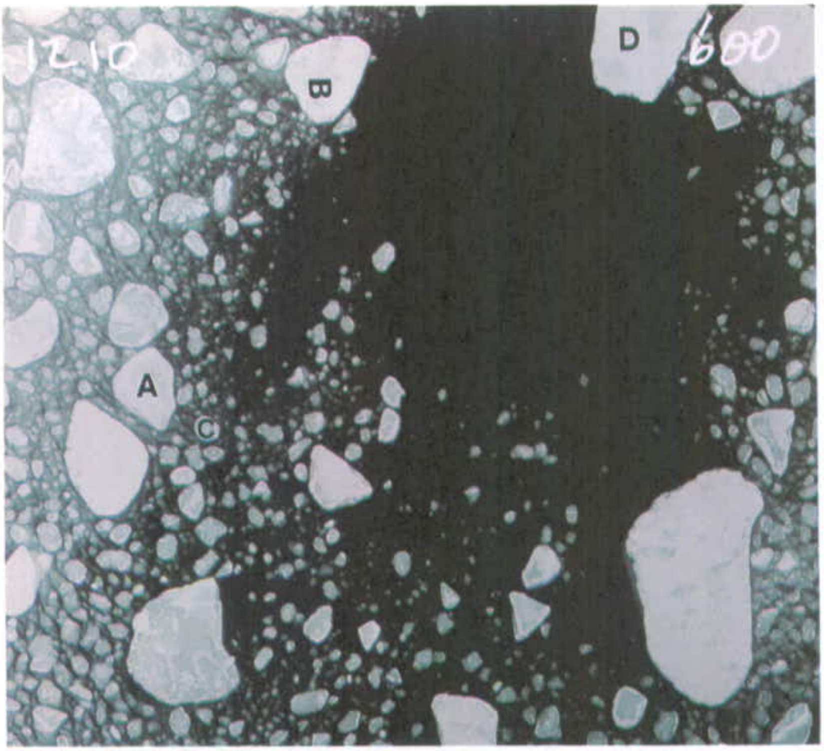


Figure 17a - Aerial view of ice conditions in the vicinity of Spill 1 at 1210. Floe D is within 25 m of the spill raft (see Figure 19). Scale: 1 mm = 0.5 m

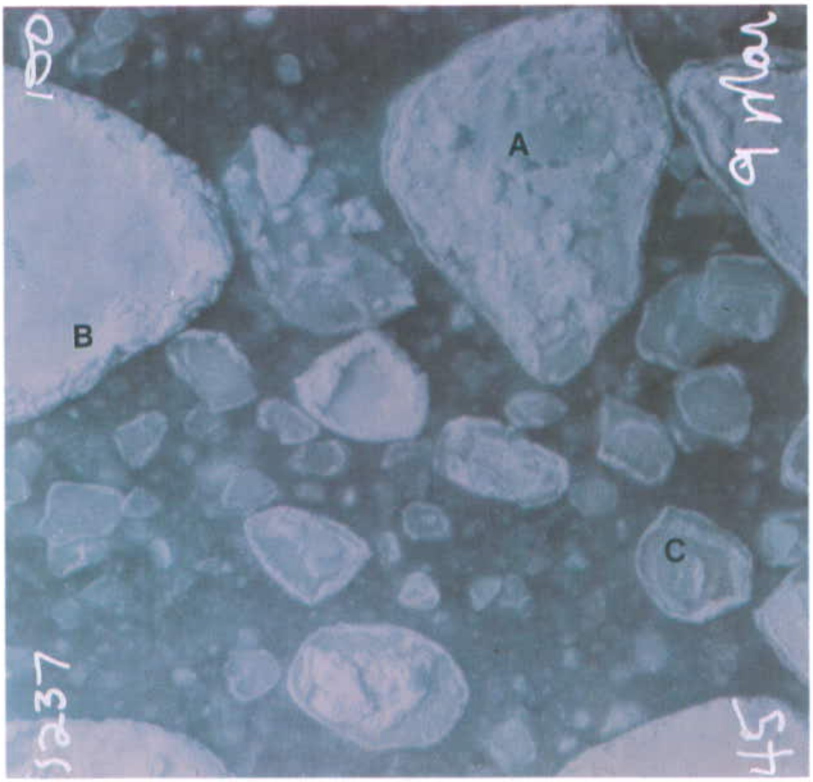


Figure 17b - Close-up view of conditions shown in Figure 16 (match marked floes) Time: 1237. Scale: 1 mm = 0.08 m

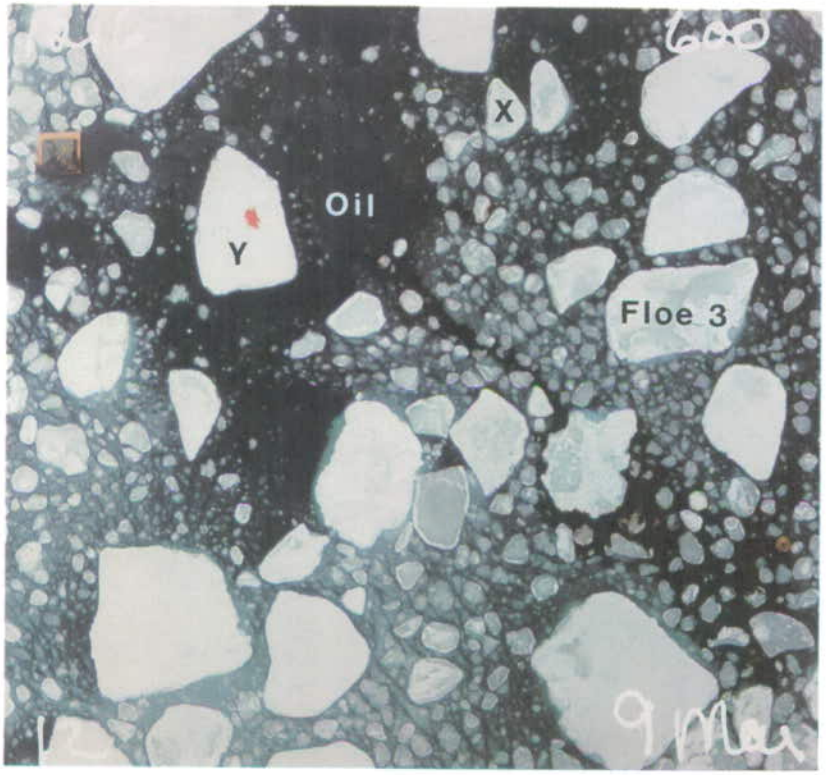


Figure 18 - Aerial photograph showing the spill raft and oil distribution 6 minutes after oil release on March 9. Scale: 1 mm = 0.5 m. Floes marked X&Y also appear in Figure 19 22 min later. Floe 3 was boarded and documented 4 h later (see Table 4, and Figures 22 and 23).

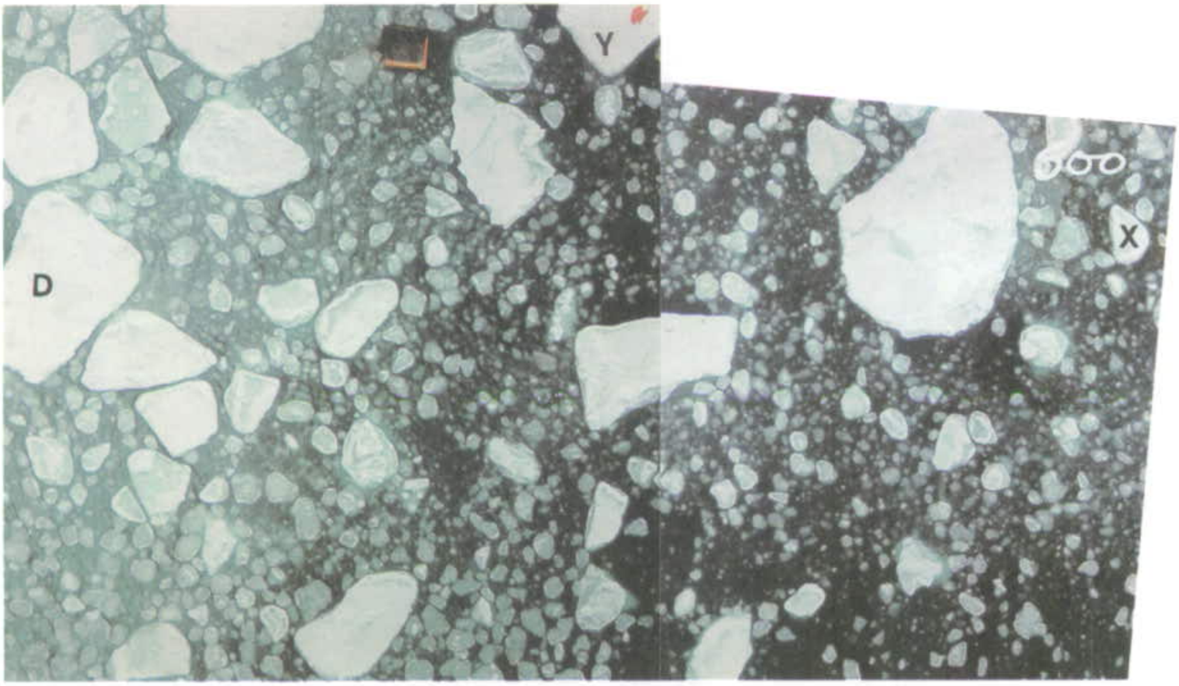


Figure 19 - Aerial photograph showing ice conditions around the spill raft 28 min after oil release. Relative floe movements can be seen by comparing positions of floes marked X&Y between this and Figure 18. Floe D is also visible in Figure 16

Figure 20 - Shipboard view of ice conditions surrounding the spill raft at the time of oil release.

Figure 21 - Surface view of ice conditions surrounding the spill raft immediately following oil release.

Four floes were boarded during Spill 1. The ice characteristics noted from thickness and elevation measurements are given in Table 4.

Cores were taken for salinity and temperature on Floe 4. The entire core was within 0.7°C of freezing (-1.7°C), with a minimum temperature of -2.4°C in the upper 10 cm. Ice salinity ranged from 0.5 ppt in the upper 5 cm (snow ice) to 5 ppt through most of the core. Surface water salinity was 24 ppt, which is less than ambient salinity as a result of slush and brash ice in the water.

Several other cores were taken at the edge of Floe 3 where oiled slush and brash were in contact with the floe edge. Ice in these cores was quite rotten with large internal cavities (Figure 22).

TABLE 4

Spill 1 ice floe characteristic dimensions

FLOE #	ICE THICKNESS		ICE FREEBOARD AT THE EDGE	
	RANGE	MEAN	RANGE	MEAN
1	81-105 cm	67 cm	----	----
2	----	50	9-44 cm	25 cm
3	----	51	7-23	15
4	----	77	----	----

Notes: All four floes were in the size range 7-10 m. Due to the proximity of the floes to the open water edge and the 3-4 m swell, only a very limited time was available on each floe. The concern was that the floes would start to break up on the swell crests as they neared the open sea.

Snow depth on the ice was 2-3 cm of loose snow beneath a hard upper crust.

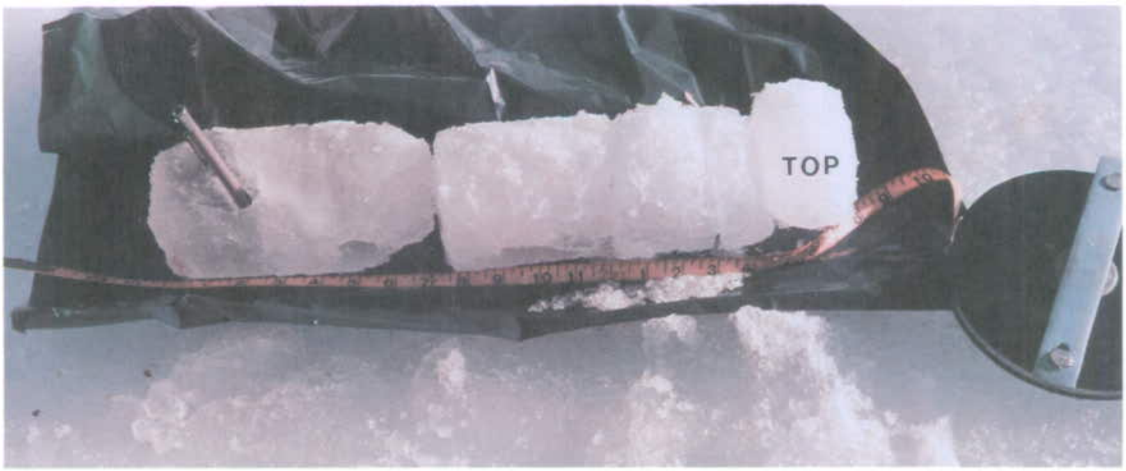


Figure 22 - Rotting ice core removed from the edge of Floe #3

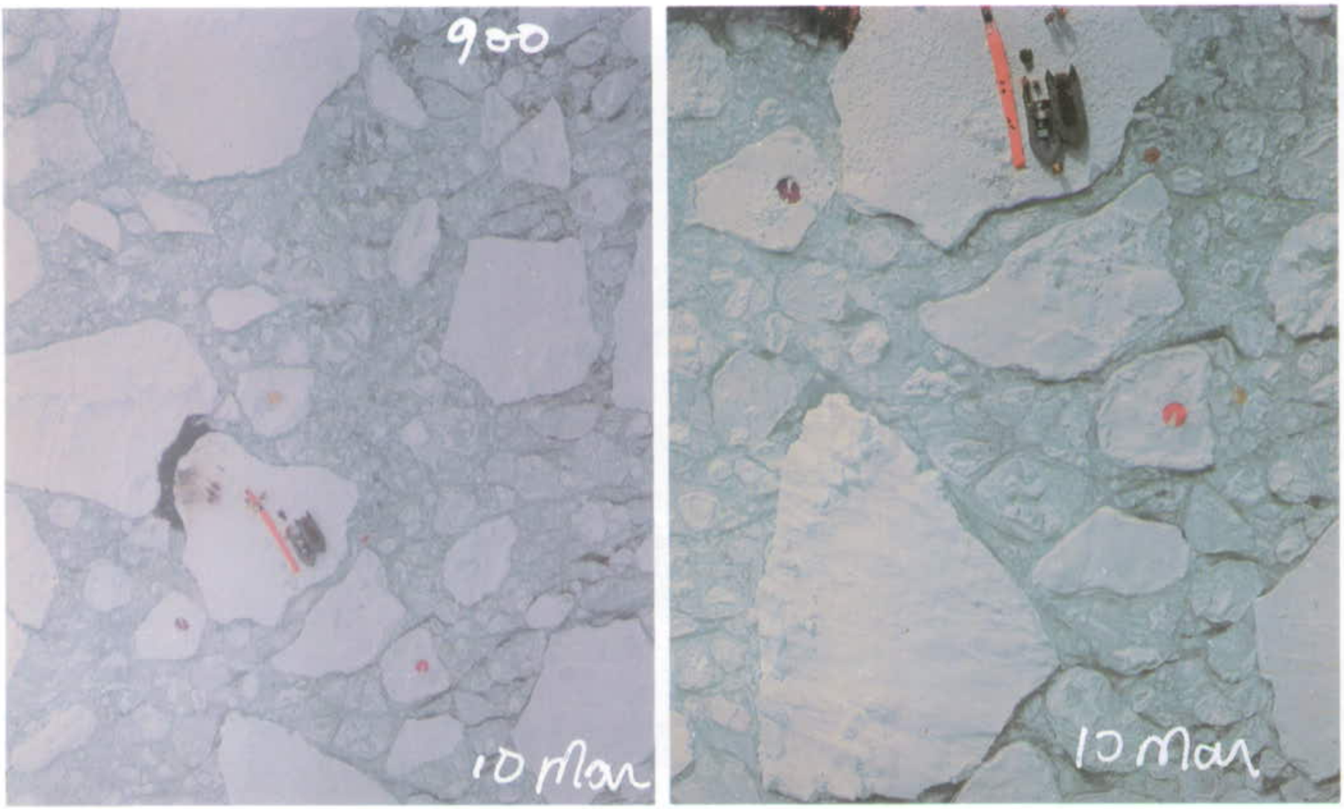
Spill 2: March 10, 1986

Spill 2 took place in pack ice under a state of moderate compression, unlike Spill 1 which was characterized by an expanding pack ice environment. Conditions surrounding the spill consisted of 3-4/10 medium first-year ice floes, and 3/10 pancakes. The remaining area was covered with a compressed slush ice layer up to 40 cm thick. Figure 23 shows aerial photographs of Spill 2. The two floes containing the oil are separated by a distance of 2 m.

Unlike Spill 1, where the swell played a major role in displacing the oiled ice floes relative to one another, conditions in Spill 2 were relatively static. The swell was strongly damped and barely noticeable. Adjacent floes shifted slowly over small distances and maintained the same relative orientation over several hours. Relative movement rates between the two floes acting as boundaries to the spill ranged from 1 to 2 cm/s. Absolute displacements were less than 20 cm.

Compared with Spill 1, the ice floes in Spill 2 were larger (mean diameter, 13 m; maximum diameter, 30 m) and thicker, as a result of ice rafting. The 28 m x 16 m floe used as a base during Spill 2 had a solid ice thickness between 78 and 95 cm. Below this depth, various slush and hard ice layers were encountered down to 160 cm. Fresh snow ranging in depth from 17 to 40 cm covered the floes and explained the heavy accumulation of slush ice in the water.

The internal ice temperature was within 0.6°C of the freezing point, except for the upper 5 cm which reached 2.8°C. Ice salinity was consistently 5-6 ppt throughout the core; the absence of a salinity gradient indicated that significant brine drainage had occurred in the ice.



