Behaviour of Oil Spilled at Sea (BOSS): Oil-in-Ice Fate and Behaviour

with

Fleet Technology Limited

March 1992

Environment Canada

U.S. Minerals Management Service

American Petroleum Institute

Behaviour of Spilled Oil at Sea (BOSS):

Oil-in-Ice Fate and Behaviour

by

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in association with

Fleet Technology Limited
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for

Environment Canada
Conservation and Protection

and

U.S. Department of the Interior
Minerals Management Service

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ERRATA

Several figures received as digital files from Environment Canada were scanned incorrectly, resulting in a landscape orientation, or, in one case, a full 180° change in orientation.. This problem can not be fixed within the WordPerfect for Windows software

The following figures (from the Literature Reviews) require changes:

Figure 8, Tsang, 1979 (vertical axis label is cropped)	pg 4-22
Figure 8, Topham 1979	pg 4-106
Figure 2, Wotherspoon et al., 1985	pg 4-110
Figure 4, Scott 1973 (figure is upside down)	pg 5-28
Figure 6, McMinn 1972	pg 6-6

ACKNOWLEDGEMENTS

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PROJECT TEAM

Ingrid Bjerkelund was responsible for overall project coordination. George Comfort, Fleet Technology Limited, summarized and evaluated the literature describing oil behaviour under continuous ice. Ann Godon and Ingrid Bjerkelund, DF Dickins Associates Ltd., developed the section on oil in broken and developing ice; and Rob Bowen, also of DF Dickins, was responsible for oil on snow and ice. David Dickins assisted with the introductory text and provided comments.

DELIVERABLES

The project deliverables include a paper copy of the report and an electronic file in WordPerfect 5.1 for Windows.

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APPENDICES

TABLES

FIGURES

1.0 INTRODUCTION

1.1 Project Objectives

The overall objectives of this project are as follows:

1. To complete a comprehensive review of all available material (published and unpublished) which relates to an understanding of the fate and behaviour of oil in ice (one of 17 topics identified as part of the overall BOSS project);

2. To prepare a summary by specific sub-topics (or situations) in accordance with specifications established for the overall Behaviour of Spilled Oil at Sea (BOSS) project. The BOSS section in each sub-topic area includes both reviews of individual projects that contributed data or process equations and a discussion summarizing the present understanding and identifying suitable data and processes equations.

1.2 Scope of Work

The project scope covered essentially any written material pertaining to the subject of oil and ice whether the material was available as a consultant's report, internal memorandum, part of conference proceedings, or published in the scientific literature. The only limitation was that the material had to contribute in some way to the understanding of physical processes governing the behaviour of oil under, in, among, or on top of ice.

In searching the available literature, no limitation was placed on the form of the ice cover (river, lake, or sea). Neither was there any limitation on the time period covered; the quality and content of a report were deemed more important than the age of reference.

Chemical processes are discussed in this study in summary form only to form a link with the other BOSS topics which deal directly with problems of dissolution, evaporation, emulsification. This link is established by describing how the dominant chemical processes are modified, inhibited or advanced by the presence of ice and/or cold temperatures in different situations.

2.0 Background

The problems of dealing with oil in ice have been the subject of intensive study over the past twenty years in Canada and overseas. Much of the work in this country was motivated by Dome Petroleum's application for offshore drilling authority in the mid 1970's. That development gave rise to the Beaufort Sea Project and the first large-scale spill of crude oil under sea ice at Balaena Bay (Norcor, 1975).

Over the last ten years, a numerous other medium to large-scale experimental spills have explored the interactions of crude oil with ice in different scenarios; examples include landfast ice in the presence of compressed air (Dickins and Buist, 1981), the interaction of emulsified oil with landfast ice (Buist and Dickins, 1983), and the behaviour of crude oil in broken east coast pack ice (S.L. Ross and DF Dickins, 1987).

Various industry groups have sponsored tank or basin tests aimed at documenting the interaction of oil with new ice and the behaviour of oil in lead situations; examples include Environment Canada sponsored work (Wilson and Mackay, 1987; Buist et al., 1987a), Esso's studies in their Calgary outdoor basin (MacNeill and Goodman, 1985); and ESRF sponsored experimental work (Comfort, 1986; S.L. Ross, 1987).

Information from accidental spills is available for a limited number of cases. Examples are the 1977 *Ethel H. spill* (Deslauriers, 1979), the *Bouchard #65* Buzzards Bay (Welsh et al., 1977; Ruby et al., 1977), the *Kurdistan spill* (Reimer, 1980a), and the *Antonio Gramsci* spill in Finland in 1987 (Hivri, 1990). The *Kurdistan* spill observations are particularly important as they demonstrated the importance of brash ice in controlling oil fate and behaviour under certain conditions.

A number of brainstorming sessions and workshops have dealt with the problems of arctic oil spill cleanup (e.g., 1979 joint government/industry workshop entitled Oil, Ice and Gas, 1982 COOSRA workshop, and the 1988 workshop on Arctic Offshore Oil Spill Response Technology).

A number of studies have dealt specifically with ice properties affecting oil-in-ice behaviour. Included in these are studies of under-ice roughness and storage capacity (Kovacs, 1979 and 1981; Barnes 1979a; Goodman and Holoboff, 1987), development of grease and pancake ice (Martin et al., 1976), and statistical characterization of the different pack ice environments (Dickins et al, 1986).

Work to date, including accidental spill observations, experimental field spills, and laboratory experiments has identified a number of processes and parameters which significantly affect the fate and behaviour of oil in ice.

These processes include:

- changes in oil spreading characteristics due to containment by ice pieces and brash ice;
- oil entrainment in freezing situations and oil absorption in snow and slush mixtures;
- oil particle adherence to the underside of ice;
- high under-ice currents to move or redistribute oil pools under ice;
- oil holding capacity under ice by virtue of natural variations in ice thickness;
- sea ice motion transporting oil trapped on floes;
- vertical oil migration through the ice during periods of natural brine drainage in the spring; and

- the rate of oil property changes in the presence of ice (e.g., weathering of encapsulated oil or oil in snow, emulsion formation in seas affected by wave damping in broken ice).

Appendix A lists the ice terminology used in this report. Figure 2.1 (after Bobra and Fingas, 1986) graphically depicts the various processes governing the fate and behaviour of oil in different ice situations.

The oil in ice situations depicted in Figure 2.1 could arise from a variety of scenarios, for example:

- rupture of a tank farm in a coastal area leading to oil runoff onto the bottom fast ice along the shore as well as collection in the tidal cracks paralleling shore in a salt water environment

- subsea blowout during oil exploration from a moored drillship in deep water leading to oil under pack ice of different concentrations or oil incorporated into newly forming ice (dependent on time of year)

- surface blowout from a gravity based drilling structure in ice covered waters leading to oil deposition and incorporation into the snow cover on the ice surface

- subsea blowout from a wellhead in shallow water leading to possible accumulation of oil particles underneath the ice (and eventually encapsulated in the case of spills prior to May) over a relatively large area (several square kilometres)