1219 Scale: 1 mm = 0.8 m 1310 Scale: 1 mm = 0.4 m

Figure 23 - Aerial views of ice conditions in the vicinity of Spill 2

Spill 3: March 10, 1986

The third spill took place in slush and brash ice alongside a 12-m-diameter first-year floe within open pack conditions similar to Spill 1, but without the swell, and with a greater degree of compression, creating the appearance of almost total ice cover. Figures 24 and 25 show aerial views of different scales, illustrating the mix of pack ice conditions present at the time of Spill 3. Total first-year ice concentration was 3-5/10, composed of 2-3/10 medium first-year and 1-2/10 young first-year floes. The remaining 5-7/10 was covered by pancakes and slush or brash. The mean first-year floe size measured from aerial photographs was 8.6 m. Maximum observed floe size was 22 m. Ice pancakes were in the range 2-3 m. Ice in the area was in a state of moderate compression at the time of the spill, and, after each pass, the ship track remained open for only a minute (Figure 24), closing at about 15 cm/s. The ice thickness of the flow used as a base for Spill 3 was 120 cm, and the bottom of hard ice was encountered at about 70 cm depth. Several ice layers were encountered below this depth, with slush between each layer. Figure 26 clearly shows several floes rafted together near the Spill 2 site 45 min prior to oil release, when the pack was still open.

ICE DYNAMICS

Available aerial photo mosaics and single frames were analysed in an attempt to quantify the extent and rate of oiled ice divergence and/or convergence during the dynamic conditions experienced during Spill 1. The ship's LORAN showed a gross pack ice drift, during the 5-h monitoring period, of approximately 1.1 km/h in a direction 30 - 40 degrees to the right of the wind. The purpose of the aerial photo analysis was to determine, within the pack ice interior, the finer-scale motions that would determine the maximum area of contamination following a spill under similar conditions.

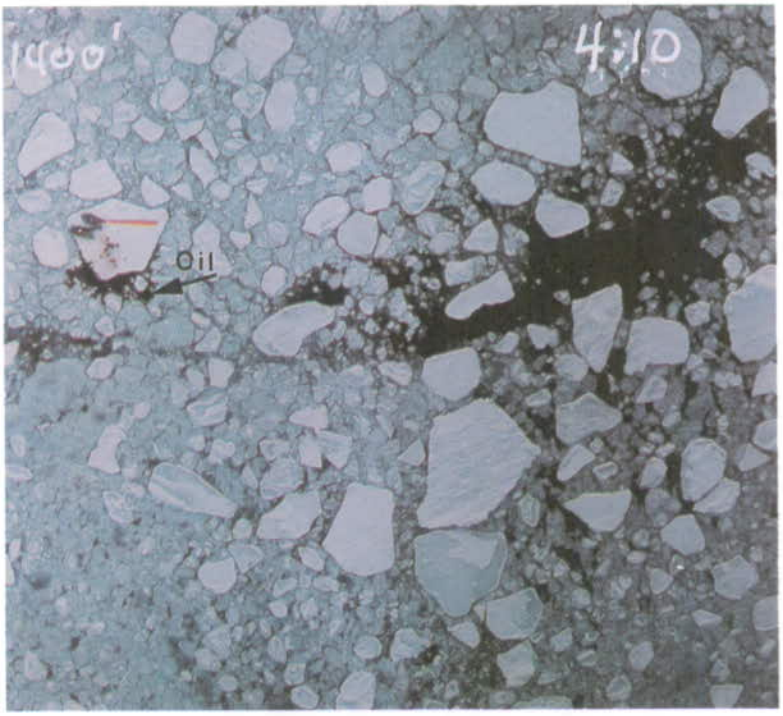


Figure 24 - Ice conditions in the vicinity of Spill 3, 1610 on March 10, 1986. Temporary clearing of ice by the ship is still visible, Scale: 1 mm = 0.8 m

Figure 25 - Close-up view of pack ice in the vicinity of the Spill 3 site prior to oil release. Scale: 1 mm = 0.3 m

Figure 26 - Rafted flow with multiple ice layers viewed from the ship in the vicinity of the Spill 3 site just prior to the pack closing in

Without a sophisticated system of beacons linked to a local positioning system, the best that could be achieved in this study with respect to ice motion determination was identification of groups of specific floes between different photographs, and measurement of their relative displacements over a known time period. These time periods ranged from 2 to 329 min, depending on the availability of the photography. Table 5 summarizes the relative floe motions obtained in this manner for Spill 1.

Table 5 shows that the pack ice in the vicinity of Spill 1 is an expanding ice environment, i.e., the ice floes tended to diverge more often than they converged.

Dickins et al. (1986) point out the strong dependence of implied ice movement rates on the time scale of the measurements. This characteristic was clearly evident in this study, where the mean rate of relative motion over several hours was only one-sixth that derived from measurements made over a time span of 2 - 10 minutes. Table 6 summarizes the relative motion values derived from short-and long-time scale measurements in this study.

An attempt was made to measure relative floe movements from aerial photography of Spill 2 over time periods ranging from 21 to 304 min. In most cases the displacements fell within the error limits of the measurement (i.e., less than 2 metres). However, several significant motions were detected, the largest producing 6-m displacement over 79 min (equivalent to 0.13 cm/s). As noted earlier, surface observations of relative floe motion showed transient rates as high as 2 cm/s lasting for 9 - 10 s.

Summary of Floe Dynamics

The rates of relative floe motion measured in Spill 1 represent an extreme condition, in that individual floes have ample opportunity to move under the influence of the significant forces of a large-amplitude swell and strong wind. Even in this situation, peak relative closure rates between floes were less than 7 cm/s.

TABLE 5

Summary of relative floe speeds derived from aerial photography

Time Period	Speed* (cm/sec)			Comments
	Min.	Mean	Max.	
1224-1226	+4	+10.3	+15.8	downwind
1222-1226	----	----	+ 4.2	single floe
1223-1552	+0.3	+ 0.4	+ 0.6	
1552-1601	-7	- 0.5	+ 8.7	open pack, downwind
1552-1601	-4.4	- 2.1	+ 1.1	close pack, downwind
1552-1601	-3.2	----	+ 2.2	crosswind
1601-1611	-1.8	+ 2.2	+ 8.5	open pack, downwind
1601-1609	+2.1	+ 4.1	+ 7.3	close pack, downwind
1601-1609	----	----	+ 2.3	crosswind
1200-1609	average 5.0			isolated floe
	average 1.1			isolated floe
OVERALL	-7.0	+ 2.4	+16	
MEAN OF ALL CLOSURES	-3.4			
MEAN OF ALL OPENINGS		+ 5.4		

* + = floes moving apart; - = floes moving towards each other

TABLE 6

Comparison of relative floe speeds according to time interval between readings

Time Scale	Relative Convergence (-)/Divergence (+) Rate (cm/s)		
	Minimum	Mean	Maximum
Minutes	-7	+2.4	+16
Hours	+0.2	+0.4	+5*

* This value applies to a single floe, which moved from within 50 m of the spill raft at the time of oil release to a position 800 m from the nearest marked floes (all near the spill raft originally) after 4h.

Compared with discrete floes, pack ice undergoing even moderate compression is characterized by much lower ice closure rates, as the freedom of movement for individual floes becomes progressively more restricted. As the pack ice concentration increases beyond about 7/10 (less in the case of significant amounts of brash and slush in the water), relative floe displacements become analogous to a lead situation in 10/10 ice. As measured during Spill 2, these displacements occur very slowly, in the order of 2 cm/s or less.

Lead closing rates derived from satellite imagery show the majority of closure rates at less than 0.6 cm/s (averaged typically over a 24-h period). Given the instantaneous closure rates needed to pump a significant quantity of oil onto the surface of the adjacent ice sheets (est. as 12 cm/s from tank tests, MacNeill and Goodman 1985), the phenomenon of oil pumping would seem to be an exceptional situation in nature.

OIL SPREADING

Figure 27 presents the results of analyses of the remote sensing (both photographs and video) to determine the areal extent of the oil.

Spill 1

The area of the oil slick was recorded at three times, at 1216 LT from the helicopter (Figure 28), visually at 1253 LT, and at 1552 LT from the helicopter (Figures 29 - 31). Because of the dynamic, low concentration ice conditions, the helicopter could not land on a floe to conserve fuel and had to return 130 km to Sydney airport. As a result, no remote sensing is available between about 1300 LT and 1500 LT. The areas shown on Figure 27, calculated from the photographs and video, exclude ice floes (i.e., the area of ice surrounded by oil is subtracted from the area of water surface containing oil) but include areas of oiled slush or brash ice.

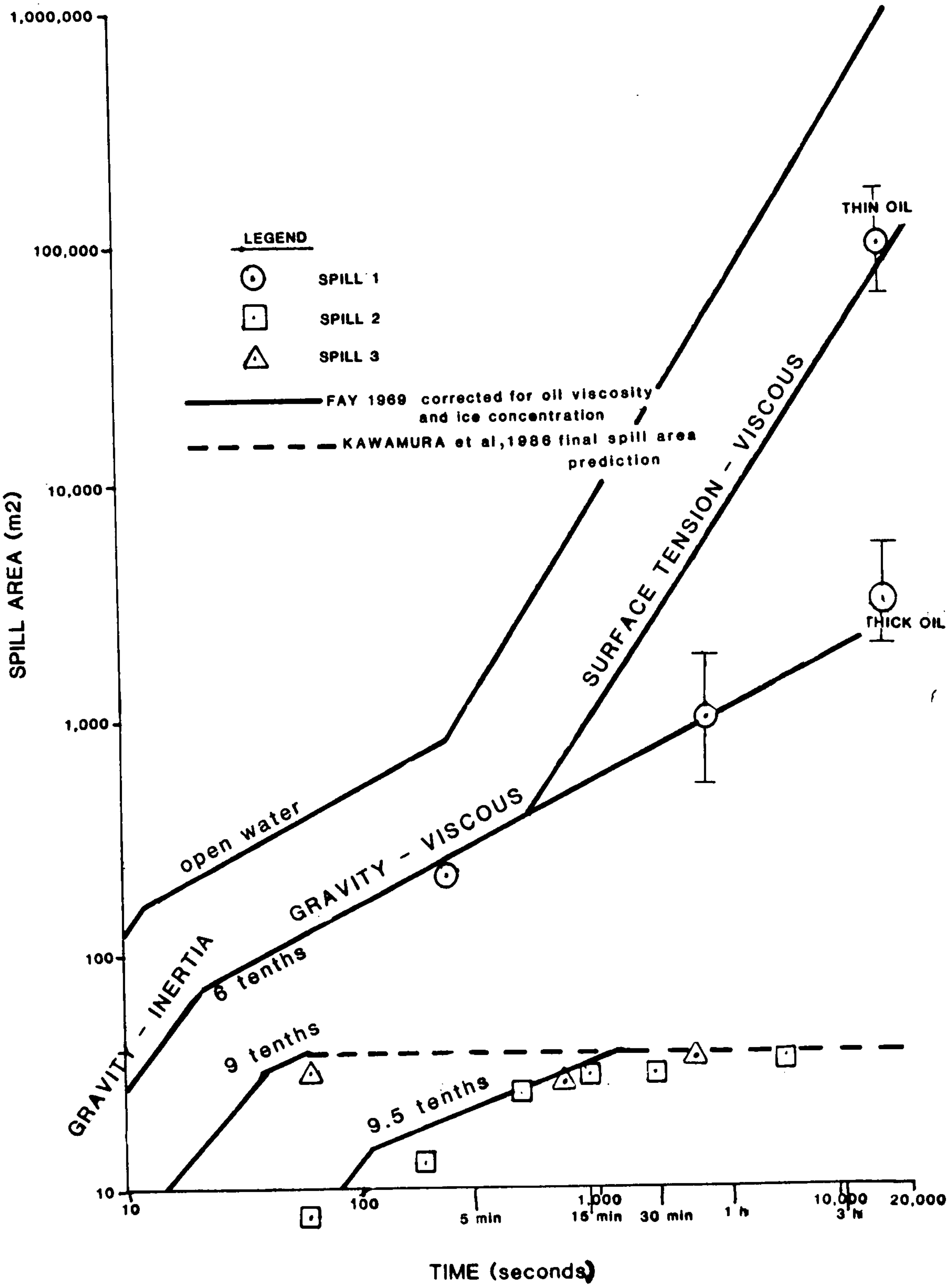


FIGURE 27 - OIL SPREADING IN PACK ICE

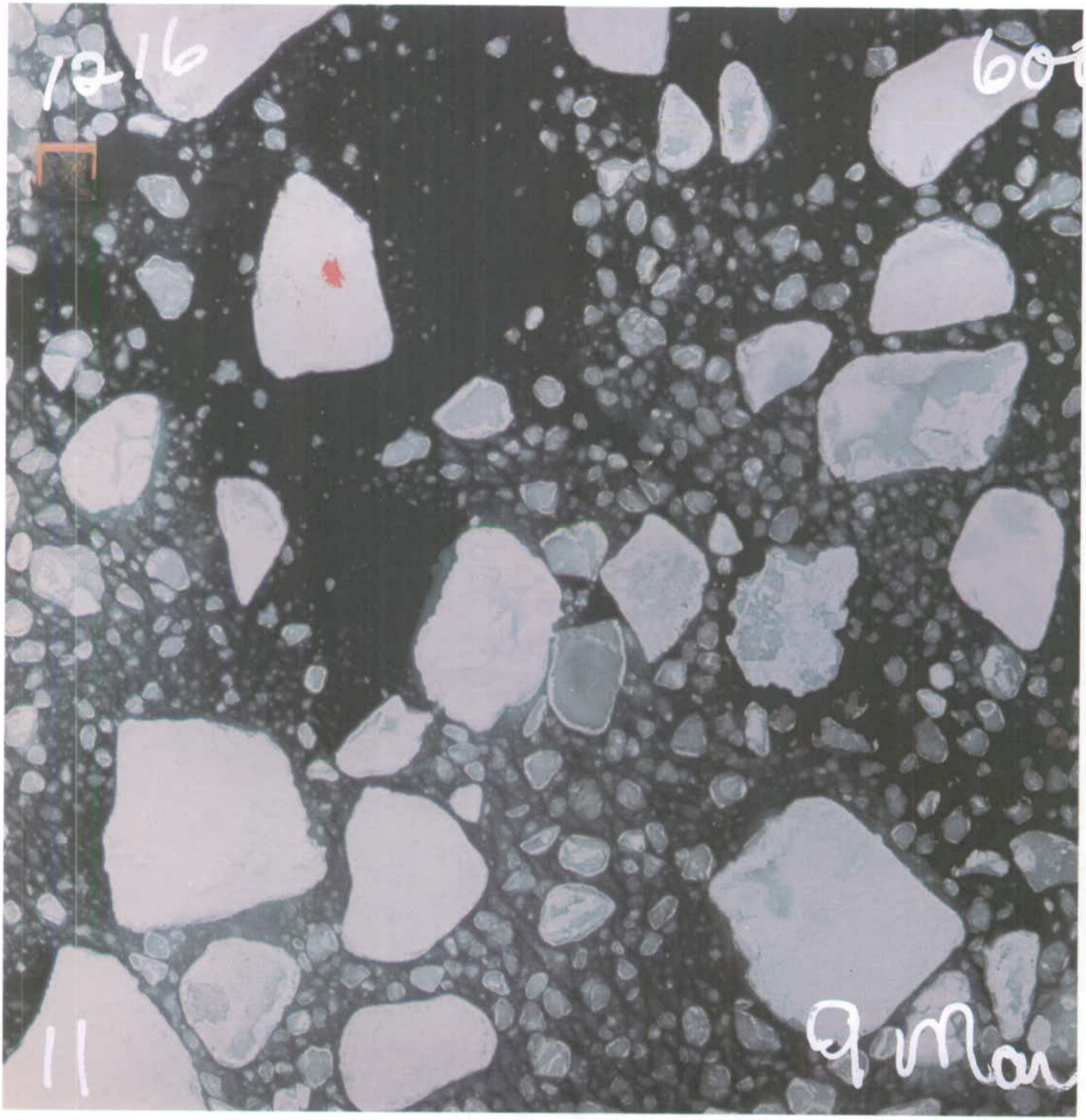
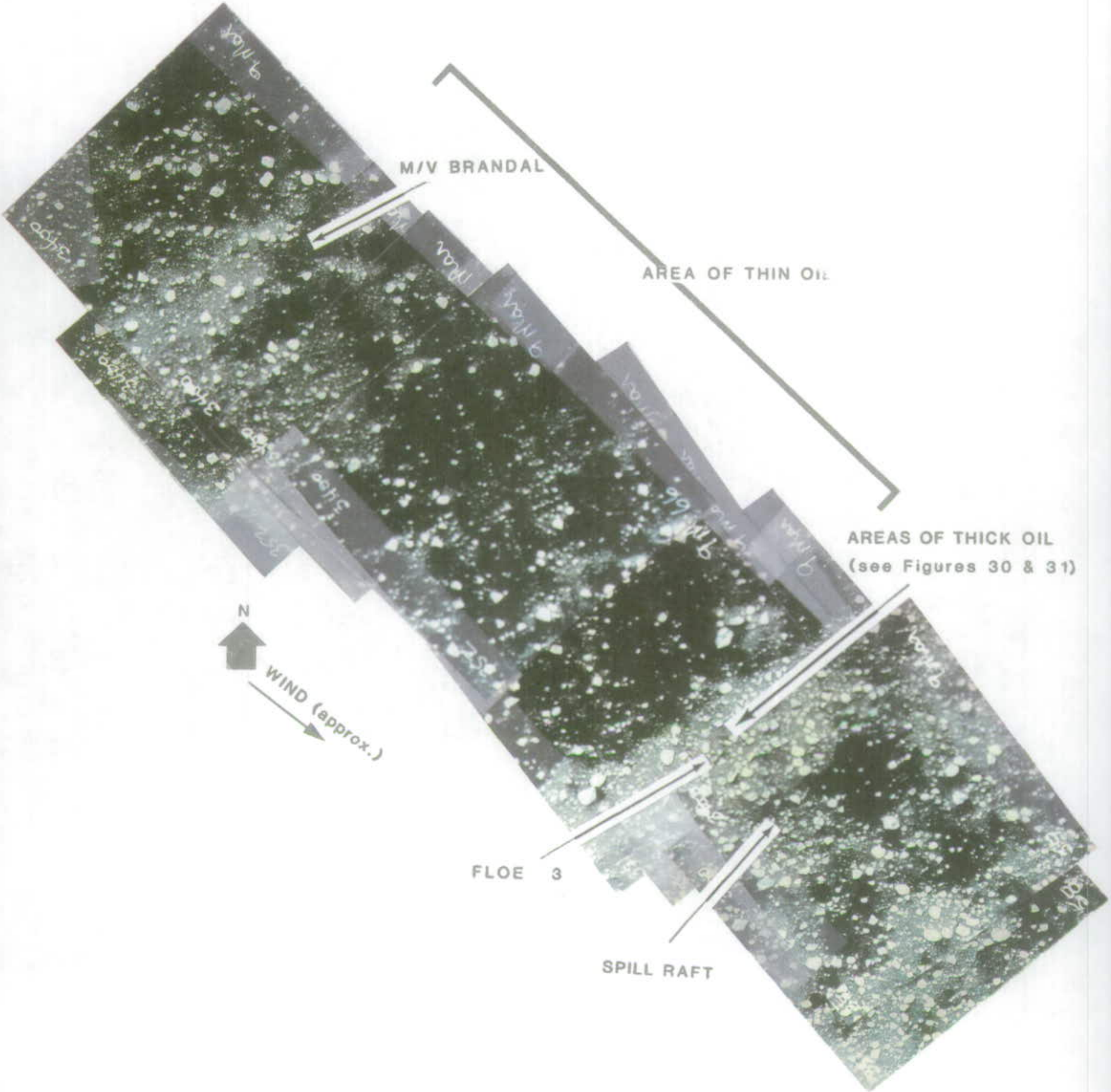