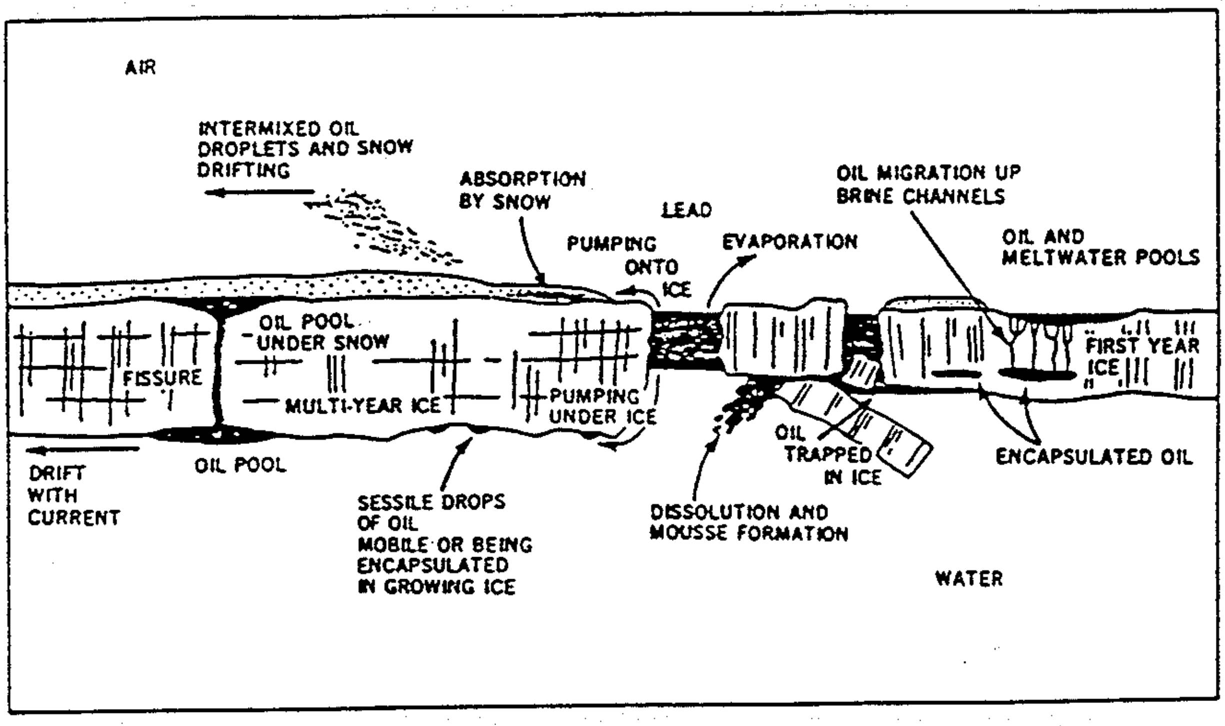
- subsea pipeline rupture leading to oil underneath and encapsulated within both landfast and pack ice (depending on water depth). Pipeline ruptures in a river crossing situation could also lead to oil deposition beneath the ice (subsequently swept downstream depending on flow).

- holing of a commercial cargo ship's bunker fuel tanks leading to release of oil in a short period of time into a broken ice field

- collision, grounding, or severe ice damage leading to rapid loss of tanker product or crude from one or more tanks into a pack ice field or near an ice edge

- sinking of barge or ship with potential for slow release of cargo over months or years

Figure 2.1 Oil Behaviour and Fate in Broken Ice (after Bobra and Fingas, 1986)



3.0 METHODOLOGY

3.1 Data Sources and Acquisition

There are a number of Arctic-specific oil spill bibliographies available (e.g., Keevil, 1974; Young, 1986), specific oil spill conferences (AMOP plus the bi-annual U.S. conferences), reports series of research agencies (COOSRA, ESRF, APOA, CRREL) as well as numerous generic bibliographies dealing with worldwide spill incidents. All of these were investigated for possible literature. Full use was made of the resources of the River Road Environmental Technology Centre (RRETC) throughout the project. A comprehensive search of international literature and spills of opportunity was carried out to uncover studies that might not be reported in the North American literature. Author contacts (see discussion below) were also used to confirm that all possible literature was reviewed.

All literature with any possibility of value was skimmed and ancillary material was identified (e.g., overviews, literature reviews, contingency plans, countermeasure studies). Detailed screening further limited the literature to those sources that present original data or new analytical models. All literature eliminated during the preliminary screening and detailed screenings are included in the Ancillary References (often with comments attached) to provide a starting point for future researchers.

3.2 Report Structure

The oil and ice section has been divided into three major topics:

1. Oil Under Continuous Ice
   - including spreading, encapsulation, and migration of oil under ice
2. Oil in Leads and Broken Ice
   - including oil in developing ice
3. Oil Behaviour On Snow and Ice
   - mainly spreading of oil on ice

Literature was divided along these topic lines as the oil spill scenarios and processes acting in each situation are quite different.

Within each topic the key papers are grouped according field tests, laboratory tests, theoretical or modelling studies, and spills of opportunity (where applicable). The papers are then presented by date, starting with the earliest paper. A discussion of the key processes in each topic follows the literature reviews. Table 3.1 lists all of the key studies reviewed according to study type. Key physical properties of the oils discussed in the reviews is given in Table 3.2 and ice terminology is defined in Appendix A.

The individual literature reviews are structured as follows:

- author, date, title, and source of paper reviewed,
- reference to any other papers from the same study,
- study background or methodology,
- study results, and
- study conclusions.

All text in the review that is quoted from the original paper is indented 1/2 inch on the left and is single spaced. Ellipses are used if only part of a sentence is quoted or if one or more sentences or paragraphs is omitted. All other text is left justified and is spaced at 1 1/2. Figure and table numbers were left unchanged from the original papers.

The key papers included in the literature reviews are cited in Oil and Ice References. The Ancillary References include citations of papers that were not considered to be key references on oil fate and behavior but would be listed in a key word search of oil-in-ice literature and papers cited as part of a quote in the literature reviews. Where appropriate, comments on the ancillary references are included.

Table 3.1 Summary of Oil-in-Ice Interaction Studies

SPILLS OF OPPORTUNITY	Location	References
Arrow	N.S.	McLean, 1972
Tank Rupture - Fuel Oil Spill	Deception Bay, Que.	Ramseier et al., 1973
Bouchard #65 - No. 2 Fuel Oil	Buzzard's Bay, MA	Deslauriers & Martin, 1978; Ruby et al., 1977; Welsh et al., 1977
Ethel H. Spill - No. 6 Fuel Oil	Hudson River, NY	Deslauriers, 1979
Spill at Fjord Shore	Spitsbergen, Norway	Carstens & Sendstad, 1979
Diesel Oil No. 2 Spill on Snow	AK	Allen, 1978
Kurdistan	N.S.	Reimer, 1980a & b, 1979, 1981; C-CORE, 1980; Vandermeulen & Buckley, 1985
Cepheus - JP-5 Jet Fuel	Cook Inlet, AK	Payne et al., 1984
Spill in Grease Ice Field	Matane, Que.	Wilson & Mackay, 1987 & 1986
Neva Bay		Al'Khimenko, 1989
Antonio Gramsci	Gulf of Finland	Hirvi, 1990
LARGE-SCALE FIELD TESTS	**Location**	**References**
Oil under Static First-Year Ice	Balaena Bay, N.W.T.	NORCOR, 1975
Oil under Static Multi-Year Ice	Griper Bay, N.W.T.	Comfort et al., 1983; Comfort & Purves, 1980 & 1982; Arctec Canada Ltd., 1983
Oil Recovery Under River Ice with Slots	N. Saskatchewan R.	Tsang, 1979; Quam, 1978
Oil & Gas Under Static First-Year Ice	McKinley Bay, N.W.T.	Dickins & Buist, 1981; Dickins et al., 1981; Buist et al., 1981
Emulsified Oil Under Static First-Year Ice	McKinley Bay, N.W.T.	Buist & Dickins, 1983; Buist et al., 1983
Oil in Pack Ice	Cape Breton, N.S.	S.L. Ross & D.F. Dickins, 1987; Buist & Dickins, 1987; Buist & Bjerkelund, 1986

Table 3.1 Continued

SMALL-SCALE FIELD TESTS	Location	References
Oil Spreading on & under Ice	Chukchi Sea	Glaeser & Vance, 1971
Oil Spreading on Snow & Ice	Bering Sea	McMinn, 1972; Chen, 1972; McMinn & Golden, 1973
Oil in Freezing Ponds	Ontario	Scott, 1973
Oil Spreading on Snow	Ont., N.W.T., & Lab.	Mackay et al., 1975
Oil Spreading Under Freshwater Ice	Ont.	Greene et al., 1977
Effect of Petroleum on Snow-Ice Cover	Arctic	Izmaylov, 1980
Oil Migration & Effect on Sea Ice	Prudhoe Bay	Nelson & Allen, 1981
Oil Spreading on Snow	Norway	Bech & Sveum, 1991
Spreading Chemicals on Ice & Snow	Ontario	Kawamura et al. 1986
Modelling of Oil Spills on Snow	Ontario	Belore & Buist, 1988; S.L. Ross & D.F. Dickins, 1988
RELATED ICE STUDIES	**Location**	**References**
Field Measurement of Under-Ice Roughness	Prudhoe Bay	Kovacs, 1977
Field Measurement of Under-Ice Roughness	Prudhoe Bay	Barnes et al., 1979a & b
Field Measurement of Under-Ice Roughness	Prudhoe Bay	Kovacs et al., 1981
Field Measurement of Under-Ice Roughness	Prudhoe Bay	Comfort, 1986
Storage Capacity of Under Ice Surface	Cdn. Beaufort Sea	Goodman & Holoboff, 1987; Goodman et al., 1987
Dynamics of Leads and Floes	Cdn Arctic	Dickins et al., 1986
Oil Encapsulation and Vertical Migration	Balaena Bay, N.W.T.	Martin, 1979
LARGE-SCALE LABORATORY TESTS	**Location**	**References**
Oil Movement in a Lead	Esso, Calgary, Alta.	MacNeill & Goodman, 1985 & 1987
Oil & Ice in a Freezing Lead	SL Ross Env. Res. Ltd.	Buist et al., 1987a

Table 3.1 Continued

SMALL-SCALE LABORATORY TESTS	Location	References
Oil & Gas Under Static Ice		
Oil Entrapment Under Static Sea Ice	USCG	Wolfe & Hoult, 1972 & 1974
Oil Spreading Under Static Freshwater Ice	CCIW	Keevil & Ramseier, 1975; Chen et al., 1976a & b
Containment by Simulated Ridge Keels	CCIW	Moir & Lau, 1975
Oil-Ice Interfacial Tension	Esso, Calgary	Rossenegger, 1975
Oil-Ice Interfacial Tension	Univ. of Toronto	Mackay et al., 1976
Oil & Gas Migration	Arctec Canada Ltd.	Purves, 1978
Oil & Gas Spreading, Encap. and Release	Univ. of Toronto	Mackay et al, 1979; Kisil, 1981
Oil-Ice Interfacial Tension	Memorial Univ., Nfld	Malcolm, 1979; Malcolm & Dutton, 1979
Equil. Thickness & Oil-Gas Configuration	Memorial Univ., Nfld	Malcolm & Cammaert, 1981a & b; Cammaert, 1980
Oil Migration in First-Year Ice	SAIC, San Diego, CA	Payne et al., 1984
Oil Behaviour in Multi-Year Ice	SAIC, San Diego, CA	Payne et al., 1987
Oil Spreading Under Ice	Clarkson Univ., NY	Yapa & Chowdhury, 1990, 1989a & b
Oil Under Ice - Current Driven Transport		
Smooth Ice	Fleet Tech. Ltd., Ont.	Uzuner et al., 1979; Weiskopf & Uzuner, 1977
Recovery Under River Ice with Slots	CCIW	Tsang & Chen, 1978; Tsang et al., 1978; Tsang, 1979; Quam, 1978
Transport Under Rough Ice	ACRES	Cammaert, 1980; Malcolm & Cammaert, 1981a & b
Transport Under Rough Ice with Currents	Arctec Inc.	Cox et al., 1980; Cox & Schultz, 1980, 1981a & b
Transport Under Smooth Ice	Waterloo Univ.	Puskas et al., 1987
Shelon River, Gulf of Finland		Al'Khimenko, 1989

Table 3.1 Continued

Oil with New Ice Growth		
Oil in Pancake Ice	Univ. of Wash.	Martin et al., 1976
Oil in Developing Ice Field	Esso, Calgary, Alta.	Metge and Telford, 1979; Metge, 1978
Oil with New Ice Growth	Univ. of Toronto	Wilson & Mackay, 1987 & 1986
Oil in Winds/Waves with New Ice	Ottawa, Ont.	Buist et al., 1987a & b; Joyce, 1987
Oil in Broken Ice		
Transport in Broken Ice	Arctec Inc.	Free et al., 1982 & 1981
Spreading in Broken Ice	USCG, Groton, CT	Tebeau, 1983
Tests in Multi-Year Ice with Waves	SAIC, San Diego, CA	Payne et al., 1987
Spreading in Broken Ice	Clarkson Univ., NY	Belaskas & Yapa, 1991

ANALYTICAL MODELLING	**References**
Oil & Gas Under a Moving Continuous Sheet	NORCOR, 1977
Rupture of an Ice Sheet by a Gas Bubble	Topham, 1977
Configuration of Oil and Gas Under Pressure	Topham, 1979 & 1980
Oil & Gas Under Static Ice with/out Currents	Wotherspoon et al., 1985
Oil & Gas Under Static Ice Without Currents	Comfort, 1987
Spreading Under Ice & in Broken Ice	Venkatesh et al., 1990a & b; El-Tahan et al., 1988

Table 3.2 Crude Oil and Oil Product Properties (from Bobra et al., 1990)

Type of Oil	Weathering (%)	Density (g/mL)	Dynamic Viscosity (mPas)	Pour Point (°C)	Interfacial Tension with Seawater (mN/m)
Adgo Crude Oil	0	0.959	165	-26	16.8
Alberta Crude Oil	0	0.85	17.6	-24	-
Alberta Sweet Mixed Blend	0	0.847	47.3	-8	17.5
Atkinson Crude Oil	0	0.9219	65.1	-38	18.7
Automotive Gasoline	0	0.746	0.75	-	19.8
BCF 24 Crude Oil	0	-	-	-51	-
Diesel Fuel Oil	0	0.838	3.9	-20 to -30	28.2
Diesel Fuel Oil	27.9	0.845	-	-	-
Kopanoar Crude Oil	0	-	57	-37	-
Mixed Sour Blend CrudeOil	0	-	-	-6	-
No. 2 Fuel Oil	0	0.849-0.908	7.74	-27 to -6	16.2
No. 4 Fuel Oil	0	0.914-0.938	47.2	-7 to -3	-
No. 5 Fuel Oil	0	0.932-0.957	-	-9.4	-
No. 6 Fuel Oil (Bunker C)	0	0.980-0.9941	1.4 E6-7.35 E6	-1 to 15	-
Norman Wells Crude Oil	0	0.840-0.8581	8.76-14.2	-85 to -50	16.5
North Slope Crude Oil	0	-	-	-21	-
Prudhoe Bay Crude Oil	0	0.9037-0.915	19-577	-27 to 0	15-23.8
Prudhoe Bay Crude Oil	16.2 - 24.1	0.9342	1700	-18	24.2
Virgin Motor Oil 10W30	0	0.8892	727.4	-37	18.2

Note: All properties listed above are based on a temperature of 0° C. All properties for weathered oils assume approximately 20% weathering.

3.3 Author Contacts

The intent here was to obtain the author's permission to reprint data directly from published papers and to obtain previously unpublished data for inclusion in the reviews. The first author of each paper was contacted and requested to consent in writing to the use of their material. (It should be noted that this written consent does not imply that the original publisher's copyright restrictions have been waived). Only authors of papers used in the literature reviews were contacted. References listed as ancillary were not included in this task.

The task of contacting the authors was particularly difficult in the case of older material where individuals have changed companies and/or careers. In the cases where first authors could not be reached, often the second author, the corporate source, or the sponsor of the study was contacted for consent.

Consent was received for two thirds of the papers. The remaining authors either did not return correspondence (at least two phone call plus facsimile transmission of request were made to each author) or their whereabouts were unknown. In many cases, the author's organization and even other authors of the same paper could not provide the whereabouts of some individuals.

Appendix B provides a summary of the authors contacted.

4.0 CONTINUOUS ICE

This section provides a summary of the available literature that relates to the fate and behaviour of oil and gas released under a static continuous ice sheet. This case has been studied extensively and the processes that will occur are relatively well understood. In sequence, starting with the release of the oil and gas, the following will occur:

Under-ice spreading. The oil and gas will rise to the under-ice surface and spread laterally, accumulating in the under-ice cavities.

Encapsulation. For spills that occur when the ice sheet is still growing, the pooled oil and gas will be rapidly encapsulated in the growing ice sheet. An ice lip will form around the edges of the oil and gas within hours of the discharge and subsequently, ice will grow beneath the oil and gas. Once encapsulated, the oil and gas are effectively immobilized.

Vertical Migration and Release of the Oil and Gas in the Ice Sheet. In the spring, as the ice sheet begins to deteriorate, the encapsulated oil and gas will rise to the surface through the brine channels in the ice. Oil will also be released by ablation of the ice surface down to the level of the lens.

Some of the reviewed papers deal with several aspects of the above cycle while others are focused on one of the processes. As all of the above processes relate to one case (i.e., the fate and behaviour of oil and gas released under a static continuous sheet of sea ice).