Figure 28 - Spill 1 oil near raft 6 min after release.
Scale: 1 mm = 0.2 m

Figure 29 - Aerial photo-mosaic of Spill 1 3 hours after release. Scale: 1 mm = 8.4 m



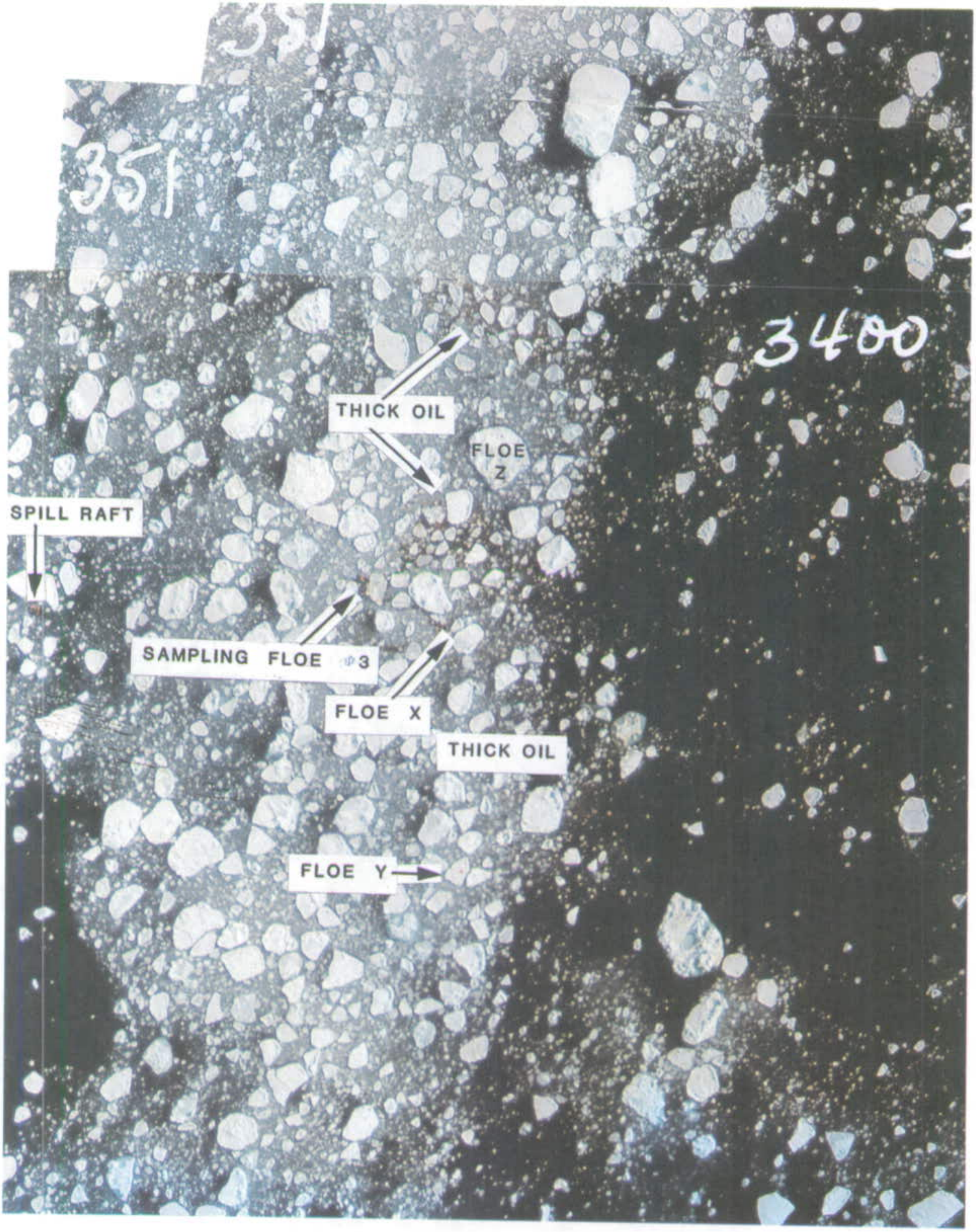


Figure 30 -Blow-up of area near spill raft on Figure 29; Scale: 1 mm = 1.9 m

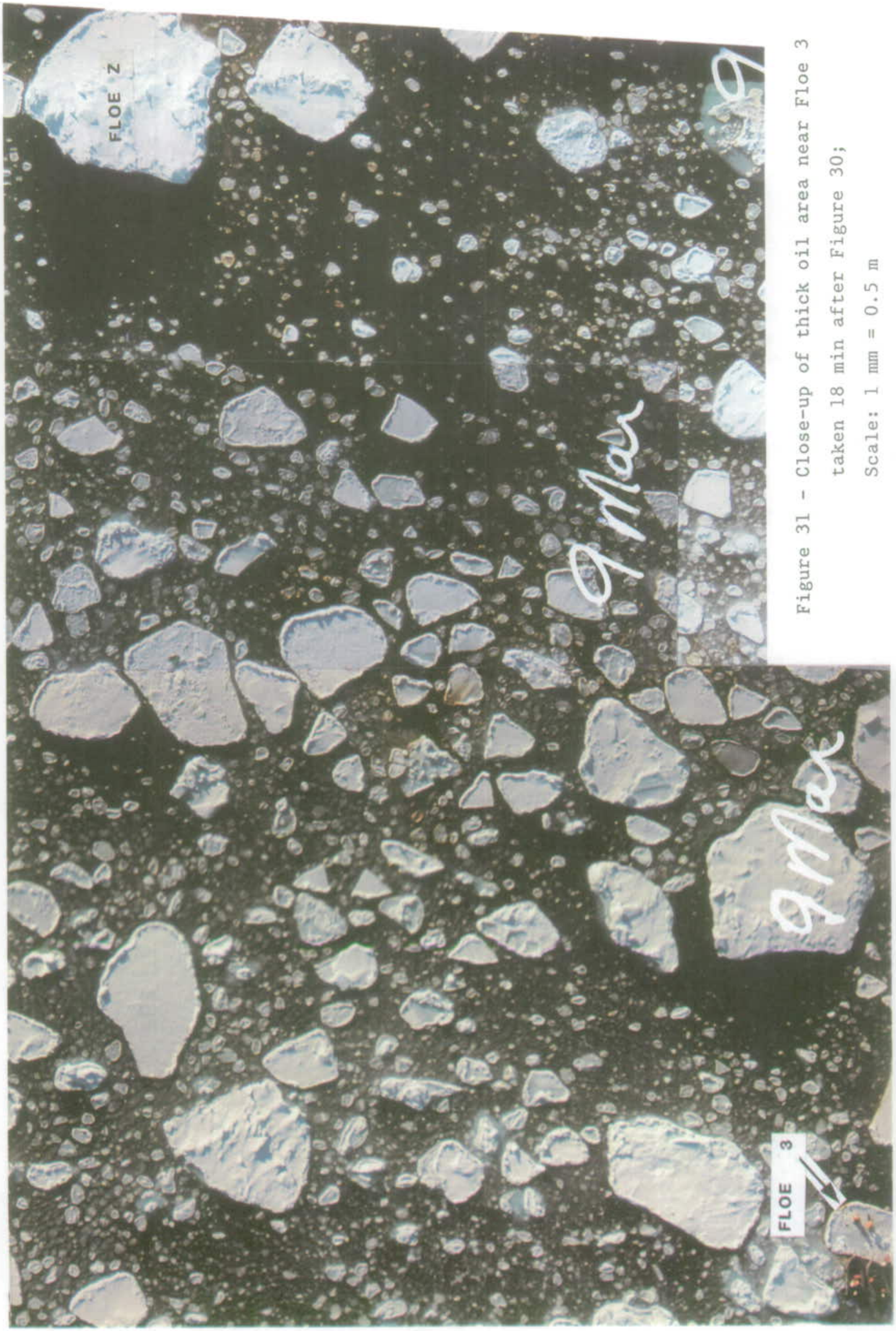


Figure 31 - Close-up of thick oil area near Floe 3 taken 18 min after Figure 30; Scale: 1 mm = 0.5 m

Modelling. In order to model the spread of oil spilled in pack ice, Fay's (1969) equations were modified to account for oil viscosity and ice concentration. The spread of an oil slick on the open sea goes through three phases: gravity-inertia (G-I), gravity-viscous (G-V), and surface tension - viscous (S-V).

The rate of spreading is calculated from:

$$A = 4.1\ (\Delta g V t^2)^{1/2} \quad \text{(for G-I)}$$

$$A = 6.6\ (\Delta g V^2\, t^{3/2} \rho\, /\, \mu^{1/2})^{1/3} \quad \text{(for G-V)}$$

$$A = 16.6\ (\sigma^2 t /\ \rho\ \mu\ )^{1/2} \quad \text{(for S-V)}$$

where: A = spill area (m^2)
Δ = fractional buoyancy of oil
= $(\rho - \rho_o)/\rho$
g = acceleration of gravity (9.81 m/s^2)
V = spill volume (m^3)
t = elapsed time (s)
ρ = density of water (kg/m^3)
ρ_o = density of oil (kg/m^3)
μ = dynamic viscosity of water (Pas)
σ = spreading coefficient (N/m)

S.L. Ross and Energetex (1985) have suggested a viscosity correction factor $(\mu_o/\mu)^{-0.15}$, where u_o is the oil viscosity, for the gravity-viscous regime based on spreading experiments conducted with a range of oil viscosities. It is interesting to note that the power on μ in Fay's gravity-viscous spreading equation is -0.167: it is possible that Fay's equations should contain oil viscosity rather than water viscosity in the energy dissipation term.

In addition to this, it seems reasonable that, because the oil can spread only on water, the area taken up by ice floes should be excluded. This is accounted for by a term $(1-f_I)$, where f_I is the fraction of the sea surface covered by ice. The final spreading rates can then be calculated from:

$$A_{\mu I} = (\mu_o/\mu)^{-0.15} \quad (1-f_I)A$$

The model prediction for the ASMB crude oil spreading in 6/10ths ice at 0°C is shown on Figure 27. The fit to the data is surprisingly good.

Figure 32 shows the slick thickness data collected during Spill 1 compared with the model prediction. Though not as consistent as the fit to the spill area data, the model generally fits the spill thickness data and follows the trends. That the model correlates well with two independent data sets indicates that it is suitable for this application.

One interesting fact is that, even though surface tension spreading dominates the areal coverage of the slick, gravity spreading continues to spread the thicker portions which contain most of the oil.

Spills 2 and 3

The second two spills took place in high ice concentrations and spread much less than did Spill 1 (Figure 27). Spill 2 was released in brash ice 30 - 40 cm thick between two floes, initially spread at 0.3 cm/s over the brash ice, and slowly saturated the brash ice until it reached an equilibrium area after about 15 min (Figure 33a-f).

Spill 3 was released off the edge of a floe just after the ship had passed by the floe edge (Figure 34a). The effect of the ship's passing was to clear the surrounding brash ice immediately prior to the spill. Initially the oil spread more rapidly than that of Spill 2 (Figure 27) but, as the

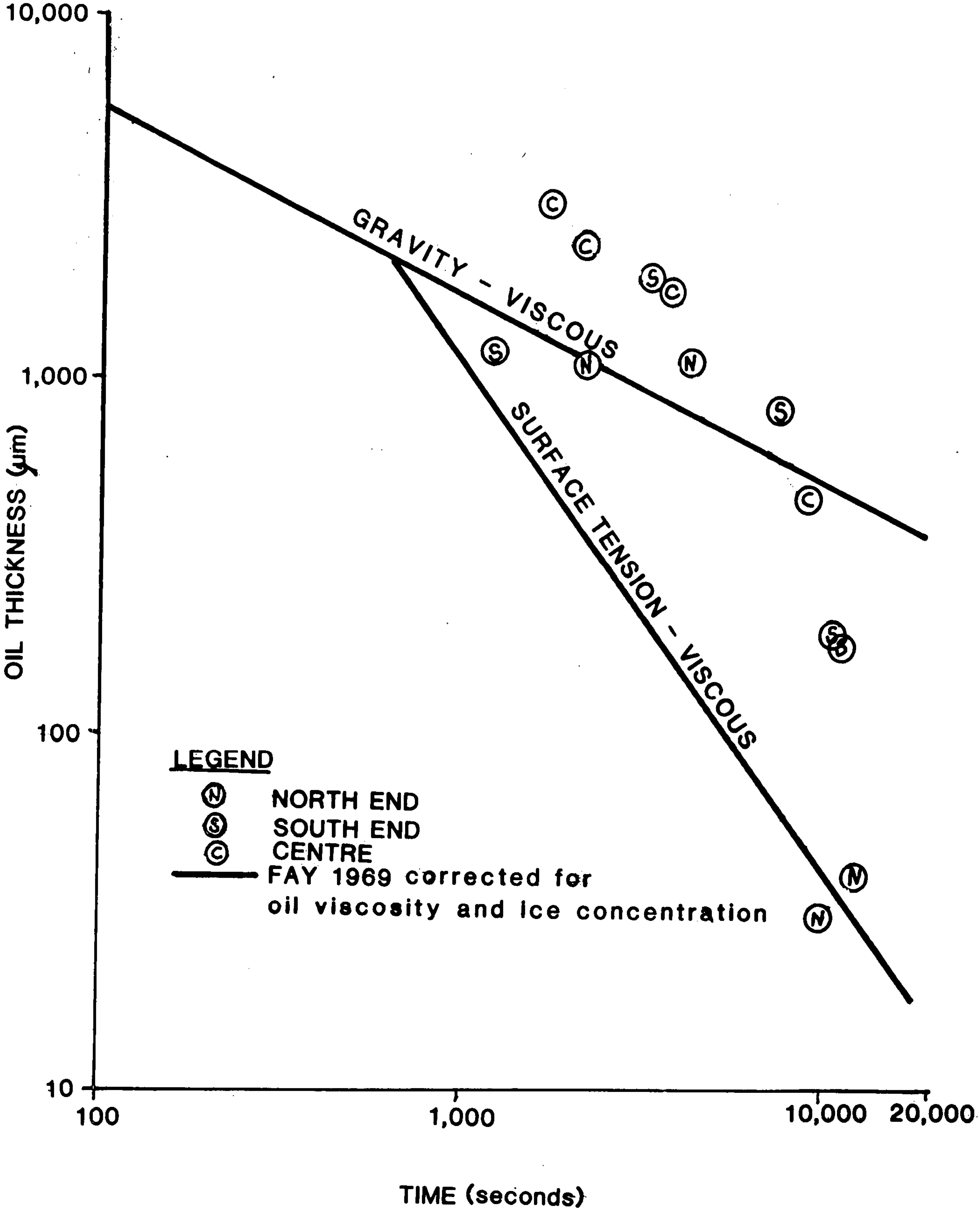
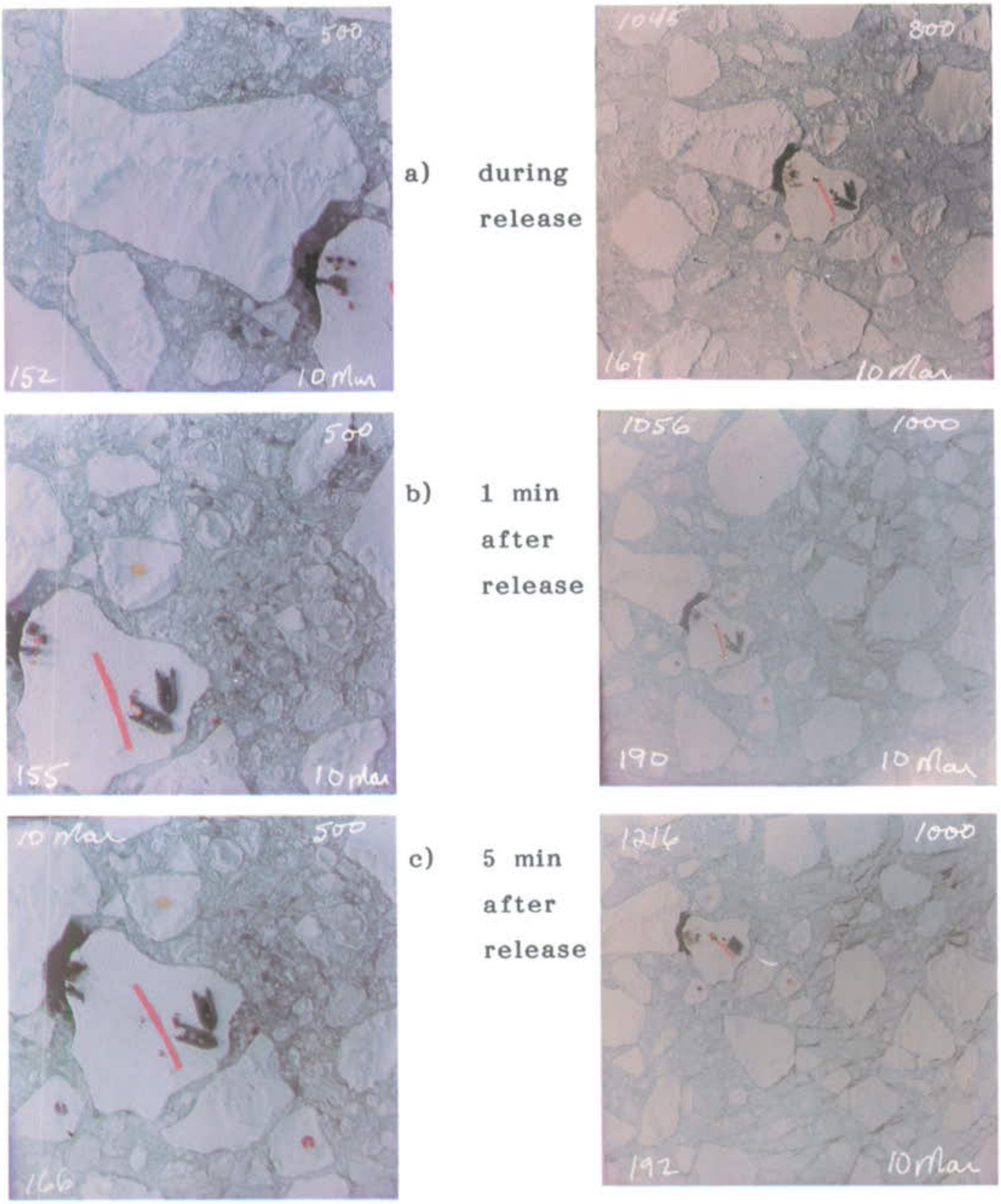