The reviews have been grouped into five sections:

1. Field Studies
2. Associated field studies of under ice roughness
3. Laboratory tests of under-ice spreading , encapsulation, and release
4. Laboratory tests of under-ice spreading only
5. Analytical and modelling studies

Programs with both field and laboratory components are reviewed in Field Studies. Within each section, studies are reviewed by date.

Table 4.1 Summary of References Reviewed by Process Addressed and Study Type

Reference(s) (See Note Below)	Study Type				Process(es) Addressed		
	Field	Lab	Anal.	Ice-Related	Spread	Encap.	Release
Al'khimenko, 1989	X		X		X		
Barnes et al., 1979a, 1979b	X			X	X		
Buist and Dickins, 1983; Buist et al., 1983	X				X	X	X
Comfort and Purves, 1980, 1982 Comfort et al., 1983; ARCTEC, 1983	X				X	X	X
Comfort, 1986	X				X		
Comfort, 1987			X		X	X	X
Cox et al., 1980; Cox and Schultz, 1980; Cox and Scuhulz, 1981a; 1981b		X	X		X		
Dickins et al., 1981a; Dickins and Buist, 1981; Buist et al., 1981	X				X	X	X
Glaeser and Vance, 1971	X				X		
Goodman and Holoboff, 1987; Goodman et al., 1987	X			X	X		
Greene, Leinonen, and Mackay, 1977	X				X		
Keevil and Ramseier, 1975; Chen et al., 1976a; 1976b		X	X		X	X	
Kisil, 1981		X	X		X	X	X
Kovacs, 1977	X			X	X		
Kovacs et al., 1981	X			X	X		
Mackay et al., 1976		X	X		X		
Mackay et al., 1979		X	X		X		
Malcolm, 1979; Malcolm and Dutton, 1979		X	X		X		
Malcolm and Cammaert, 1981a; 1981b; Cammaert, 1980		X	X		X		
Martin, 1979	X					X	X
Moir and Lau, 1975		X			X		
Nelson and Allen, 1981	X					X	X
NORCOR, 1975	X				X	X	X

Reference(s) (See Note Below)	Study Type				Process(es) Addressed		
	Field	Lab	Anal.	Ice-Related	Spread	Encap.	Release
NORCOR, 1977			X		X	X	X
Payne et al., 1984		X	X				X
Payne et al., 1987		X	X		X		
Purves, 1978		X	X		X	X	X
Puskas, McBean and Kouwen, 1987		X	X		X		
Rosenegger, 1975		X	X		X		
Topham, 1977			X		X	X	
Topham, 1979; Topham, 1980			X		X	X	
Tsang, 1979; Quam, 1978; Tsang et al., 1978; Tsang and Cheng, 1978	X	X	X		X		
Uzuner et al., 1979; Weiskopf and Uzuner, 1977		X	X		X		
Venkatesh et al., 1990a; 1990b; El-Tahan et al. 1988			X		X		
Wolfe and Hoult, 1972; 1974		X				X	
Wotherspoon et al., 1985			X		X		
Yapa and Chowdhury, 1989a; 1989b; 1990		X	X		X		

Note: Multiple references that refer to the same project were reviewed together. These are grouped together above.

4.1 Field Studies - Literature Review

Glaeser, LTJG J.L. and Vance, LCDR G. 1971. A Study on the Behaviour of Oil Spills in the Arctic. NTIS Report AD 717 142, U.S. Coast Guard Headquarters, Washington.

Small scale spills were conducted in the Chukchi Sea in July 1970. The subjects that were investigated include (a) the spreading behaviour of crude oil on an ice surface; and (b) the spreading of oil under ice.

Results

Spreading of Oil on Ice

> "The purpose for conducting the spreading experiments on ice was to obtain qualitative information on the spreading process in an arctic environment and to obtain quantitative data which could be used to scale the experimental spreading rates to large spills".

Tests were conducted by releasing oil in volumes of 50 to 100 gallons above the ice surface. Two oils (diesel and North Slope crude) were used for the tests. The authors describe the ice surface as follows:

> The surface had gradual undulations ranging up to approximately six inches and generally sloped downward from the center of the spill. In addition, the upper surface consisted of recrystallized ice which had the appearance of snow but could withstand a fairly large amount of weight. Measurements showed the recrystallized ice thickness to average approximately two inches, and core samples showed the density of the upper layer to range from .46 to .61 gm/cm^3.

It was observed that "any oil released on the upper surface was quickly absorbed into the ice". Based on an analysis of cores taken, "the ice absorbed approximately 25 percent of its volume in oil." The oil drained down through the surface ice, which was quite permeable, and collected on the surfaces of melt pools (which were below the surface ice level).

Glaeser and Vance, 1971, found that the following equation fitted the test data:

$$l = 2.75\ V^{1/4}\ t^{3/4}$$

where: l = slick length
V = oil volume
t = time

They advise that

> . . . specific gravity, temperature, and viscosity, which are interrelated, are not taken into consideration in this equation because either the effect of each is minimal on the resulting spread or the differences in the test conditions were too small to have an effect.

Spreading of Oil Under Ice

The objective of these tests was to provide qualitative insight into the under-ice spreading process, and in particular, the effect of under-ice cavities.

One drum of crude oil was pumped under the ice at each of two sites and its spreading was photographed by divers. At both sites, the oil rose to the ice bottom where it collected in under-ice roughnesses.

The authors note that the oil remained in the under-ice depressions and suggest that this "was most likely due to a lack of turbulence in the area at the time of the tests." They conclude that "it appears that the various large pockets, pressure ridges, and other under ice obstructions would be able to contain a fairly large volume of oil, provided that non-turbulent conditions exist."

NORCOR Engineering and Research Ltd. 1975. The Interaction of Crude Oil with Arctic Sea Ice. Prepared for the Beaufort Sea Project, Department of the Environment, Victoria, Beaufort Sea Technical Report No. 27.

Summary of Study Objective and Scope (after NORCOR, 1975)

The principal objectives of the study were to assess the impact of an offshore oil well blowout on the thermal regime of the Beaufort Sea, and to evaluate potential countermeasure techniques.

The main program, which consisted of nine controlled discharges involving 54 m^3 (11,900 gallons) of crude oil, was undertaken in a small bay 20 km to the south west of Cape Parry (70°01' N, 124°53'W). Two types of crude were injected under the ice at various stages of growth, between October 1974 and May 1975. The initial spreading and entrainment was documented by means of divers and a remote video system. An array of eleven point thermistor chains was logged hourly to assess the rate of migration and the effect of the oil on the thermal regime of the sheet. Oil, water and ice samples were recovered at regular intervals to determine the degree of weathering and dissolution of the oil. Detailed radiation studies were undertaken in the spring to assess the impact of surface oil on ice depletion. As well, two small discharges were conducted 30 km north of Cape Parry in April 1975, to determine the importance of currents on the transport of oil under solid ice cover. The oil was injected under the ice in the presence of a 10 cm sec^{-1} current, and the movement documented by means of divers.

Results

Under-ice spreading and pooling

NORCOR, 1975, observed that

> When oil is released in the water column, it rises towards the surface in a conical-shaped plume. The oil tends to be unstable, and breaks into small spherical particles about 1 cm in diameter or less. On striking the underside of the ice, the oil radiates outward, progressively filling depressions in the sheet. . . .

NORCOR, 1975, further observed that

> The areal extent of spreading along the underside of the sheet is controlled by a number of factors. . . . A very small quantity of oil was deposited on the ice in the form of small spherical particles (editor's note: with diameters of 1 cm or less). These normally occurred near the periphery of the contaminated ice, in areas where the currents were feeble, and the chance of collision with other oil particles was small.
>
> . . . . In the tests at Balaena Bay, over 95 percent of the oil was contained in pools larger than one metre [in diameter]. . . .
>
> The maximum film thickness is determined by variations in ice thickness, which take two basic forms. Due to differential growth at the skeletal layer, there is a small scale variation which is randomly oriented, and produces pockets about 5 to 10 cm wide and up to several centimetres deep late in the season. It is this pattern which likely accounts for the meandering in the oil rivulets. Consequently, although lenses as thin as 0.8 cm are possible, the minimum thickness tends to be in the range of one to two centimetres. The second form of irregularity is of much larger scale and is caused by variations in snow cover. . . .
>
> These large scale variations effectively contained the oil and controlled the maximum lens thickness. With the exception of the early tests, 7.3 m^3 (1620 gals) was insufficient to fill even a single depression. On NW4, [this refers to a discharge no.; i.e., discharge no. 4 with Norman Wells crude oil] when the ice was about 64 cm thick, the oil covered approximately 400 m^2 for an average lens thickness of 2.0 cm. With NW7, when the ice was 154 cm thick, 180 m^2 was covered, yielding an average lens thickness of 4.5 cm. The maximum oil thickness measured was 20 cm, while the average oil thickness for all tests was 2.1 cm.

Encapsulation

NORCOR, 1975, observed that

> Within a matter of hours of the oil coming in contact with the ice, a lip of ice forms around the lens, preventing horizontal movement. During the depth of winter, a new layer of ice forms beneath the oil within several days. Once

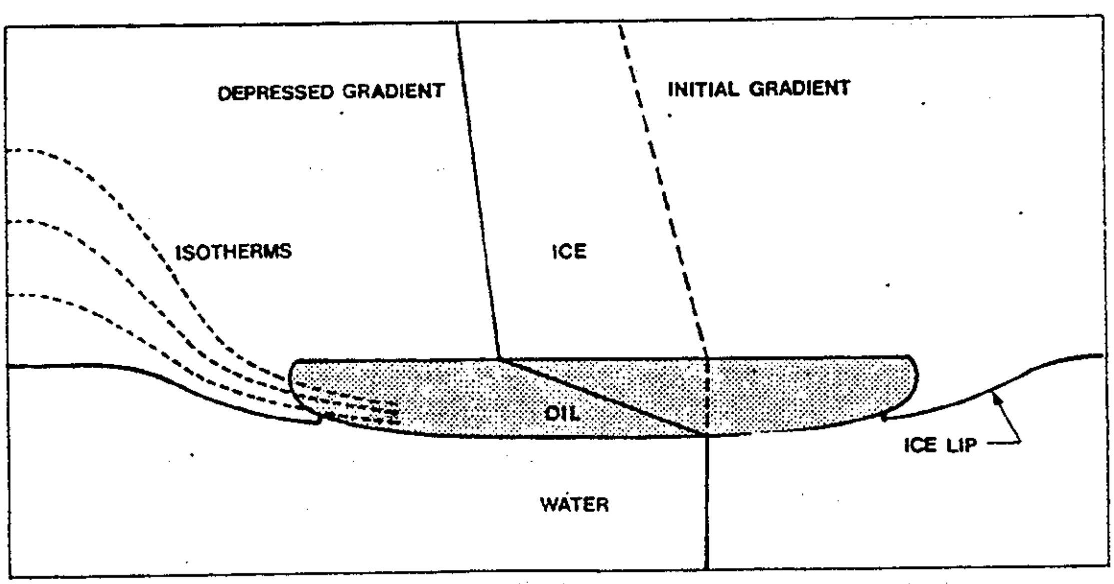
entrapped, the oil is stabilized until spring. The properties of the oil remain unchanged and there is little evidence of weathering or degradation.

. . . . The time required for a new sheet of ice to form beneath the oil is primarily a function of the thickness of the oil and the thermal gradient. During the late fall, when the gradient is steep and the lenses relatively thin, new ice was detected within about five days. This period increased to approximately seven days for a typical lens during the depth of winter, and over ten days in the spring. . . .

NORCOR, 1975, noted that the ice lip is an important part of the encapsulation process and attributed its formation to the added thermal resistance of the oil. See Figure 6.1.

The thermal conductivity of most crudes is about one fifteenth that of natural sea ice, and the insulating effect is detectable within hours. Although free convection could be significant in very thick oil lenses . . . the required

Figure 6.1: Initial Effect of Oil Lens



conditions are rarely encountered in the natural environment. For the more typical lens thicknesses encountered in Balaena Bay, the added thermal resistance of the oil caused a depression in the thermal gradient through the ice. Temperature drops of over 1.0°C were observed immediately above the oil within 24 hours. The horizontal transition from a normal temperature gradient through the uncontaminated ice to a depressed gradient above the oil, caused sub-freezing temperatures at the edge of pools, which resulted in the formation of an ice lip. Figure 6.1 shows schematically the depressed thermal gradient and the realignment of isotherms.

Vertical Migration

NORCOR, 1975, observed that

> Throughout the winter the oil only penetrates between 5 and 10 cm into the loose skeletal layer on the bottom of the sheet. As the sheet begins to warm in the spring, activity intensifies in the brine channels and the oil begins to migrate upwards. Initially the movement is slow; typically in the range of 15 to 20 cm during the months of February and March. The rate of migration increases with the level of solar radiation and the ambient air temperature.

Oil released in late April under 150 cm of ice was detected on the surface within one hour. However, all the oil is not released until the melt actually reaches the level of the lens . . . . The maximum concentration of oil in the ice, even late in the season, is about 5 percent by volume.

The migration, or upward movement of oil through the ice is controlled primarily by the condition of the ice, and to a lesser extent, the physical properties of the oil. The process can be reasonably correlated with the dominant periods in the growth and depletion of the ice sheet. During the depth of winter when the sheet is cooling and growing rapidly, the ice is relatively solid, with the exception of the skeletal layer. Although the oil is less dense than water or sea ice, there are very few passages for it to penetrate, and movement tends to be limited. As the sheet starts to warm in the spring, brine channels begin to open, and the oil slowly moves upward, filling the voids. As the oil approaches the surface, increased solar radiation is absorbed and the process is accelerated [see Figure 6-8]. Late in the spring, when the ice is very porous, the oil flows freely through the sheet.

Effect of Oil on Ice Growth and Depletion

NORCOR, 1975, observed that

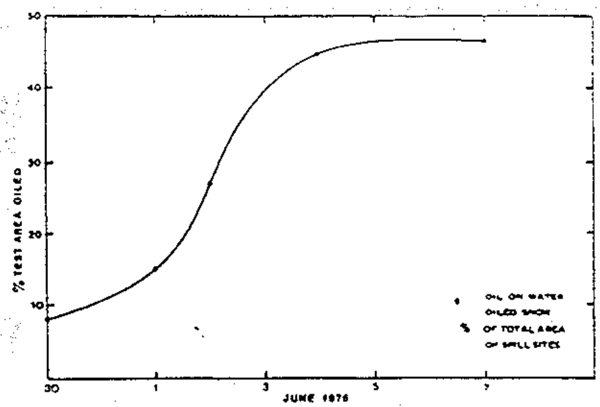
> Although the thermal conductivity of most crude oils is about one fifteenth that of natural sea ice, the insulating effect is partially offset by free convection, once the lens is encapsulated. Convective heat transfer increases as the thickness of the oil increases, and under certain conditions a lens can actually enhance rather than retard ice growth . . . . In general, the effect of the oil tends to be relatively insignificant in comparison to natural variations. The thermal resistance of the average oil lens at Balaena Bay was equivalent to between 5 and 8 cm of ice, or less than 20 percent of the natural variation in ice thickness late in the season [see Figure 7-3].
>
> On reaching the surface of the ice, the oil saturates the snow cover, and substantially reduces the albedo [see Figure 7-20]. This causes an increase in the level of absorbed solar radiation, which accelerates the process. Oiled melt pools quickly develop. The albedo of an oil film on water is about one quarter that of oiled snow, and consequently the melt is further accelerated. Oil is splashed on the surrounding snow by wind and wave and pools gradually enlarge until interconnected. New oil is continually being released until the melt reaches the initial level of the oil lens . . . . Once the melt holes develop and surface drainage patterns are established, the sheet rapidly deteriorates. Depending on the nature and location of the sheet, oiled areas are likely to be free of ice between one and three weeks in advance of the gross failure of the sheet.

Oil Spreading in the Presence of a Current

(excerpted from NORCOR, 1975)

> The principal objectives of the offshore studies were to investigate the spreading of crude oil under sea ice in the presence of a current, and the interaction of oil with a pressure ridge keel.

Norman Wells crude oil was discharged under the ice at two sites. A quantity of 0.82 m^3 (180 gallons) was discharged at each site.