FIGURE 32 - THICKNESS OF SPILL 1 vs. TIME



a) during release

b) 1 min after release

c) 5 min after release

d) 14 min after

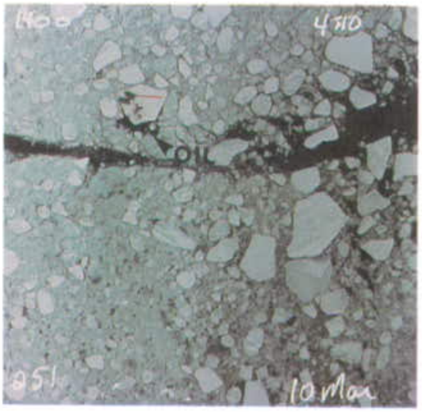
e) 25 min after release

f) 1 h: 45 min after release

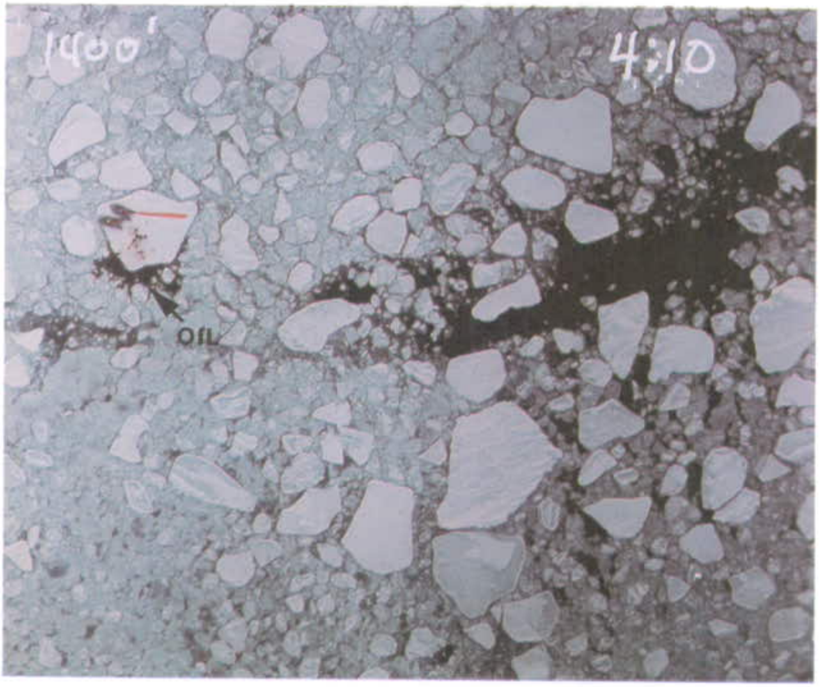
Scale: nylon strip = 10 m

Figure 33 - Aerial photographs showing spreading of Spill 2.

a) during release



b) 15 min after release (note proximity of ship's track)



c) 15 min after release (note ship's track closed with no effect on oil)

Scale: nylon strip is 10 m long

Figure 34 - Aerial photographs of Spill 3 oil spreading

ship's track closed rapidly (in about a minute), the oil soon reached an equilibrium area as in Spill 2. Repeated passes of the ship near the oiled ice did not result in the oil spreading further (Figure 34b - c).

Modelling. Oil spilled in brash ice in quiescent conditions seems to spread to an equilibrium area that is independent of the concentration of ice floes nearby. Kawamura et al. (1986) have developed an equation to predict the final area (A_f)of a spill in snow:

$$\frac{A_f}{V^{2/3}} = \frac{0.45 \; V^{0.2} \; d^{0.2} \; \rho_o^{\;0.8675} \; g^{0.4125} \; \mu_o^{\;0.05}}{(\varphi \; \rho_s)^{0.48} \; \sigma^{0.4375}}$$

where: d = snow depth (m)

φ = snow crystal factor

= 1.0 for crystalline snow

= 0.1 for spherical snow

ρ_o = oil density (kg/m^3)

ρ_s = snow density (kg/m^3)

σ = surface tension of spilled substance (N/m)

V = spill volume (m^3)

μ_o = oil viscosity (Pas)

g = acceleration of gravity (m/s^2)

Substituting $d = 0.05$ m (the freeboard of the brash ice), the properties of the crude oil at 0°C, and $\rho_s = 800$ kg/m^3 yields a final area of 38 m^2, very close to the final observed areas of 36 and 35 m^2 for Spills 2 and 3, respectively. An equation to estimate a time constant (the time to reach 63% of the final area) for a spreading rate relationship was also proposed by Kawamura et al (1986). Substitution of the oil and brash ice properties into the equation yields a value of 1.4×10^5 s for the time constant, which is several orders of magnitude greater than the observed value of about 400 s. It seems that oil in brash ice spreads according to the modified Fay equation until it saturates the brash ice above the water surface, then ceases spreading, resulting in a final area as predicted by

Kawamura et al. (1986).

OIL DRIFT

Table 3 lists the measured drift speed and direction for the centre of each of the three releases. Also shown is the range of average wind speeds and directions, measured at a 10 m height above sea level.

As discussed previously, in general there was very little relative oil/ice motion on a large scale, even in the open ice conditions of Spill 1. The thick oil in Spill 1 stayed in the vicinity of the floes amongst which it was first released, even though the pack ice overall drifted some 5.5 km over the course of the experiment.

Figure 35 compares the measured drift with a prediction based on the vector sum of 3% of the 10 m wind speed (including a 10 degree clockwise Coriolis effect) and the residual surface currents (10 cm/s, C-CORE 1980) for the area of the spills. Taking into account the error inherent in the LORAN-C position fixes, the variations in wind speed and direction, and the uncertainty about the value of the residual currents, the correlation between measured and predicted trajectories is quite reasonable.

Also shown on Figure 35 is the predicted trajectory of Spill 1 using the residual current as determined from readings taken through a core hole in a floe at the site. The measured residual current is stronger than the historical residual current (30 versus 10 cm/s) and sets slightly further south. The predicted slick drift based on the measured current is directionally more accurate than that based on the historical current; the distance errors are equal. No currents were measured at the sites of Spills 2 and 3 because of equipment problems.

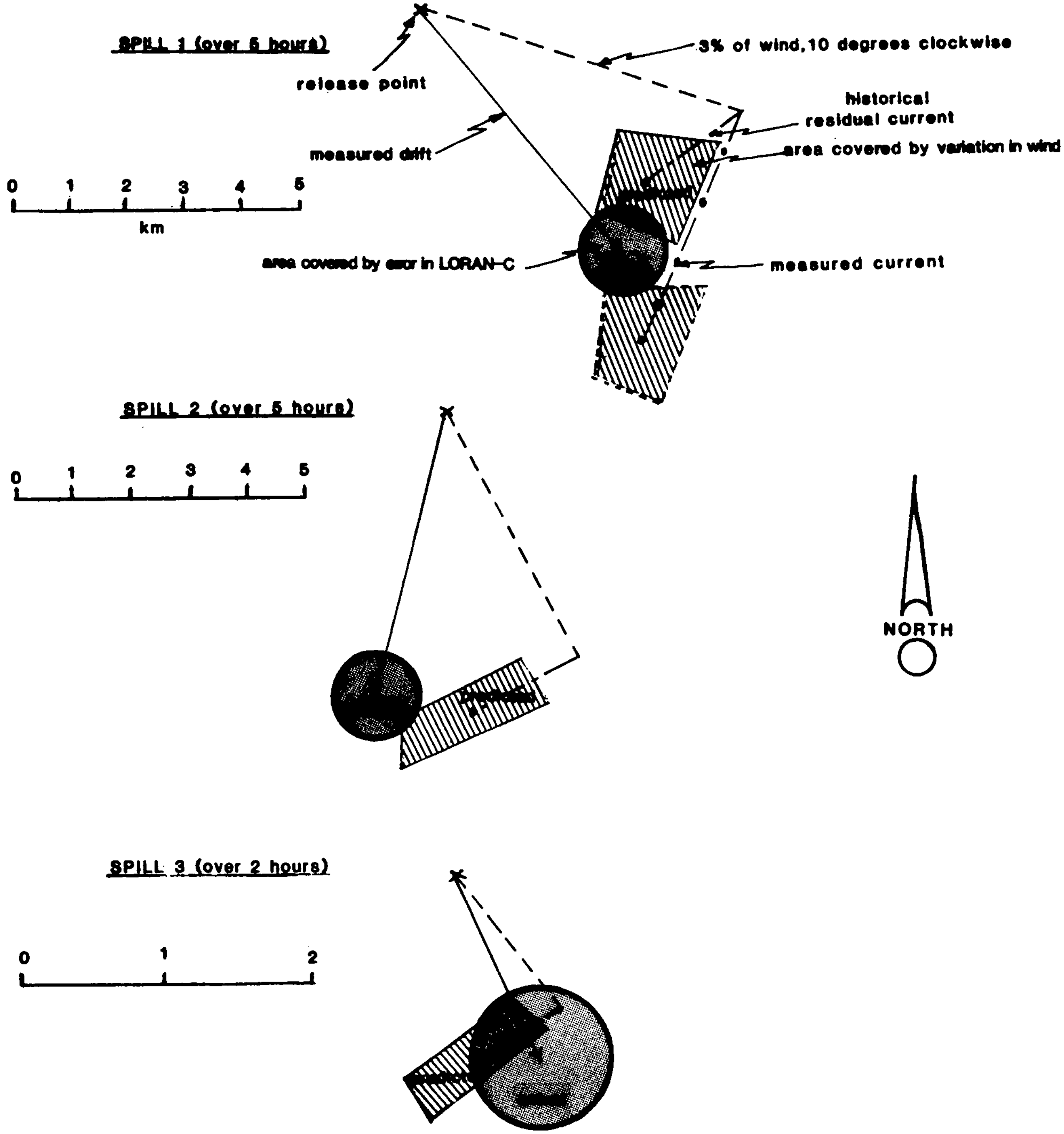


FIGURE 35- COMPARISON OF ACTUAL AND PREDICTED OIL DRIFT

OIL/ICE INTERACTIONS

Spill 1

In the absence of any wave action (as opposed to swell), there was very limited opportunity for any oil to be deposited on top of the floes or pancakes. Figure 36 shows an exceptional situation where a small pancake was coated in oil, possibly after being squeezed between two larger floes, and as a result being upended while in a heavily oiled slush area. Figure 37 shows an area of lightly oiled slush and brash being slowly compressed between two floes. Figure 38 shows a broader view of oiled slush and brash ice residing between relatively uncontaminated pancakes soon after oil release. The raised edges of the pancakes have likely been smeared with oiled slush during periods of ice convergence. Heavier concentrations of oiled ice are shown in Figure 39, taken 2 h after oil release. The ice pancakes in the midst of the heaviest oiling still remain virtually uncontaminated (see also Figure 31). Some oil was deposited around the rims of the larger floes as they pitched while riding the swell. Two cores taken within 15 cm of the floe edge contained oil drops that had migrated up from the bottom of the ice, in one case by as much as 25 cm (at 1630, 4 h post-spill). The ice thickness in the region of the floe edge was 50 cm. Figure 40 shows a close-up view of the end of one of the oiled cores showing oil drops within the core.

Spill 2

Unlike Spill 1, where the spilled oil quickly warmed to within 0.5°C of the water/slush temperature (-1.6°C), the oil in Spill 2 lay on top of the compressed slush and remained at a depressed temperature of -4°C for over an hour after release. In Spill 2, the oil spread between the two bordering floes on top of the slush layer, at about 20 cm/min for the first 10 minutes, after which time the rate slowed dramatically. Over the following hour, the total extent of spreading was less than 30 cm. Figures 41 and 42 show one of the leading edges of the oil advancing slowly along the slush-filled "lead."

Figure 36 - Surface view showing small pancake coated in oil alongside Floe 2 at 1505. MV Brandal is visible on the horizon. Note the long period swell visible in the background.

Figure 37 - Close-up view of oiled slush and brash ice being squeezed between two first-year floes. Part of an ice pancake is visible to the right.

Figure 38 - View of oiled slush and brash adjacent to Floe 1 at 1300. Note that the interiors of the pancakes with raised edges remain unoiled.

Figure 39 - General view of oiled ice area 2 h after release. Note swell clearly apparent on horizon.

Figure 40 - Close-up view of ice core showing oil drops contained in bottom 25-cm section

Figure 41 - Oil on top of slush and brash ice between the two floes in the lower left and upper right corners of the photograph. Picture taken within 20 min of oil release

Figure 42 - Close-up view of above

Spill 3

As was the case with Spill 2, the slush and brash effectively contained the oil from Spill 3 and prevented any significant spreading from the source. Figure 43 is a shipboard view of the oiled area prior to burning. The photograph shows the base floe surrounded by compressed pack ice. This condition developed very quickly between the time of the decision being made to deploy the oil and equipment and the time actually taken to sling the gear over the ship's side.

OIL WEATHERING

Evaporation

Figure 44 shows the measured evaporative loss (see also Appendix 4) for the sorbent and grab samples plotted against evaporative exposure. Evaporative exposure is a dimensionless number that contains time, slick volume divided by area (i.e., thickness), and an air-side mass transfer coefficient (Stiver and Mackay 1983). These are related by:

$$\theta = \frac{K\ At}{V_o} = \frac{kt}{x}$$

where: θ = evaporative exposure
K = mass transfer coefficient (m/s)
= $0.002\ U^{0.78}$
U = wind speed at 10 m (m/s)
x = slick thickness (m)

This definition of θ involves an integration with the assumption that A (or x) is constant in time. A more rigorous expression for θ should include the fact that the oil is constantly spreading and thinning. This is dealt with by Mackay et al. (1983), who used the above expression for θ in a finite difference equation in which A (or x) changes with time.

Figure 43 - Shipboard view of Spill 3 showing limited extent of oil spreading and compressed pack condition.

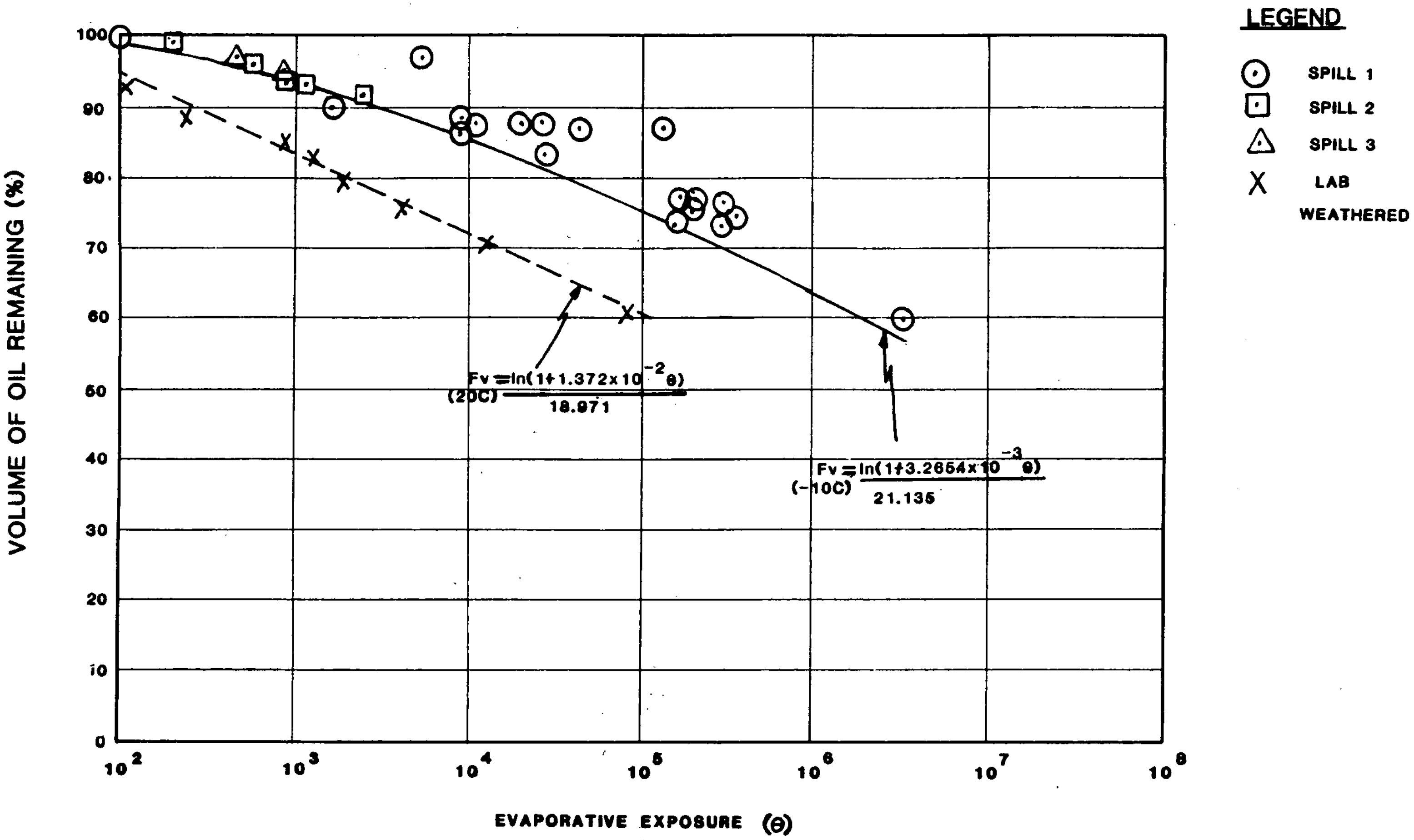


FIGURE 44 - EVAPORATIVE LOSS

For the purposes of this study, it is necessary to reintegrate the equation, including the modified Fay spreading equation presented earlier, resulting in:

$$\theta = \frac{16kt^{3/2}}{1.5V_o} \quad \text{(for G-V)}$$

$$\theta = \frac{3 \times 10^{-2}\ k\ t^{5/2}}{2.5V_o} \quad \text{(for S-V)}$$

The values of θ for each sample were calculated using the above equations and plotted on Figure 44.

Also shown on Figure 44 is the data obtained from gas stripping (Stiver and Mackay 1983) a sample of the oil in the lab at 20°C (see Appendix 5) and the prediction of a model, based on a modified ASTM distillation procedure (Stiver and Mackay 1983; see Appendix 5), for both data sets. Considering the differences between the two data sources -one is a laboratory weathering experiment with controlled slick thickness and the other is slicks at sea that ranged in thickness from 30 µm to 5 cm -the fit of the model is quite satisfactory.

Physical Property Changes

Figure 45 shows the change in density of grab samples of the crude oil as a function of percentage volume loss to evaporation for all three spills. The density of the oil in Spills 2 and 3 changed little because the oil was thick and sampling took place over only 2 h.

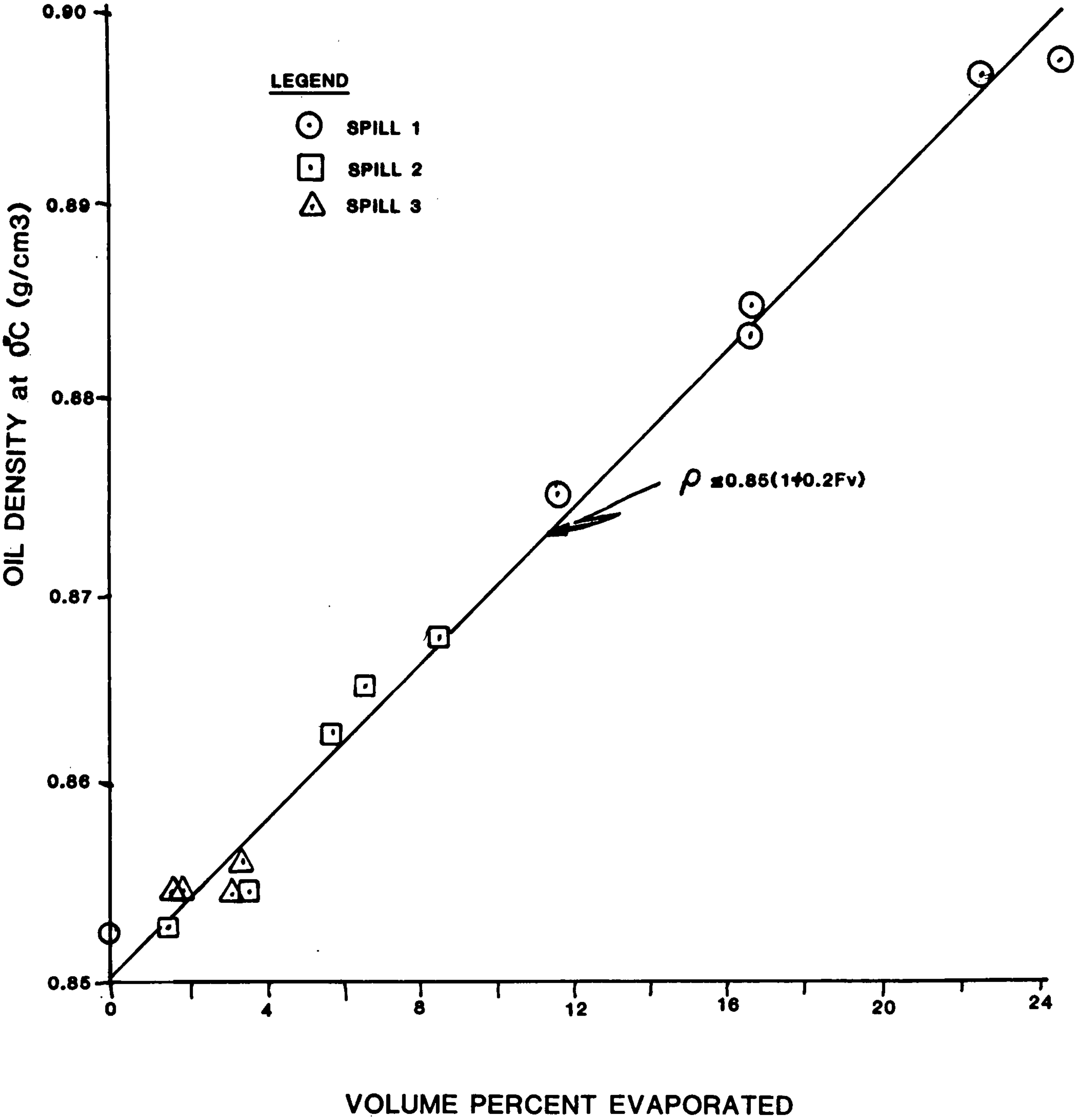


FIGURE 45 - DENSITY vs. EVAPORATION

The fit of the data to a model proposed by Mackay et al (1983) is almost perfect.

Figure 46 shows the increase in oil viscosity for the same sample set. Again, because of thickness and short sampling time, the oil from Spills 2 and 3 underwent little change. The fit of the data to a model similar to one proposed by Mackay et al. (1983) is excellent.

Compositional Changes

Figure 47 compares gas chromatographs of the fresh oil, as sampled from a drum prior to Spill 1, with that of the last grab sample taken in Spill 1 (taken from oiled slush near the middle of the slick; see Figure 29). Comparison shows that, over the 3 h and 22 min exposure time, the oil lost virtually all the components with vapour pressures less than that of nonane (C_9H_{20}). Figure 48 shows the gas chromatographs for the first and last slick thickness samples taken from Spill 1. These chromatographs are different from those of the grab samples as the thickness sample sorbents were kept in hexane to minimize loss of light ends during storage; this results in dilution of the oil sample. Sample 1 came from a 1.2-mm-thick area, near the spill centre, 20 min ($\theta = 5.8 \times 10^3$) after the oil release. It shows a 10% volume loss to evaporation. Sample 13 came from a 40-um-thick sheen, northeast of the slick centre, 3 h and 20 min ($\theta = 2.5 \times 10^6$) after the oil release. It shows a 40+% volume loss to evaporation with all compounds with vapour pressures less than that of undecane ($C_{11}H_{24}$) absent.

Samples from Spills 2 and 3 did not weather significantly over the time period of the experiments because of their thickness (3 - 5 cm).

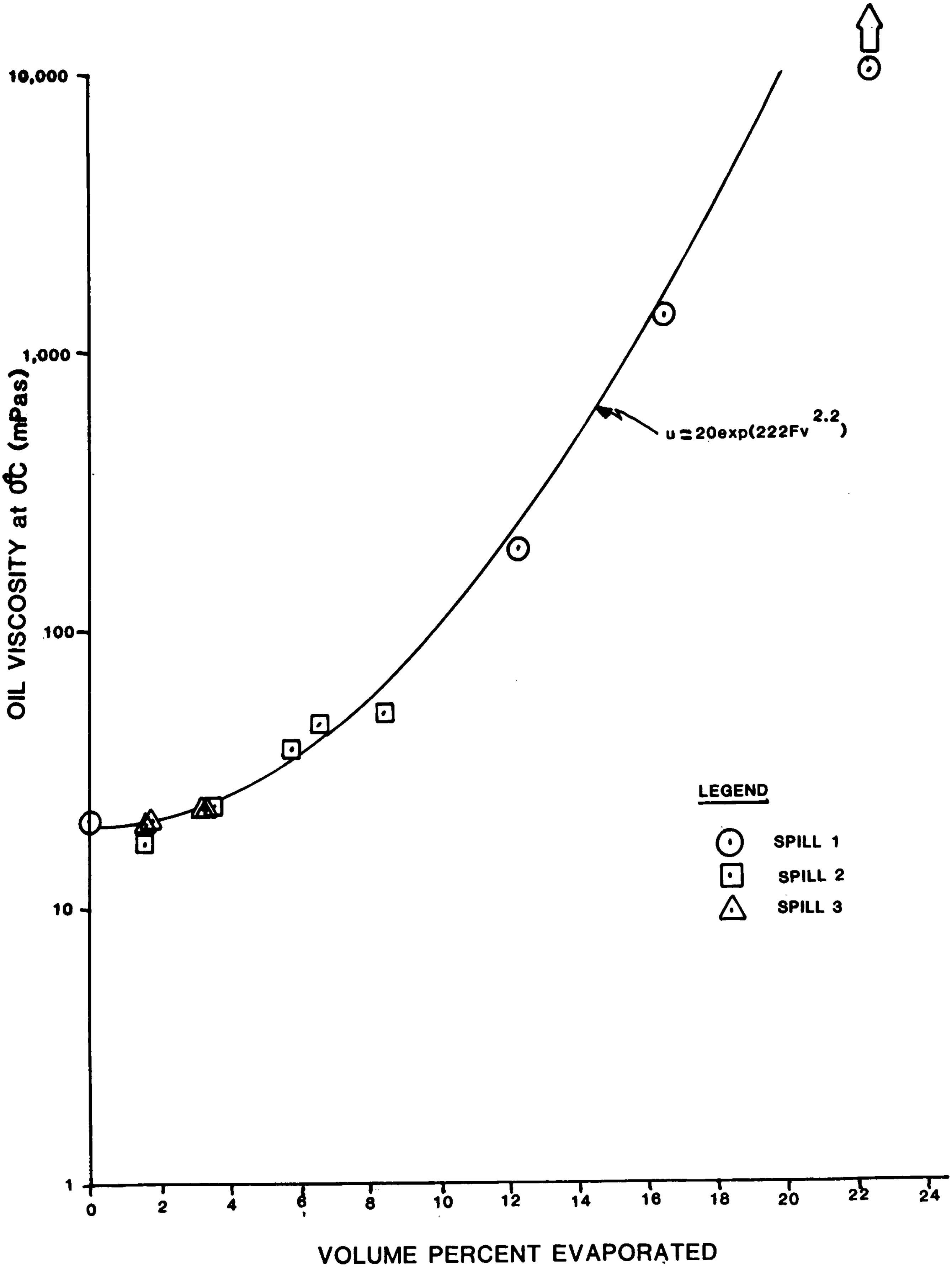
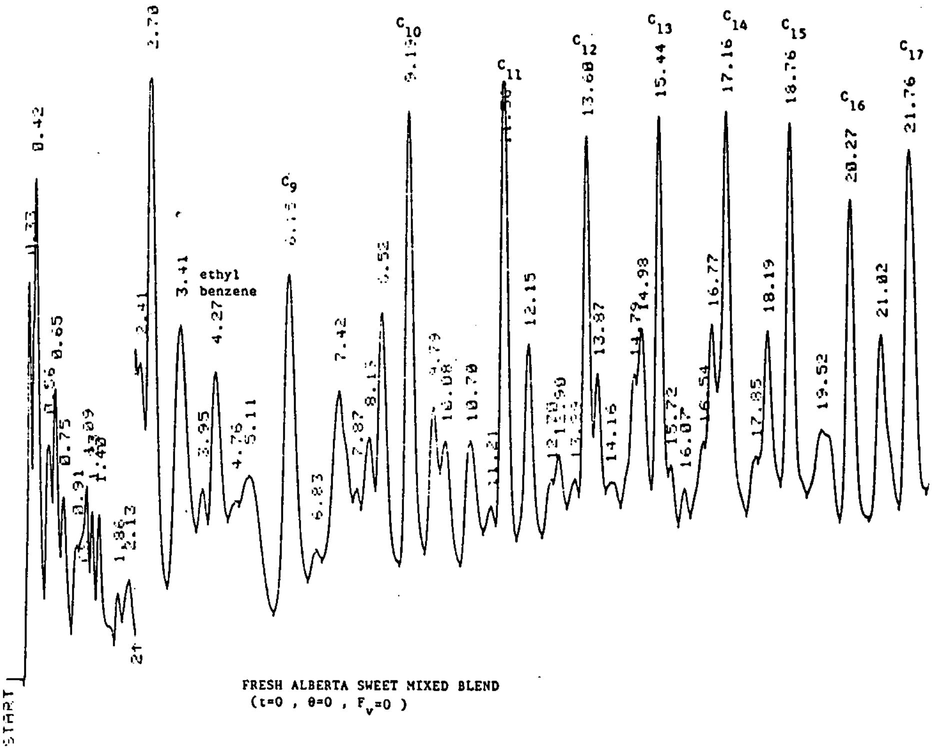
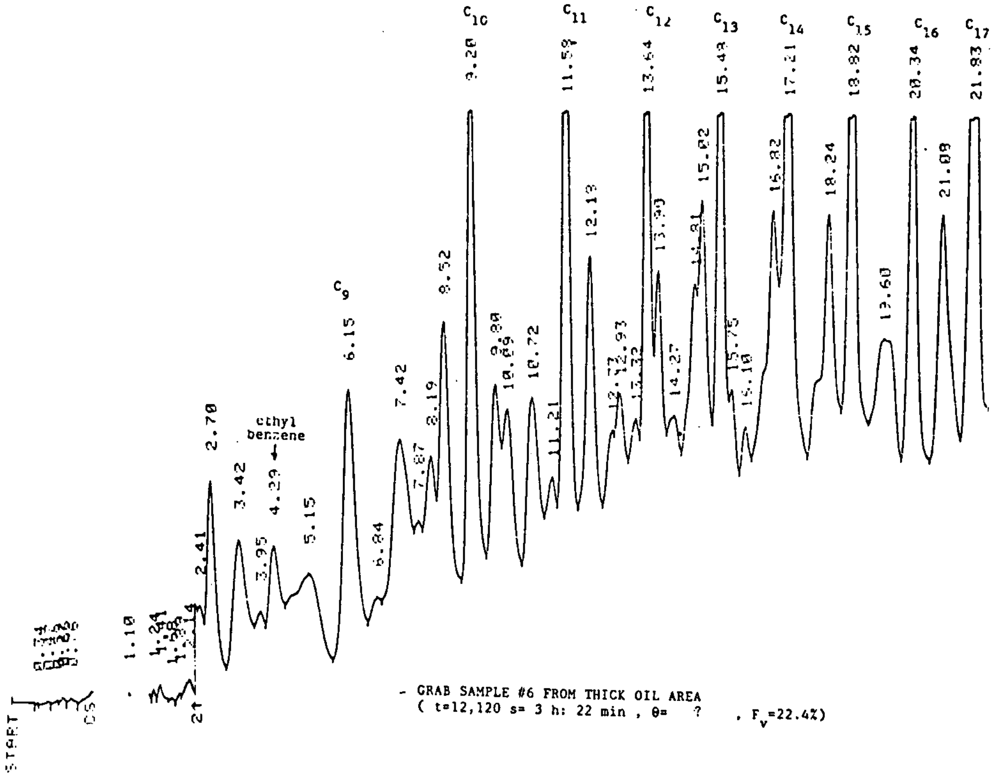


FIGURE 46 VISCOSITY vs EVAPORATION

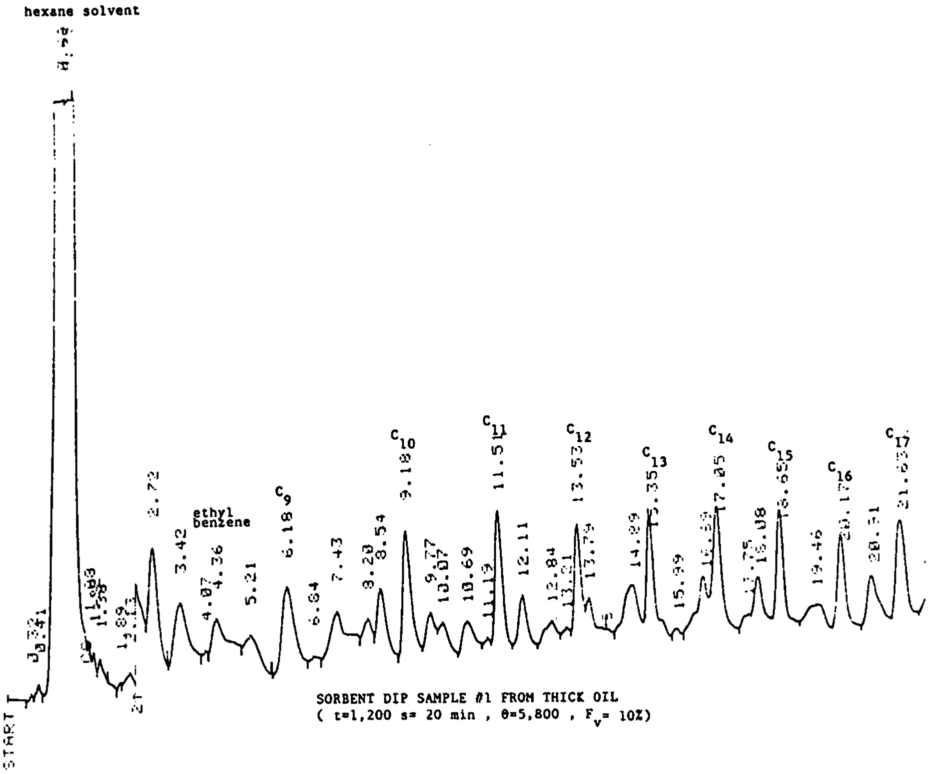


FRESH ALBERTA SWEET MIXED BLEND
(t=0 , θ=0 , F_v=0)