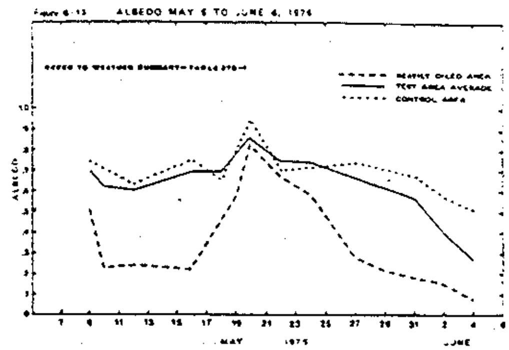


Figure 6-8 Oiled Area Coverage vs Time

Figure 6-13 ALBEDO May 5 to June 6, 1975.

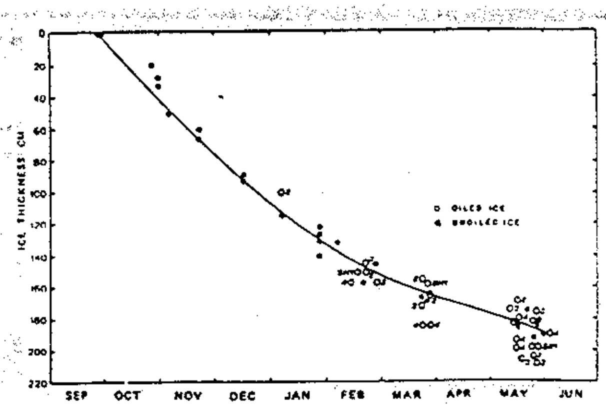


Figure 7-3 Ice thickness measurements in oiled and clean areas normalized to zero snow equivalent values

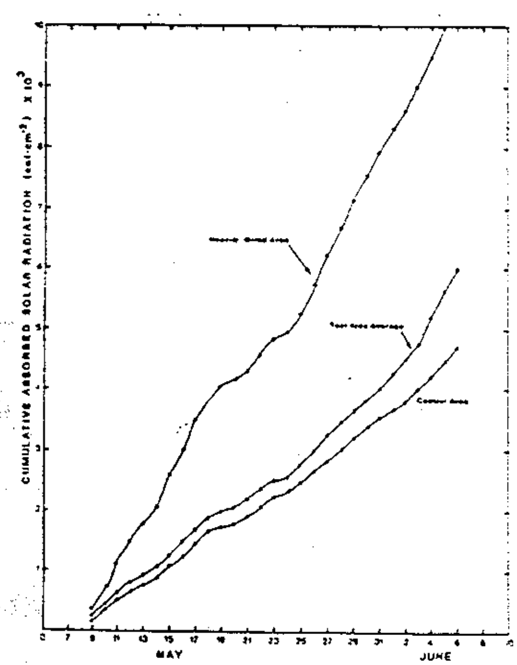


Figure 7-20 Cumulative Radiation, May to June, 1975.

NORCOR, 1975, concluded that

> The offshore study was hampered to some extent by the relatively small quantity of oil finally permitted, and the reduction in tests. It is impossible, with the limited data, to draw any firm conclusions as to the influence of current. The oil performed in a similar fashion during static tests in Balaena Bay. For example, rivulets were generated when the oil was released beneath a dome in the ice, while a pool was created if the release was below a depression. However, there were some notable differences offshore:
>
> 1. With both discharges, the direction of fingers tended to be oriented in the direction of the current. The direction was random with static tests. As well, the fingers were far more elongated.
>
> 2. In both cases, the mass of oil moved down-current from the discharge point. The probability that the first discharge hit on the up-current side of a depression, and the second discharge on the down-current side of a dome is remote.
>
> 3. Although there were gravitational forces present in the second offshore discharge, current did appear to have a definite influence on the movement of the oil at the offshore site. In static tests at Balaena Bay, even with an exit velocity 20 times greater, and with the oil striking a well defined dome on the undersurface, rivulet velocity was much less than that observed offshore in the presence of a current.
>
> 4. The tests provided some indication of the importance of surface roughness and under-ice topography. The numerous clear patches in discharge No. 1, are indicative of small irregularities on the ice. . . . Since the average oil thickness was about 1.75 cm, and the maximum stable thickness was about 0.8 cm, the clear areas had to be a minimum of about 1.0 cm thicker than the surrounding ice. This roughness would have a considerable influence on the boundary condition for both the oil and the current. The large area coverage of the oil would suggest that the sheet was relatively smooth. It is more difficult to interpret the behaviour of the oil and the current for the second discharge. The fact that the trough existed gives some indication of the influence of the pressure ridge keel on current flow. However, the oil stabilized once it reached the main pool, suggesting that gravitational forces were dominant.

5. The pressure ridge keel, although small, presented a minimum barrier of about 75 cm over the entire length examined. Even in the presence of a considerably higher current, the trough and keel combined would hold back an enormous volume of oil.

6. Once encapsulated in the ice, the oil performed in an identical fashion to that observed on static tests with much larger volumes. Other work indicated that this process of being included in the ice sheet with a fresh interface below the oil took less than one week.

Greene, G.D., Leinoen, P.J., and MacKay, D. 1977. An Exploratory Study of the Behaviour of Crude Oil Spills Under Ice. Canadian Journal of Chemical Engineering, Vol. 55, pp 696-700.

> This paper describes an experimental spill of 0.88 m^3 (84 Imp. gal.) of crude oil in an ice covered fresh water pond in Ontario. The objectives were to study the nature of the processes of oil rise and coling through the water column to an ice-water interface, impingement on the ice surface, movement along the subsurface of the ice sheet, dissolution of hydrocarbons, and finally, to test some clean-up techniques.

Mixed sour blend Alberta crude oil was released 1.5m below the ice sheet, which was 0.2 m thick. The spread of the oil was followed from above the sheet by observing the silhouette of the oil, which was illuminated by lights on the bottom of the pond. Water and ice temperatures were also measured.

Results

Under-ice Spreading

After impinging on the ice surface, the oil radiated outward. Initially, the under-ice spreading occurred as a series of waves in concentric circles emanating outward from th oil contact point. Later on, the boundary of the oil became more elongated as the oil began to follow the topography of the under-ice relief. Greene et al. report that "the flow was dominated by the under-ice topography and no evidence of oil adhesion to the ice was observed."

Greene et al., 1977, summarize the fate of the released oil as follows:

> An estimated 0.04 m^3 of oil reached the surface of the ice through cracks. The remaining 0.34 m^3 of oil spread to cover an area of 16 m^3, and thus acheived

an average thickness of 2.1 cm after thirty minutes. During the next 15 h there was no further spreading the the oil appeared to be at equilibrium under the ice sheet at the ice-water interface.

Oil Interaction with New Ice Growth

Although the principal aim was to study the behaviour of oil under ice, two cracks in the ice permitted the oil to reach the surface and provided an opportunity to examine the behaviour of crude oil spreading on a freezing water surface. Two surface oil slicks formed of areas 1 m^2 and 3 m^3 with an oil thickness of about 1 cm. These slicks stopped spreading within a few minutes of formation and did not spread further during the 16 hours of observation. The slicks appeared to have a stable edge about 0.5 cm thick which showed no tendency to become thinner. The slick was easily herded into a smaller area by light wave action but returned to this original coverage when the waves stopped. This is in contrast to behaviour on warmer water surfaces where some oils may spread to form very much thinner slicks, under the influence of surface tension and viscous forces. Whether the spreading behaviour is a function of temperature or oil composition or both is not known.

Overnight a thin film of fresh ice formed on the surface water and partly under the oil at the edges of the slicks. No ice formation occurred under the slick centres probably due to the lower thermal conductivity of the oil. The easy herding and relatively thick oil slicks observed suggest that oil spills on near freezing open water may be more easily contained than under warmer conditions.

Tsang, G., 1979. Recovery of Oil Spilled Under River Ice Cover. Proceedings, Oil Spill Conference, American Petroleum Institute, pp 387-396.

This study is also reported in Tsang, Chen, Carson, 1978; Tsang and Chen, 1978; and Quam, 1978.

Editor's Note: This project involved a combination of analytical studies, laboratory tests and a field experiment. Tsang, 1979, provides an overview of the project and presents results for all portions of the work. More detailed information on the analytical and laboratory work is provided in project reports by Tsang, Chen and Carson, 1978, and Tsang and Chen, 1978. Quam, 1978, describes the field experiments. As these references all relate to the same project, they have been summarized together in the following review.