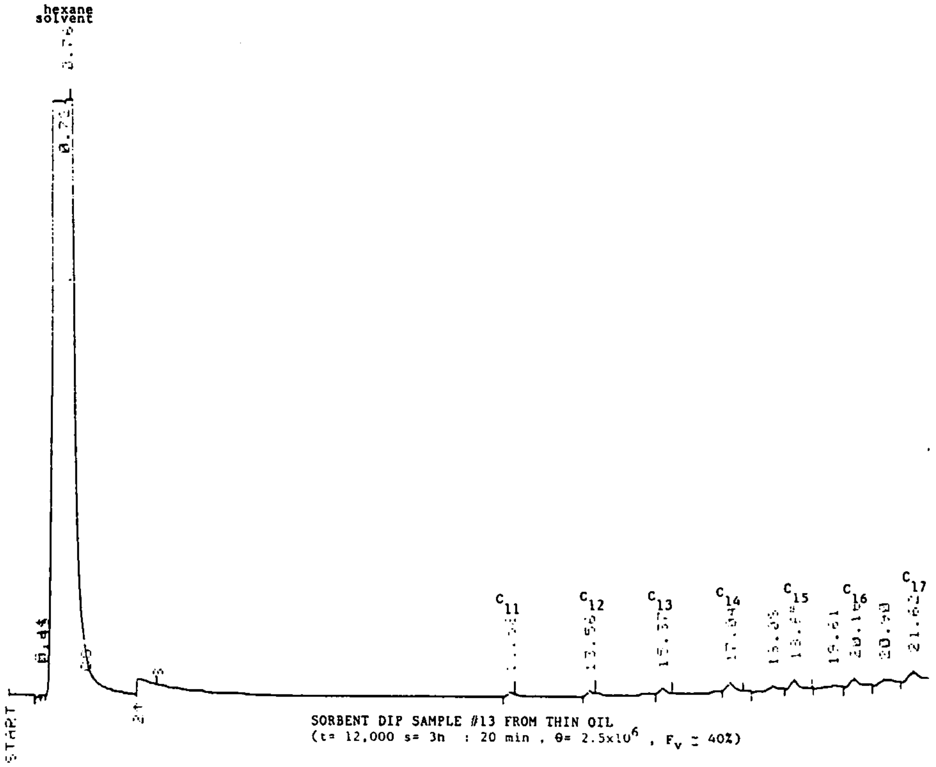


- GRAB SAMPLE #6 FROM THICK OIL AREA
(t=12,120 s= 3 h: 22 min , θ= ? , F_v=22.4%)

Figure 47 - Comparison of thick oil from Spill 1 after 3 hours 22 minutes with fresh oil.



SORBENT DIP SAMPLE #1 FROM THICK OIL
(t=1,200 s= 20 min , θ=5,800 , F_v= 10%)



SORBENT DIP SAMPLE #13 FROM THIN OIL
(t= 12,000 s= 3h : 20 min , θ= 2.5x10^6 , F_v ≍ 40%)

Figure 48 - Comparison of oil from sorbent pad samples taken 20 minutes and 3 hours 20 minutes after release

Emulsification and Dispersion

Only during Spill 1 were conditions such that the processes of water-in-oil emulsion formation (emulsification) and natural dispersion could be expected.

Emulsification. Despite the energetic conditions (3-4 m swell, 35-45 km/h winds) and the fact that the crude oil is known to be susceptible to forming stable emulsions at cold temperatures (S.L. Ross 1986; Bobra and Chung 1986), no evidence of emulsification was found, either visually or analytically. Mixing of oil into brash ice occurred throughout the test site; however, these separated quickly once the samples were placed in a funnel. This phenomenon could not be considered to be emulsification.

It is possible that, despite the energetic conditions, the presence of ice floes and brash ice effectively damped out the spectrum of energy required to emulsify oil; certainly no wind waves or breaking waves were observed at the site despite the high wind speeds measured. Though there was significant relative motion and bumping between floes it seems that this type of motion does not emulsify oil.

Natural Dispersion. Though no water samples were taken, evidence of some dispersion of the oil was obtained in the form of underwater video (Figure 49) and cores taken through a floe. Visually, the entrained drops were large (1-3 mm) and seemed to be created periodically by the rocking action of the floe as it passed over a wave crest. The dispersed drops were then swept beneath the ice by the prevailing currents, following which they rose to the underside of the ice. From there they worked their way up into the soft, porous under-ice surface. Cores taken near the floe edge contained oil droplets up to 3 mm in diameter that had migrated 25 cm up through the ice floe. The concentration of oil in these cores was 110 - 120 mg/L, equivalent to an coverage of about 0.15 L/m^2 or a slick thickness of 150 um. The distance inward from the edge of the floe that this oiling extended was not determined. Calculations, based on the rise

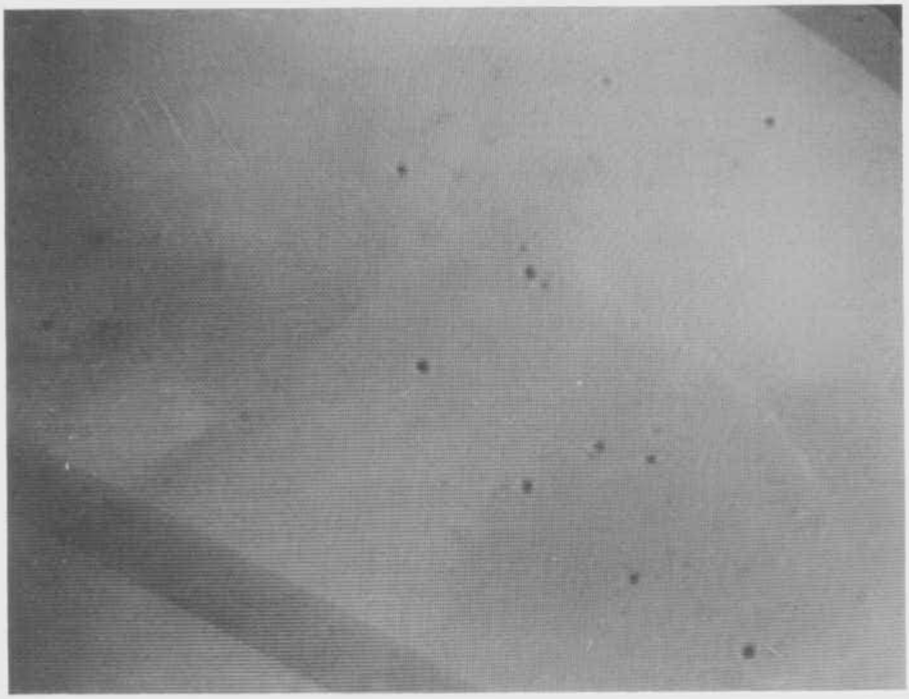


Figure 49 - Underwater video of dispersed oil droplets

velocity of a 1-mm oil drop in a current of 0.3 m/s from a depth of 0.3 m, indicate that it is unlikely that the contamination extends more than 1 or 2 metres inward from the floe edge.

Overall, very little natural dispersion occurred in Spill 1, and that which did occur involved temporary dispersion of large droplets which collected at under-ice surfaces. In similarly energetic sea conditions in open water such a spill of this oil should rapidly disperse naturally, with a half-life of only a few hours (S.L. Ross 1985). The presence of pack ice dramatically damps wind waves, removing the type of turbulent energy required for high rates of natural dispersion.

COUNTERMEASURES

Remote Sensing and Tracking

Of the sensors used from the helicopter, the best for seeing oil in pack ice were the colour aerial photographs, colour video, and, for very thick oil, infra-red video. The L^3TV could not distinguish between oil and water, and the black & white ultraviolet photos did not show the sheen (perhaps because they were taken looking directly down rather than at an angle). Without directions from the surface, it was extremely difficult to see the oil in Spill 1 from the air or from the ship from any substantial distance.

Two Orion tracker buoys were released, one at the site of Spill 1 and one at Spill 2. Despite the fact that both buoys had been tested on land just prior to the experiments, neither could be picked up by the receivers located on the ship and the helicopter.

Recovery

Though an oleophilic disc skimmer was carried on board the ship, it was never deployed. The oil from Spill 1 was considered to be too thin and widespread for recovery, and the ice concentrations precluded booming to concentrate it (Figure 50). The suggested use (S.L. Ross 1983) of barge-mounted rope mop skimmers would not have been effective because the areas where the thicker oil existed were choked with brash ice (Figure 51). The oil from Spills 2 and 3 was certainly thick enough for recovery, but it was considered easier to burn off the oil and then recover the residue manually. In any case, an oleophilic disc skimmer was not an appropriate recovery device. The thick oil in Spills 2 and 3 was intimately mixed with, and floating on, brash ice (Figure 52). Based on observations of the oil, the only suitable recovery devices would be vacuum systems or direct pumping of the oil and brash ice. It would be necessary to manoeuvre the suction quite accurately around ice chunks, as these would quickly clog pump intakes. Another possibility would be the recovery of the entire oil/ice mixture using dredging buckets or backhoes mounted on a ship's deck, although this would be feasible only for small spills.

In-Situ Burning

As the oil from Spills 2 and 3 was thick and concentrated, it was decided to burn the oil (Figures 53 and 54). This was accomplished by igniting the slick with a burning, oil-soaked sorbent pad. The residue from the burning of Spill 2 was easily recovered using shovels and sorbent pads. Burn times and areas were recorded to calculate the volume of oil consumed (Table 7). A slick regression rate of 2 mm/min was used in these calculations (S.L. Ross and Energetex 1985).

The smoke plume from the burns dispersed rapidly downwind (Figure 55). The soot fall-out from Spill 2 covered an area of about 120 m^2 extending 10 m downwind (Figure 56). Samples of the fresh oil, burn residue, and soot were analyzed for polycyclic aromatic hydrocarbons (PAH's) by the Analytical Services Division of the Environmental Protection Service. The results are shown in Table 8. Though the concentrations of some compounds do vary, overall the levels of PAH's in the residue and soot are not significantly different from those in the fresh crude oil.

Figure 50 - Oil from Spill 1 after three hours (near centre)

Figure 51 - Thick oil near spill centre

Figure 52 - Oil from Spill 3 containing ice

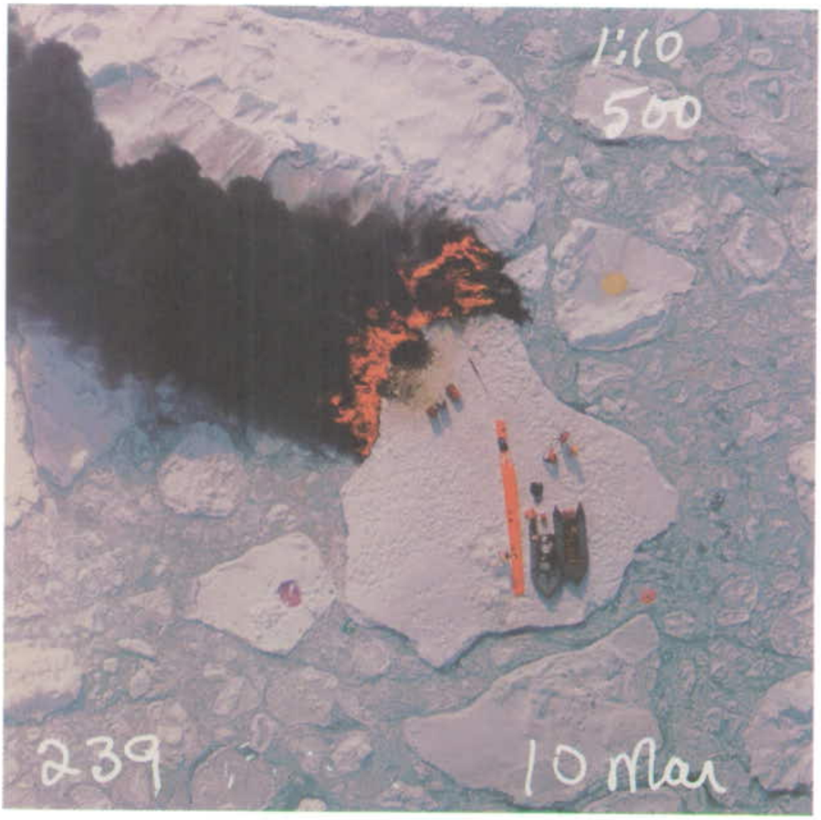


Figure 53 - Aerial photograph of Spill 2 burning

Figure 54 - Burning Spill 3

TABLE 7

Insitu combustion data

	Spill 2	Spill 3
Ignition time(s)	30	45
Burn time (min: s)	15:30	37:15
Max. Burn Area (m^2)	30	17
Volume of oil consumed (L)	930	800
Removal Efficiency (%)	93	80

Figure 55 - Smoke plume during burning of Spill 2

Figure 56 - Soot deposition from burning of Spill 2

TABLE 8

PAH results uncorrected for recovery (ug/g)

SAMPLE	FRESH CRUDE OIL	BURN RESIDUE, Spill 2	BURN SOOT, Spill 2	BURN RESIDUE, Spill 3
SAMPLE SIZE,g	0.225	0.275	0.051	0.224
PAH*				
Acenaphthylene	8.8	17.6	40.8	49.2
Acenaphthene	9.4	--	--	6.9
Fluorene	65.0	15.8	17.2	38.5
Me-Fluorene	97.3	11.3	--	97.1
Phenanthrene	82.0	34.7	59.0	86.9
Anthracene	80.0	3.7	12.0	--
Fluoranthene	7.9	13.7	40.2	24.9
Pyrene	14.8	21.7	56.1	37.7
B(a)Fluorene	17.1	14.3	20.8	22.8
B(b)Fluorene	10.7	10.2	14.1	14.7
Me-Pyrene	18.7	16.6	15.3	4.6
B(qhi)F	--	1.6	16.3	6.0
B(b)A	--	--	24.1	39.5
Chry+Trip	18.5	14.8	17.4	3.7
Me-B(a)A	--	--	--	35.9
B(b)F+B(k)F	3.1	4.5	26.9	14.4
B(e)P	--	4.5	19.0	1.8
B(a)P	4.8	1.4	8.0	17.9
O-Phen-P	--	1.4	19.9	--
B(qhi)P	1.4	2.6	14.9	--
Anthanthrene	--	--	--	5.5
TOTAL PAH (ng/g)	439.5	190.4	422	508

Abbreviations used: A = Anthracene; B = benzo; Chry = chrysene; F = Fluorene; P = pyrene; Phen = phenanthrene; Me = methyl; Trip = triphenylene

NOTE:"--" DENOTES VALUE BELOW 0.1 ug/g (0.01 ng/ul/COMPOUND/SAMPLE)

Applicability of Dispersants

Dispersants may have been effective on the areas of thin oil in Spill 1; however, it is unlikely that they would have worked on the thicker oil in brash ice. Despite the swell running at the time, the mixing energy was observed to be low. The fact that much of the thick oil was mixed with brash ice and the likelihood that conventional dispersants would dissolve in the water before having a chance to act on the oil suggest that dispersants would have been ineffective. Perhaps the addition of long-lasting, more oleophilic dispersants that stay with the oil for days would be more suitable. In any case, the application of dispersants to oil in dynamic pack ice should be the subject of future field trials.

CONCLUSIONS

1) The spreading of oil in pack ice is dramatically reduced, compared with that in open water, by the presence of ice forms; simple correction factors to Fay's (1969) equations to account for oil viscosity and ice concentration seem to be adequate to predict oil spreading in pack ice in the absence of thick brash ice. High concentrations of brash ice, regardless of the concentration of larger ice forms, stop oil from spreading. The final area of oil spreading in brash ice is well predicted by the equation proposed by Kawamura et al (1986).

2) Over the time periods of the experiments, the data indicate that, in general, oil in pack ice does not drift relative to the surrounding floes. As a rough approximation, the oil and ice floes drift according to the vector sum of 3% of the wind speed at 10 m, including a 10-degree clockwise Coriolis rotation, and the residual current.

3) Evaporation and subsequent oil property changes can be adequately predicted, for oil spilled in pack ice, using the evaporative exposure approach of Stiver and Mackay (1983) and the predictive equations of Mackay et al. (1983).

4) Despite the fact that the crude oil is known to emulsify in cold water at low sea states, no evidence of emulsification was found, despite the large swell running during Spill 1.

5) Though evidence of natural dispersion was found, the observed oil droplets were large and rapidly rose to collect on under-ice surfaces. Natural dispersion does not seem to play as important a role in determining the fate of an oil spill in pack ice as it does in open water.

6) During the most dynamic of the three spills of this study, oiling of

floes occurred principally through compression of oiled slush and brash between thicker floes and pancakes. This process resulted in smearing and deposition of oiled ice around the raised edges characteristic of floes in a marginal ice zone. There was very little opportunity for oil transport into the interior surface of floes. This situation could change if the volume of slush and brash were substantially reduced, thereby introducing the potential for wind driven spray between floes in an open pack situation. Individual floes could then also impact directly without the slush "buffer" present during this study.

7) No evidence of lead pumping of oil was observed, despite the dynamic conditions during one of the experimental spills.

8) In-situ burning proved to be an effective technique for removing oil spilled in high concentrations of brash ice; no other countermeasures technique seemed feasible for brash ice or medium concentration pack ice.

RECOMMENDATIONS

Based on the results of these preliminary, small-scale field experiments, larger-scale field experiments should be undertaken to:

- investigate more fully the spreading of oil in loose pack ice and pack ice with lower brash and slush ice concentrations (i.e., in warmer, springtime conditions);
- determine natural dispersion and emulsification rates for oil spilled in dynamic pack-ice situations;
- investigate the potential for chemical countermeasures for oil spilled in dynamic pack ice;
- test additional remote sensing technologies to detect and map oil in pack ice.