The objective of the work was to investigate the containment and diversion of oil spilled under a river ice cover by means of slots cut in the ice cover and/or barriers extending below the ice cover. Both laboratory and field tests were carried out.

Results

Holding Capacity of a Slot Normal to the Flow

Laboratory experiments were conducted in a recirculating flame. An ice cover was formed on the flame, and after a slot was cut in it, oil was released upstream. Three oil types (Norman Wells crude, Texas Blend crude, and Coleville Smiley crude) were used.

The holding capacity was found to depend upon the thickness of the oil slick (T_o), The holding capacity was found to depend upon the thickness of the oil slick (T_o), the width of the slot (b), the ice thickness (T_i), and the Weber number. See Figure 4.

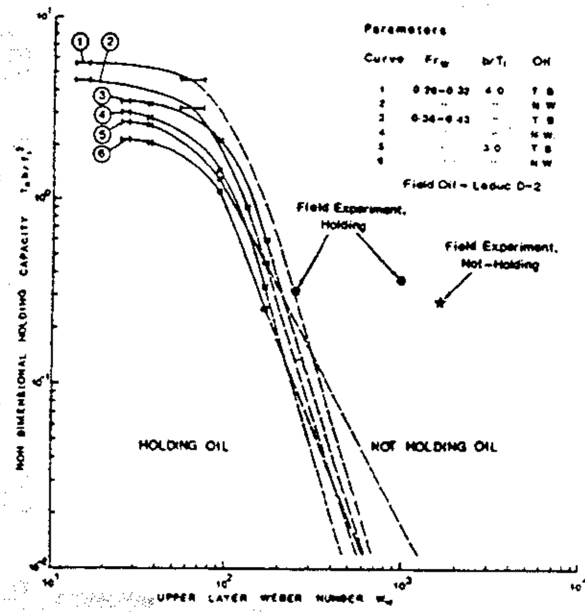


Figure 4 Holding Capacity as Function of Weber Number for a Slot

Field experiments were conducted on the North Saskatchewan River in March, 1978. Rapeseed oil was released upstream of slots that were cut in the ice normal to the flow. These data are also shown on Figure 4.

Tsang, 1979, notes that the laboratory tests underpredicted the holding capacity of the slot and attributed this to the higher turbulence levels that were present during

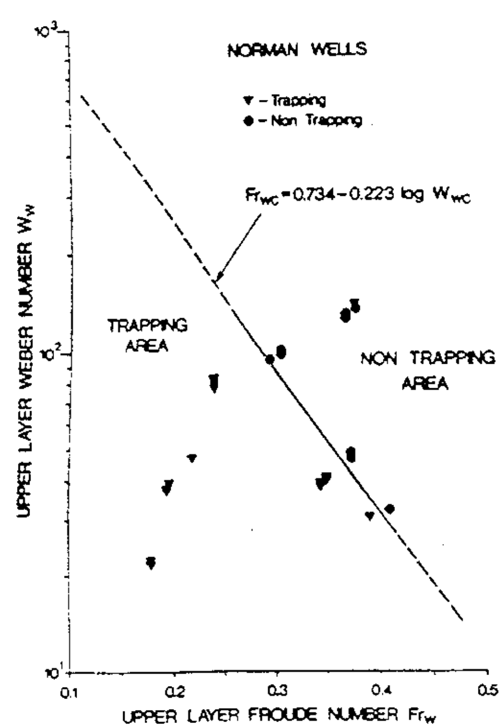
Laboratory tests were undertaken (using the same experimental setup and oil types) to investigate the conditions under which slicks, patches, and droplets moving under an ice cover would be trapped by a slot. Results for the Norman Wells crude oil tests shown in Figure 7.

Containment and Diversion of Oil by Angled slots

Laboratory tests were conducted (using the same experimental setup and oil types) to investigate the conditions under which oil moving under an ice cover could be contained and diverted.

This was found to depend upon the angle of the slot, the oil type, the Froude number, and ratio of the slot width to the ice thickness. See Figure 8.

Figure 7 **Weber Number and Froude Number Criteria for Critical Trapping Norman Wells Crude**



Field experiments were conducted on the North Saskatchewan River in March, 1978, using Leduc-2 crude oil and rapeseed oil. The field results were found to correlate well with the laboratory test results. See Figure 8.

Diversion of Oil by Embedded Barriers

Laboratory tests were conducted (using the same experimental set up and oil types) to investigate the conditions under which slicks moving beneath a river ice cover can be diverted by barriers fixed beneath the ice sheet.

The experimental results are summarized in Figure 9.

Field tests were conducted subsequently in the North Saskatchewan River using rapeseed oil. The field observations were found to agree with the laboratory test results. See Figure 9.