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APPENDICES

APPENDIX I - OCEAN DUMPING PERMIT

Environment Canada   Environnement Canada

Environmental Protection Service
3rd Floor, Queen Square
45 Alderney Drive
Dartmouth, N.S., B2Y 2N6

November 25, 1985

Mr. S. L. Ross
President
S. L. Ross Environmental
Research Ltd.
346 Frank Street
Ottawa, Ontario
K2P 0Y1

Your file   Votre référence

Our file   Notre référence

4543-2-01898

Dear Sir:

RE: OCEAN DUMPING CONTROL ACT
PERMIT FOR: MULGRAVE (OIL SPILL TEST), GUYSBOROUGH CO., N.S.
(#01898)

We enclose Ocean Dumping Permit No. 4543-2-01898 to cover the dumping operation you propose to carry out at the above location.

This was published in a regular edition of The Canada Gazette on November 23, 1985 and is valid from February 1, 1986 to April 30, 1986.

The terms and conditions of this permit stipulate that the Permittee shall provide the Regional Director, Environmental Protection Service, Atlantic Region, with a tentative schedule for the experimental discharge at least seven days prior to the start of this operation. This schedule shall be confirmed or revised by telex or telephone at least 24 hours prior to commencing the experiment. The Permittee shall advise the Fisheries Environmental Coordination Office (902-426-3929), Department of Fisheries and Oceans, at least 48 hours prior to commencement of the experiment regarding the exact coordinates of any proposed oil release.

The approval of this Permit does not obviate the need for you to comply with all other Acts and Regulations which may pertain to the proposed operations.

Please advise this office when the proposed operation concludes.

Yours truly,

Alan R. McIver
A/Chairman
RODAC, Atlantic Region

C.C. R. J. Prier
S. Day
RODAC Members

Canada

DEPARTMENT OF THE ENVIRONMENT

OCEAN DUMPING CONTROL ACT

Pursuant to the provisions of the Ocean Dumping Control Act, the following permit is approved:

PERMIT NO. 4543-2-01898

Mulgrave (Oil Spill Test),
Guysborough Co., Nova Scotia

1. PERMITTEE

S. L. Ross Environmental Research Ltd., Ottawa, Ontario.

2. TYPE OF PERMIT

Experimental oil spill in pack ice.

3. TERM OF PERMIT

Permit valid from February 1, 1986
to April 30, 1986.

4. LOAD SITE

45°36.50' N; 61°23.50' W.

5. DUMP SITE

An area southeast of a line drawn between the following coordinates:

47°00.00' N; 59°00.00' W;
46°36.00' N; 59°30.00' W;
46°~~01.20'~~ 20.00 N; 58°36.00' W;
45°~~18~~ 30.00' N; 60°00.00' W.

at a depth of 79 - 381 m.

The distance offshore of this area shall be more than 25 nautical miles.

6. ROUTE TO DUMP SITE

Most direct navigational route from load site to dump site.

7. EQUIPMENT

Oil tank, pumps and hose, skimmers, sorbent pads and discs, ice marker buoys, Loran-C.

.../2

8. METHOD OF DISCHARGE

The experimental oil spill will consist of three experiments, each conducted on separate days and likely at different locations. Each experiment will involve the discharge of 1.0 cu. m. of crude oil onto waters amongst selected pack ice conditions (i.e. 4 to 5 tenths of moving pack ice, 7 to 8 tenths of moving pack ice, and open lead in pack ice).

9. TOTAL QUANTITY TO BE DUMPED

Not to exceed 3 cu. m. of oil.

10. MATERIAL TO BE DUMPED

Alberta Sweet Mixed Blend crude oil.

11. MONITORING REQUIREMENTS AND DUMPING RESTRICTIONS

11.1 The Permittee shall provide the Regional Director, Environmental Protection Service, Atlantic Region, with a tentative schedule for the experimental discharge at least 7 days prior to the start of the experimental program. This schedule shall be confirmed or revised by telex or telephone at least 24 hours prior to commencing the experiment.

11.2 A report outlining the following shall be submitted to the Regional Director, Environmental Protection Service, Atlantic Region, within 30 days of the expiring of this permit:

i) quantity of material discharged;
ii) dates on which each discharge occurred;
iii) precise location (Lat/Long) of each discharge;
iv) amount of oil reclaimed through cleanup measures;
v) the extent of the area affected by each discharge.

11.3 The Permittee shall employ the available technology for the cleanup of oil remaining after each experiment and shall ensure that, to the best of his/her ability and to the satisfaction of the ODCA Inspector, no oil remains in a quantity or concentration which can result in adverse environmental effects. The onus for additional cleanup measures, if required, rests with the Permittee.

.../3

11.4 The operation shall not be undertaken if it appears that environmental conditions exist which are likely to transport oil to shore.

11.5 Five copies of the final report describing the experiments, the ultimate fate of the disposed oil, and the results of the experiments shall be provided to the Regional Director, Environmental Protection Service, Dartmouth, upon completion of the operations.

11.6 The Permittee shall monitor the test areas daily throughout the operation. If the spill causes significant wildlife stress, the experiments shall be discontinued.

11.7 The Permittee shall ensure that space for an ODCA Inspector is made available on either surveillance aircraft or working vessels.

11.8 No dumping shall be permitted unless an ODCA Inspector is present at the site.

11.9 The Permittee will be required to terminate the operations immediately if the operations are not carried out according to the terms and conditions of this Permit.

11.10 The Permittee shall advise the Fisheries Environmental Coordination Office (902-426-3929), Department of Fisheries and Oceans, at least 48 hours prior to commencement of the experiment regarding the exact coordinates of any proposed oil release.

E. J. NORRENA

for A/REGIONAL DIRECTOR
ENVIRONMENTAL PROTECTION SERVICE
ATLANTIC REGION
FOR THE MINISTER OF ENVIRONMENT

Environment Canada Environnement Canada

Environmental Protection Service
3rd Floor, Queen Square
45 Alderney Drive
Dartmouth, N.S., B2Y 2N6

April 7, 1986

S. L. Ross Environmental Research Ltd.
346 Frank Street
Ottawa
Ontario
K2P 0Y1

Your file Votre référence

Our file Notre référence

4543-2-01898

Dear Sir:

RE: AMENDMENT FOR ODCA PERMIT NO. 4543-2-01898 - MULGRAVE (OIL SPILL TEST), GUYSBOROUGH CO., N.S.

We enclose an amendment to Ocean Dumping Permit No. 4543-2-01898 to cover the dumping operation you propose to carry out at the above location.

This was published in a regular edition of The Canada Gazette on April 5, 1986.

Please advise this office when the proposed operation concludes.

Yours truly,

Alan R. McIver
A/Chairman
RODAC, Atlantic Region

C.C. R. J. Prier
S. Day
RODAC Members

DEPARTMENT OF THE ENVIRONMENT

OCEAN DUMPING CONTROL ACT

Notice is hereby given that, pursuant to the provisions of the Ocean Dumping Control Act, the conditions of permit No. 4543-2-01898 are amended as follows:

PERMIT NO. 4543-2-01898

Mulgrave (Oil Spill Test),
Guysborough Co., N.S.

5. DUMP SITES

An area southeast of a line drawn between the following coordinates:

a) 47°00.00'N; 59°00.00'W;
b) 46°36.00'N; 59°30.00'W;
c) 46°20.00'N; 58°36.00'W;
d) 45°30.00'N; 60°00.00'W.

at a depth of 79-381 m.

The distance offshore of this area shall be more than 25 nautical miles.

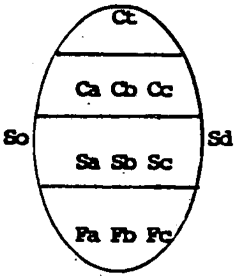
E. J. NORRENA

A/Regional Director
Environmental Protection Service
Atlantic Region
For Minister of the Environment

APPENDIX 2 - KEY TO ICE CHARTS AND TERMS

KEY TO INTERNATIONAL SEA ICE SYMBOLS
(THE EGG CODE)

THE MAIN SYMBOLS



Ct - Total concentration of ice in the area, reported in tenths.

Ca Cb Cc - Partial concentration in tenths of thickest (Ca), second thickest (Cb), and third thickest (Cc) ice types. with Ca, Cb, and Cc one tenth or more. if only one thickness type present Ca equals Ct and the second level is left blank.

Sa Sb Sc - Stage of development (age) of ice concentration reported by Ca, Cb, and Cc.

Fa Fb Fc - Predominant form of ice (floe size) corresponding to Sa, Sb, and Sc. respectively.

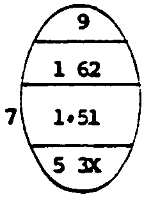
So Sd - Development stage (age) of remaining ice types. So if reported is a trace of ice type thicker/older than Sa. Sd is a thinner ice type which is reported when there are four or more ice thickness types.

Fa Fb Fc Form of Ice	(width)	
0	Pancake	
1	Brash	
2	Ice Cakes	- < 20 m
3	Small floe	- 20-100 m
4	Medium floe	- 100-500 m
5	Big floe	- 500-2000 m
6	Vast floe	- 2-10 km
7	Giant floe	- > 10 km
8	Fast Ice	
9	Icebergs	
X	No Form	
∿C	Ice is in strips in which concentration is C.	

Sa Sb Sc Stage of Development		(thickness cm)
1	New	- < 10 cm
2	Nilas	- < 10 cm
3	Young	- 10-30 cm
4	Grey	- 10-15 cm
5	Grey-white	- 15-30 cm
6	First Year	- > 30 cm
7	Thin First Year/White	- 30-70 cm
1.	Medium First Year	- 70-120cm
4.	Thick First Year	- > 120cm
7.	Old	no defined ranges
8.	Second Year	
9.	Multi-year	
△	Icebergs	

Note: All ages to left of "." are decoded from table as having "." (see example)

Example



9 tenths ice present
1 tenth type 1. (medium first year) in big floes (1,1.,5 reading down)
6 tenths type 5 (grey-white ice) in small floes (6,5,3 reading down)
2 tenths type 1 (new ice) no floe size
THERE IS a trace of ice type 7, (old ice)

Additional Symbols

▨	open water	■	fast ice
☰ △	bergy water	☰	ice free

PART I

ICE TERMS ARRANGED BY SUBJECT

1. FLOATING ICE: Any form of ice found floating in water. The principal kinds of floating ice are *lake ice*, *river ice*, and *sea ice* which form by the freezing of water at the surface, and *glacier ice (ice of land origin)* formed on land or in an *ice shelf*. The concept includes ice that is stranded or grounded.

1.1 Sea ice: Any form of ice found at sea which has originated from the freezing of sea water.

1.2 Ice of land origin: Ice formed on land or in an *ice shelf*, found floating in water. The concept includes ice that is stranded or grounded.

1.3 Lake ice: Ice formed on a lake, regardless of observed location.

1.4 River ice: Ice formed on a river, regardless of observed location.

2. DEVELOPMENT

2.1 New ice: A general term for recently formed ice which includes *frazil ice*, *grease ice*, *slush* and *shuga*. These types of ice are composed of ice crystals which are only weakly frozen together (if at all) and have a definite form only while they are afloat.

2.1.1 FRAZIL ICE: Fine spicules or plates of ice, suspended in water.

2.1.2 GREASE ICE: A later stage of freezing than *frazil ice* when the crystals have coagulated to form a soupy layer on the surface. Grease ice reflects little light, giving the sea a matt appearance.

2.1.3 SLUSH: Snow which is saturated and mixed with water on land or ice surfaces, or as a viscous floating mass in water after a heavy snowfall.

2.1.4 SHUGA: An accumulation of spongy white ice lumps, a few centimetres across; they are formed from *grease ice* or *slush* and sometimes from *anchor ice* rising to the surface.

2.2 Nilas: A thin elastic crust of ice, easily bending on waves and swell and under pressure, thrusting in a pattern of interlocking "fingers" *(finger rafting)*. Has a matt surface and is up to 10 cm in thickness. May be subdivided into *dark nilas* and *light nilas*.

2.2.1 DARK NILAS: *Nilas* which is under 5 cm in thickness and is very dark in colour.

2.2.2 LIGHT NILAS: *Nilas* which is more than 5 cm in thickness and rather lighter in colour than *dark nilas*.

2.2.3 ICE RIND: A brittle shiny crust of ice formed on a quiet surface by direct freezing or from *grease ice*, usually in water of low salinity. Thickness to about 5 cm. Easily broken by wind or swell, commonly breaking in rectangular pieces.

2.3 Pancake ice: cf. 4.3.1.

2.4 Young ice: Ice in the transition stage between *nilas* and *first-year ice*, 10–30 cm in thickness. May be subdivided into *grey ice* and *grey-white ice*.

2.4.1 GREY ICE: *Young ice* 10–15 cm thick. Less elastic than *nilas* and breaks on swell. Usually rafts under pressure.

2.4.2 GREY-WHITE ICE: *Young ice* 15–30 cm thick. Under pressure more likely to ridge than to raft.

2.5 First-year ice: *Sea ice* of not more than one winter's growth, developing from *young ice*; thickness 30 cm – 2 m. May be subdivided into *thin first-year ice* / white ice, *medium first-year ice* and *thick first-year ice*.

2.5.1 THIN FIRST-YEAR ICE/WHITE ICE: *First-year ice* 30–70 cm thick.

2.5.2 MEDIUM FIRST-YEAR ICE: *First-year ice* 70–120 cm thick.

2.5.3 THICK FIRST-YEAR ICE: *First-year ice* over 120 cm thick.

2.6 Old ice: *Sea ice* which has survived at least one summer's melt. Most topographic features are smoother than on *first-year ice*. May be subdivided into *second-year ice* and *multi-year ice*.

2.6.1 SECOND-YEAR ICE: *Old ice* which has survived only one summer's melt. Because it is thicker and less dense than *first-year ice*, it stands higher out of the water. In contrast to *multi-year ice*, summer melting produces a regular pattern of numerous small *puddles*. Bare patches and puddles are usually greenish-blue.

2.6.2 MULTI-YEAR ICE: *Old ice* up to 3 m or more thick which has survived at least two summers' melt. *Hummocks* even smoother than in *second-year ice*, and the ice is almost salt-free. Colour, where bare, is usually blue. Melt pattern consists of large interconnecting irregular *puddles* and a well-developed drainage system.

3. FORMS OF FAST ICE

3.1 **Fast ice:** *Sea ice* which forms and remains fast along the coast, where it is attached to the shore, to an *ice wall*, to an *ice front*, between shoals or grounded *icebergs*. Vertical fluctuations may be observed during changes of sea-level. Fast ice may be formed *in situ* from sea water or by freezing of *pack ice* of any age to the shore, and it may extend a few metres or several hundred kilometres from the coast. Fast ice may be more than one year old and may then be prefixed with the appropriate age category *(old, second-year,* or *multi-year).* If it is thicker than about 2 m above sea-level it is called an *ice shelf.*

3.1.1 YOUNG COASTAL ICE: The initial stage of *fast ice* formation consisting of *nilas* or *young ice*, its width varying from a few metres up to 100–200 m from the shoreline.

3.2 **Icefoot:** A narrow fringe of ice attached to the coast, unmoved by tides and remaining after the *fast ice* has moved away.

3.3 **Anchor ice:** Submerged ice attached or anchored to the bottom, irrespective of the nature of its formation.

3.4 **Grounded ice:** *Floating ice* which is aground in shoal water (cf. *stranded ice*).

3.4.1 STRANDED ICE: Ice which has been floating and has been deposited on the shore by retreating high water.

3.4.2 GROUNDED HUMMOCK: Hummocked *grounded ice* formation. There are single grounded *hummocks* and lines (or chains) of grounded *hummocks.*

4. PACK ICE: Term used in a wide sense to include any area of *sea ice*, other than *fast ice*, no matter what form it takes or how it is disposed.

4.1 **Ice cover:** The ratio of an area of ice of any concentration to the total area of sea surface within some large geographic local; this local may be global, hemispheric, or prescribed by a specific oceanographic entity such as Baffin Bay or the Barents Sea.

4.2 **Concentration:** The ratio expressed in tenths or oktas describing the mean areal density of ice in a given area.

4.2.1 COMPACT PACK ICE: *Pack ice* in which the *concentration* is 10/10 (8/8) and no water is visible.

4.2.1.1 *Consolidated pack ice: Pack ice* in which the *concentration* is 10/10 (8/8) and the *floes* are frozen together.

4.2.2 VERY CLOSE PACK ICE: *Pack ice* in which the *concentration* is 9/10 to less than 10/10 (7/8 to less than 8/8).

4.2.3 CLOSE PACK ICE: *Pack ice* in which the *concentration* is 7/10 to 8/10 (6/8 to less than 7/8), composed of *floes* mostly in contact.

4.2.4 OPEN PACK ICE: *Pack ice* in which the ice *concentration* is 4/10 to 6/10 (3/8 to less than 6/8), with many *leads* and *polynyas*, and the *floes* are generally not in contact with one another.

4.2.5 VERY OPEN PACK ICE: *Pack ice* in which the *concentration* is 1/10 to 3/10 (1/8 to less than 3/8) and water preponderates over ice.

4.2.6 OPEN WATER: A large area of freely navigable water in which *sea ice* is present in *concentrations* less than 1/10 (1/8). There may be *ice of land origin* present, although the total *concentration* of all ice shall not exceed 1/10 (1/8).

4.2.7 BERGY WATER: An area of freely navigable water with no *sea ice* present but in which *ice of land origin* is present.

4.2.8 ICE-FREE: No ice present. If ice of any kind is present this term should not be used.

4.3 Forms of floating ice

4.3.1 PANCAKE ICE: Predominantly circular pieces of ice from 30 cm – 3 m in diameter, and up to about 10 cm in thickness, with raised rims due to the pieces striking against one another. It may be formed on a slight swell from *grease ice*, *shuga* or *slush* or as a result of the breaking of *ice rind*, *nilas* or, under severe conditions of swell or waves, of *grey ice*. It also sometimes forms at some depth, at an interface between water bodies of different physical characteristics, from where it floats to the surface; its appearance may rapidly cover wide areas of water.

4.3.2 FLOE: Any relatively flat piece of *sea ice* 20 m or more across. Floes are subdivided according to horizontal extent as follows:

4.3.2.1 *Giant:* Over 10 km across.

4.3.2.2 *Vast:* 2–10 km across.

4.3.2.3 *Big:* 500–2,000 m across.

4.3.2.4 *Medium:* 100–500 m across.

4.3.2.5 *Small:* 20–100 m across.

4.3.3 ICE CAKE: Any relatively flat piece of *sea ice* less than 20 m across.

4.3.3.1 *Small ice cake:* An *ice cake* less than 2 m across.

4.3.4 FLOEBERG: A massive piece of *sea ice* composed of a *hummock*, or a group of *hummocks*, frozen together and separated from any ice surroundings. It may float up to 5 m above sea-level.

APPENDIX 3

METEOROLOGICAL OBSERVATIONS AND SIGNIFICANT WAVE ANALYSIS

Sources: 1. On-ice field party (surface)
2. Shipboard (MV Brandal) 10 m elevation
3. Atmospheric environment service Halifax weather office
(a) Sydney
(b) Ship reports in vicinity

	TIME	SOURCE	AIR TEMP	WIND SPEED (kt)	WIND DIRECTION
March 9					
	0600	3(a)	-12°C	7	WNW
	0700	2	-9°C	19 (26)	WNW
	1030	2	-8	25 (30)	W
	1130	2	-8	25	WNW
	1200	3(a)	-12	7	W
		3(b)	-9	15	WSW
	1200	2	-8	18 (20)	WNW
	1207	12	--	20 (25)	--
	1210	2	-8	18 (25)	WNW
	1230	2	-8.5	25 (28)	WNW
	1300	2	-8.5	23 (25)	W
	1333	2	-8.5	18 (25)	W
	1407	2	-8	22 (30)	W
	1430	2	-8	27 (30)	W
	1500	2	-8	20 (25)	W
	1530	2	-8	24	WNW
	1640	2	-8	15 (23)	WNW
	1800	3(a)	-9	1-	W
	2400	3(b)	-5	10	W
March 10	0600	3(a)	-11	7	NW
	0815	2	-13	20 (30)	NW
	0850	2	-13	20 (30)	NW

TIME	SOURCE	AIR TEMP	WIND SPEED (kt)	WIND DIRECTION
1010	2	-15	20 (25)	NW
1030	2	-14.5	15 (20)	NW
1100	1	-10	10 (15)	
	2	-14	15 (23)	NW
1200	2	-16	15	NW
	3 (6)	-14	19	NW
1300	2	-13	12 (15)	NW
1520	1	-8		
1545	2	-12	12	NW
1630	2	-11	12	WNW
1700	2	-11	5 (10)	NW
1800	3 (6)	-10	7	NW
2400	3 (6)	-12	10	NW

Canadian Forces METOC Centre

Significant Wave Analysis for March 9, 10

Date	Time	Swell Period (sec.)	Swell Ht. (m)	Wave Period	Wave Ht.	Sig. Wave	Swell Direct.
9/03	1200 Z	9	6	7	2	3.6	SSW
	1800	4	5	4	--	2.8	ESE
10/03	0000 Z	5	6	5	2	2.0	E
	0600 Z	--	--	6	2	2	--
	*1200 Z	7	7	4	2.5	4.3	ESE

* Data from 57°W

All readings as close as possible to spill sites. Ignoring waves it seems reasonable to call swell during Spill 1 as 5-6 m. Times are GMT.

APPENDIX 4 - OIL SAMPLE DATA

Time since release(s)	Evaporative* Exposure (θ)	Loc- ation	Sample** Ident.	Slick Thickness (μm)	Evap. Loss (v.%)	Density at $0^{o}C$ (kg/m^3)	Viscosity at $0^{o}C$ (mPas)
SPILL 1							
1,200	5,800	S	S1	1,200	10	----	----
1,680	9,600	C	S2	3,060	2.5	----	----
2,100	13,400	C	S3	2,350	11.5	----	----
2,100	13,400	C	G1	----	12.4	875	198
2,160	14,000	N	S4	1,120	11.5	----	----
3,240	25,700	S	S5	1,950	11.5	----	----
3,660	30,900	C	S6	1,790	11.5	----	----
3,900	34,000	C	G2	----	16.7	885	----
4,260	38,800	N	S7	1,100	11.5	----	----
7,440	89.500	S	S8	720	11.8	----	----
8,460	108,500	C	59	460	21.5	----	----
8,460	108,500	C	G3	----	24.6	898	----
9,360	----	floe	G4	----	16.5	883	1,333
9,420	127,500	N	G5	----	23.2	----	----
9,480	128,800	N	S10	30	23.5	----	----
10,500	----	S	snow	250	21.4	895	10,000+
10,620	152,700	S	S22	190	24.5	----	----
10,920	159,200	S	S12	180	24.0	----	----
12,000	2,500,000	N	S13	40	40	----	----
12,120	----	N	G6	----	22.4	896	10,000+
SPILL 2							
1,500	190	C	G7	7 cm	1.5	851	17.3
2,100	460	C	G8	5 cm	3.7	855	23.5
3,300	730	OC	G9	4 cm	5.8	863	37.4
4,500	1,250	C	G10	3.5 cm	6.6	866	45.6
8,100	2,400	C	G11	3 cm	8.5	868	50.0

APPENDIX 4 - OIL SAMPLE DATA (Cont.)

Time since release(s)	Evaporative* Exposure (θ)	Loc-ation	Sample** Ident.	Slick Thickness (μm)	Evap. Loss (v.%)	Density at 0°C (kg/m³)	Viscosity at 0°C (mPas)
SPILL 3							
1,320	520	C	G12	3 cm	1.6	855	20.3
1,320	520	C	G13	3 cm	1.7	855	20.4
2,640	970	C	G14	3 cm	3.2	855	22.4
2,640	970	C	G15	3 cm	3.4	856	22.5

* Corrected for oil spreading

** S = sorbent dip sample

G = grab sample

Fresh Alberta Sweet Mixed Blend from 500-mL Sampler Bottle Shipped with samples:

Density at 0°C: 0.8556 g/cm^3
Density at 15°C: 0.8448 g/cm^3
Viscosity at 0°C: 43.7 mPas

Interfacial Tensions:

Air/Oil: 25.7 mN/m
Oil/Seawater: 19.0 mN/m
Oil/Water: 26.2 mN/m

Pour Point: -8°C
Flash Point (closed cup): 7^{0}C

1505 Oil scraped from top of pancake 130-150 cm:

Density of oil at 0°C: 0.8949 g/cm^3
Viscosity of oil at 0°C: 10,000+ mPas
Weathering (volume %): 21.4

UV Analysis of Sample:
Total oil content: 13.25 g
14.81 mL
Total water content: 210 mL
Concentration: 63.1 g of oil/L of water
70.5 mL of oil/L of water

Core #1:

1/2 of Ice core sample
1615 March 9
Oil Particles up to 3 mm had migrated up 25 cm
weathering (volume %): 40%
(sample not stored in hexane)
UV analysis:
Total oil content: 0.03 g
Total water content: 266 mL
Concentration: 0.1128 g of oil/L of water

Core #2:

Bottom 10 cm of 10 cm core taken
1615 March 9 Sunday
Core was taken 10 cm from floe edge
Weathering (volume %): 40%
UV analysis:
Total oil content: 0.026 g
Total water content: 210 mL
Concentration: 0.125 g of oil/L of water

GAS CHROMATOGRAPHY

GC: Hewlett Packard 5830 A Gas Chromatograph
18850A GC Terminal

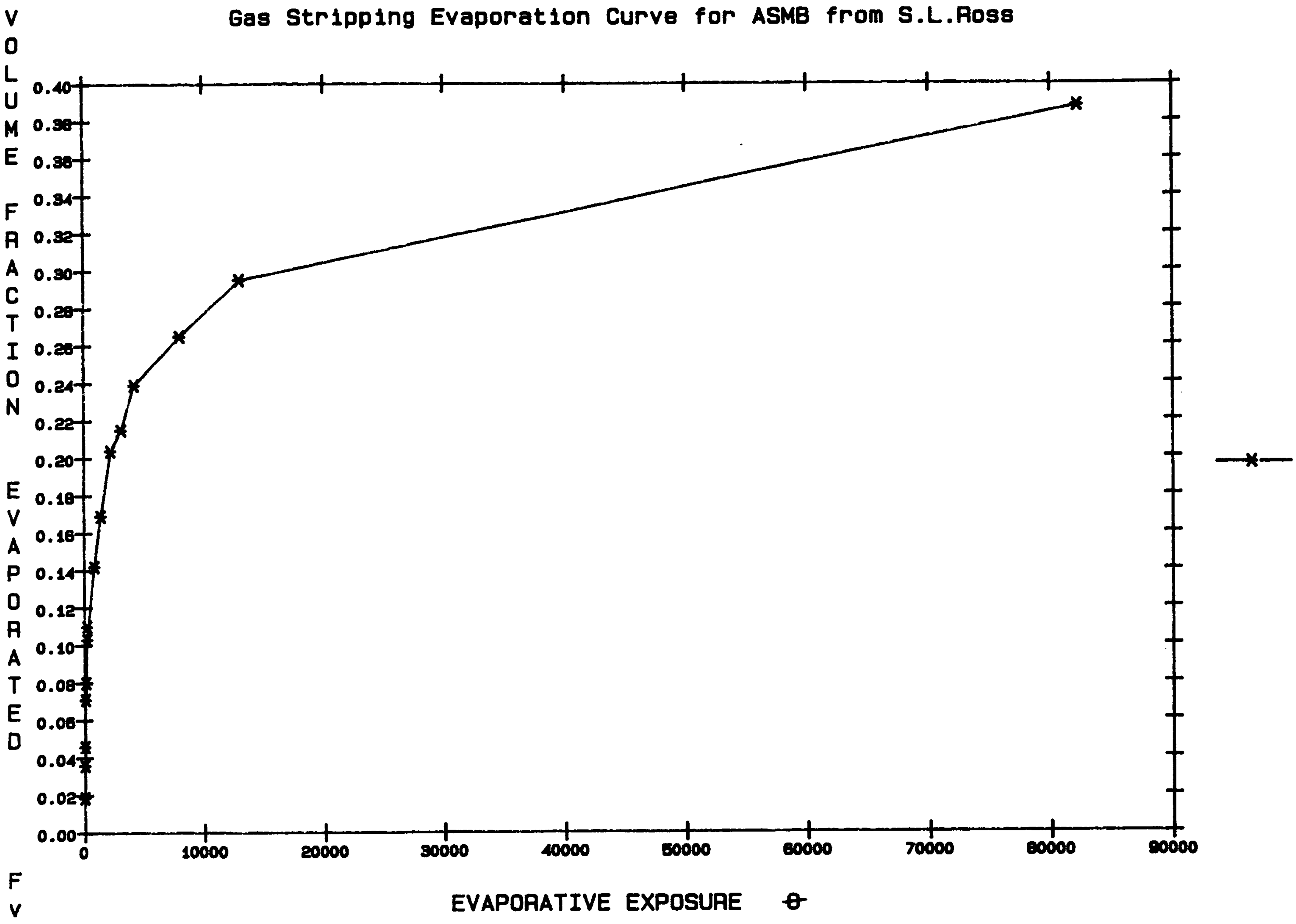
Column: 3% SP 2100
100 Supelcoport
200

G' x 1/8" SS
R 2177

Carrier Gas: N_2 30 cc/min

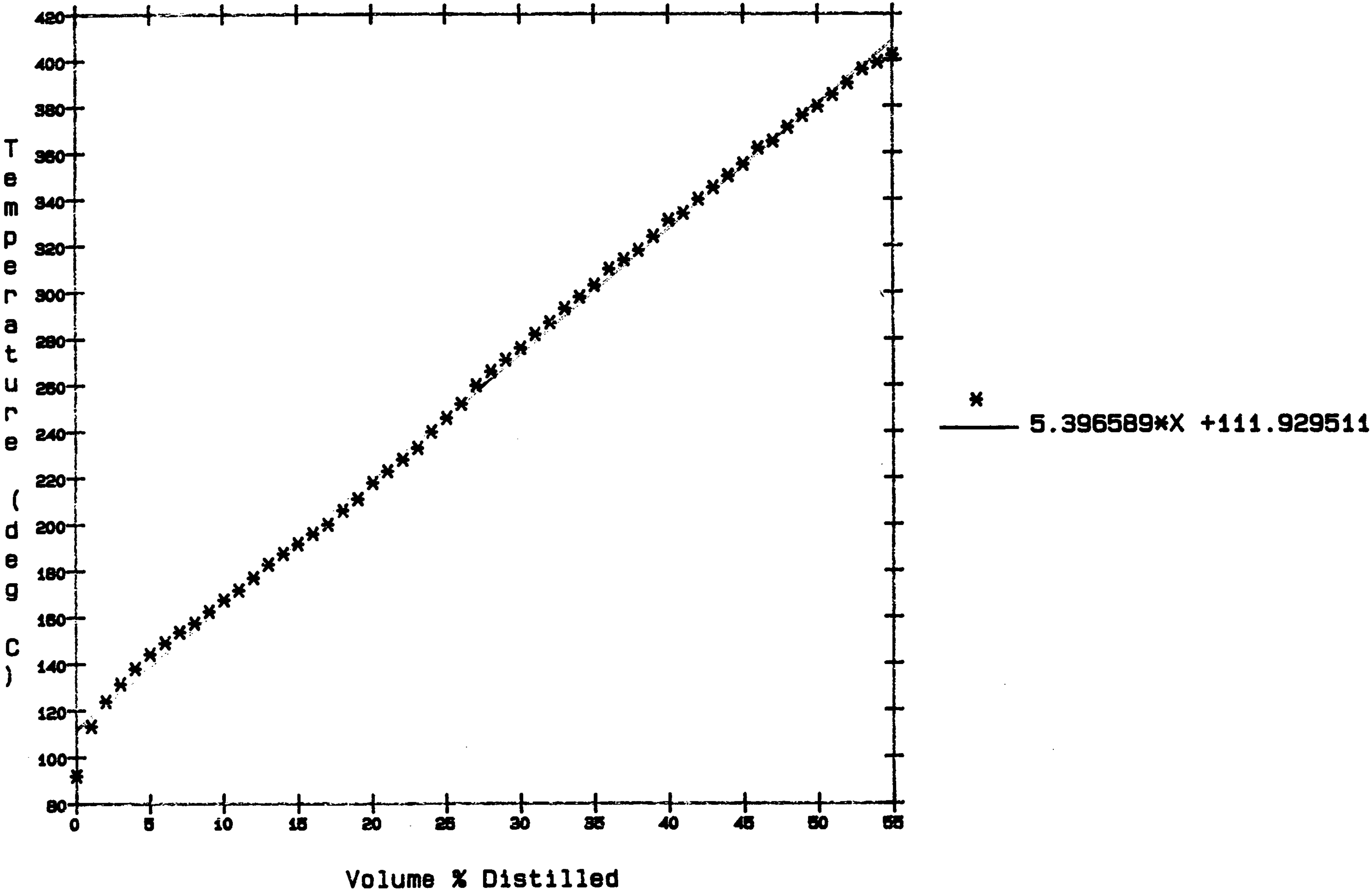
TEMP 1	400	40	40
TIME 1	5.00		
RATE	8.00		
TEMP 2	400	200	
TIME 2	10.00		
INJ TEMP	400	250	250
FID TEMP	400	250	250
AUX TEMP	400	250	250

CHT SPED	2.00		
ZERO	10.0		
ATTN 2	15		
FID SGNL	A		
SLP SENS	1.00		
AREA REJ		2000	
FLOW A	0.0	54.6	
FLOW B	0.0	63.4	
1.00 CHT SPED			1.00
2.30 ATTN 2			12


Gas Stripping Evaporation Curve for ASMB from S.L.Ross

Gas Stripping of Alberta Sweet Mixed Blend from S.L.Ross

0	1 Fv	2 θ
1	0.0188	14.7
2	0.0360	48.9
3	0.0460	53.4
4	0.0710	113.5
5	0.0800	156.7
6	0.1100	274.2
7	0.1030	275.0
8	0.1420	897.4
9	0.1690	1451.5
10	0.2040	2268.0
11	0.2150	3142.4
12	0.2390	4218.2
13	0.2650	8008.3
14	0.2950	12997.4
15	0.3880	82250.0



Modified ASTM Distillation of Alberta Sweet Mixed Blend

```
DISTIL   56R x 2C                                          5-MAY-86 10:56 Page 1

   Modified ASTM Distillation of Alberta Sweet Mixed Blend

0      1 %condensed  2 Temp(C)   0      1 %condensed  2 Temp(C)

-----------------------------   -----------------------------
 1                0      92.0   13                12     176.9
 2                1     113.2   14                13     182.8
 3                2     123.8   15                14     187.4
 4                3     131.4   16                15     191.5
 5                4     137.9   17                16     195.9
 6                5     144.1   18                17     200.0
 7                6     149.0   19                18     206.0
 8                7     153.6   20                19     211.0
 9                8     157.5   21                20     218.0
10                9     162.6   22                21     223.0
11               10     167.5   23                22     228.0
12               11     171.7   24                23     233.0
```

```
DISTIL   56R x 2C                                          5-MAY-86 10:57 Page 2

   Modified ASTM Distillation of Alberta Sweet Mixed Blend

0      1 %condensed  2 Temp(C)   0      1 %condensed  2 Temp(C)

-----------------------------   -----------------------------
25               24     240.0   37                36     310.0
26               25     246.0   38                37     314.0
27               26     252.0   39                38     318.0
28               27     260.0   40                39     324.0
29               28     266.0   41                40     331.0
30               29     271.0   42                41     334.0
31               30     276.0   43                42     340.0
32               31     282.0   44                43     345.0
33               32     287.0   45                44     350.0
34               33     293.0   46                45     355.0
35               34     298.0   47                46     362.0
36               35     303.0   48                47     365.0
```

```
DISTIL   56R x 2C                                          5-MAY-86 10:59 Page 3

Modified ASTM Distillation of Alberta Sweet Mixed Blend

0      1 %condensed  2 Temp(C)

-----------------------------
49               48     371.0
50               49     376.0
51               50     380.0
52               51     385.0
53               52     390.0
54               53     396.0
55               54     399.0
56               55     402.0
```