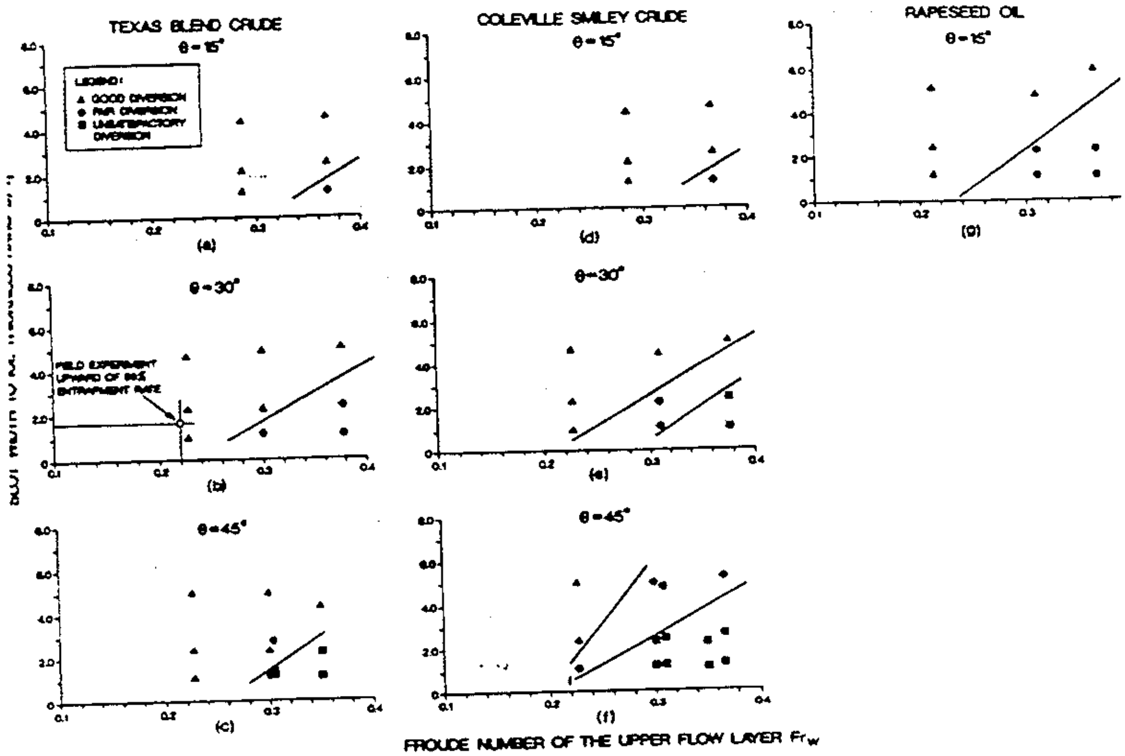


Figure 8: Diversion of Oil by Angled Slots

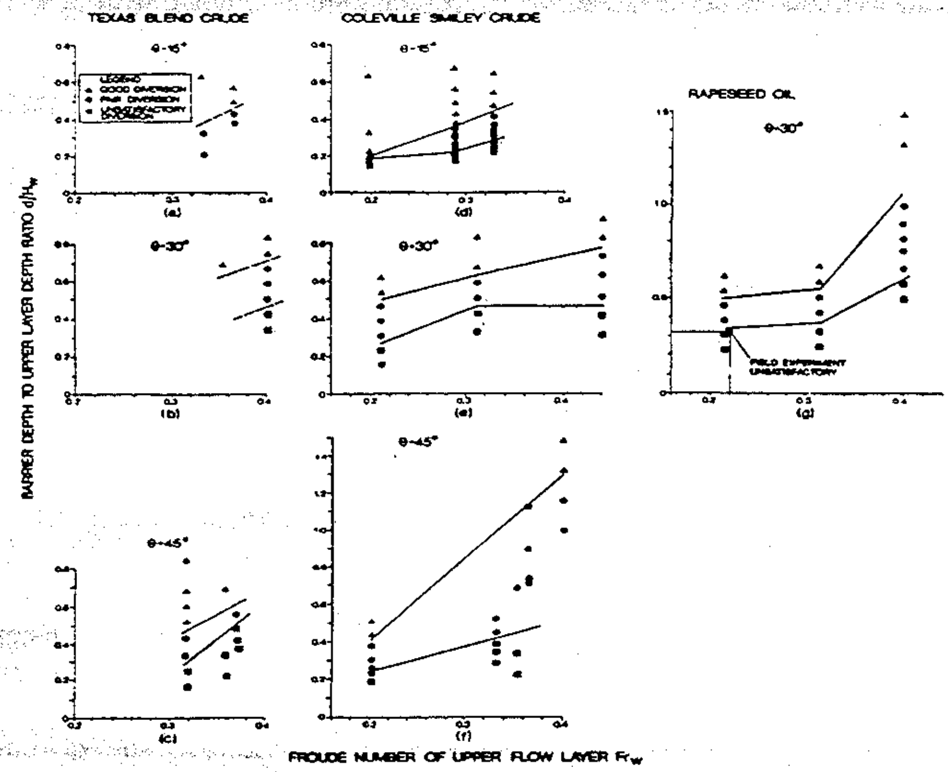


Figure 9: Diversion of Oil by Embedded Barriers

Martin, S. 1979. A Field Study of Brine Drainage and Oil Entrainment in First-Year Sea Ice. Journal of Glaciology, Vol. 22, 1979.

This paper "describes the growth and development of first year sea ice and its interaction with petroleum." With respect to oil-ice interaction, the paper discusses observations that were made during an extensive field spill program that was conducted at Balaena Bay, N.W.T. (by NORCOR, 1975).

Results

Oil Behaviour During the Winter Period

> In summary, when oil is released under young columnar ice sheets, it collects in pools under the ice, where some of it is entrained in between the platelets in the skeletal layer, and some of it flows up into the brine channels. The observations made at the site through March 1975 shows that once in this configuration, the oil in the ice remained essentially static, with only a slight rise of oil up the brine channels as the ice began to warm.

Martin, 1979, notes that the spilled oil was rapidly encapsulated in the growing ice sheet and an ice cap formed immediately below the oil which tended to pressurize the oil layer. This is supported by observations at the Balaena Bay site in that cores drilled into oil lenses in the fall resulted in a rapid upward flow of oil. Martin, 1979, concludes that

> . . . The oil, therefore, is ready to flow upward and move out of the lens as soon as a path presents itself.

Oil Migration: Spring Behaviour of Oil and Ice

Martin, 1979, presents a detailed discussion of the oil-in-ice behaviour that was observed at the Balaena Bay site during the spring period. The migration process was summarized as follows:

> . . . sometime in late April, top-to-bottom brine channels in the ice opened up and observers at the site in early May saw oil on the ice surface under the snow.

snow.

> The most important oil absorption mechanism is this opening of the top-to-bottom brine channels. This allows the oil both to rise through the ice to the ice surface, and to permeate the channel systems within the ice. There is also a complicated region near the ice surface where the oil is absorbed laterally in horizontal layers, apparently because of the interaction of melt water from the snow percolating down and oil rising up.

Martin, 1979, uses data collected during a test conducted at the Balaena Bay site on May 15, 1975 (in which 1.95 m^3 of Norman Wells crude oil was discharged under the ice) to determine an average rise velocity for the oil during migration of 0.7 mm/sec.

The volume of oil in the ice is another subject discussed by Martin, 1979. Typically, the oiled ice cores contained less than 3% oil by volume. The most heavily-oiled ice core contained 5.5% oil by volume and was found at a site where the sea ice had a preferred crystal orientation. Martin, 1979, states that this

> . . . suggests that large feeder czhannel systems within plane parallel crystals may absorb more oil than ice with non-aligned crystals.

Martin, 1979, summarized the interaction of the oil and ice in the spring and summer as follows:

> In the spring, this oil flows up to the surface through the newly-opened brine channels and distributes itself within the brine channel feeder systems, on the ice surface, and in horizontal layers in the upper part of the ice. The paper shows that these layers probably form from the interaction of the brine drainage with the percolation of melt water from surface snow down into the ice and the rise of the oil from below. Finally in the summer, the oil on the surface leads to melt-pond formation. The solar energy absorbed by the oil on the surface of these melt ponds eventually causes the melt pond to melt through the ice, and the oil is again released into the ocean.

Comfort, G., Roots, T., Chabot, L. and Abbott, F. 1983. Oil Behaviour Under Multi-Year Ice at Griper Bay, N.W.T. Proceedings of the Sixth Arctic and Marine Oilspill Program Technical Seminar, Environment Canada, Ottawa.

This study is also reported in ARCTEC 1983; Comfort and Purves, 1980 and Comfort and Purves, 1982.

Editor's Note: This was a longterm project and the above references relate to individual site visits made in 1979 (Comfort and Purves, 1980; 1982) and in 1982 (Comfort, Roots, Chabot, and Abbott, 1983; ARCTEC, 1983). In order to provide an overall description of the project, the above references have been summarized together in the following review.

This experimental spill program was undertaken at Griper Bay, N.W.T., to investigate the interaction of crude oil with multi-year ice.

Results

A total of 1.83 m^3 of Norman Wells crude oil, equally distributed between three different sites, was discharged under multi-year ice on June 1, 1978. Little information is available to describe the oil-in-ice behaviour soon after discharge. In general, the oil behaviour is believed to have been similar to that observed during other field spills (e.g. NORCOR, 1975) in that the oil rose to the under-ice surface where it spread and pooled in the under-ice depressions. It then became encapsulated in the ice. The area was overflown during the 1978 summer and a considerable amount of oil was observed on the ice surface at sites 1 and 2. A large crack which crossed site no. 3 was observed by July 1, 1978.

Comfort and Purves (1980, 1982) describe the results of a field visit made during September 1979. The three sites were drilled and cored to determine the amount of oil within the ice. Oil was found in the ice at sites 1 and 2. The amount of oil within the ice at site 3 was very small. However, oil was on the surface and bottom of the ice, in the vicinity of the crack crossing site 3.

The sites were next visited during September, 1982 (Comfort et al., 1983; Arctec, 1983). No oil was found at any of the sites.

Table 1 (from Comfort et al., 1983) summarizes the results of the September, 1979, site visit.

Table 1 Summary of September, 1979, Site Investigation

Site No.	**1**	**2**	**3**
Oil Volume in Ice:			
Amount of oil remaining in ice relative to total volume discharged at site	1 %	10 %	-
Estimated Mass Percent Evaporation	**Surface Sample**	**Oil-in Ice Sample**	
Oil Weathering:			
Minimum	37%	12%	
Maximum	43%	20%	
Mean	42%	17%	

Table 2 summarizes the oil-in-ice concentration data collected during the field program.

Table 2 Oil-in-ice Concentration Data Summary

Time	Area of Oiled Ice (m^2)	Mean Ice Thickness (m)	Volume of Oil in Ice (m^3)	Mean Oil-in-ice Concentration (%)
Spill Site 1				
June, 1978 (i.e.Discharged)	6.1[a]	2.7[b]	0.61	3.7
Sept.,1979	26.3	1.0	0.0038	0.007
Sept.,1982	0[c]	0[c]	0[c]	0[c]
Spill Site 2				
June 1978 (i.e.Discharged)	3.1[a]	2.7[b]	0.61	7.3
Sept., 1979	11.6	2.2	0.065	0.25
Sept., 1982	0[c]	0[c]	0[c]	0[c]

a Area of oil pool underneath ice immediately after discharge.

b Mean ice thickness at time of discharge.

c Below measurable limits.

This field survey has provided

information on the rate at which the quantity of oil remaining in a multi-year ice environment, due to small spill, will decay with the passage of time through the natural processes of dispersion and evaporation.

The available data can be bounded by an inverse exponential equation of the form:

$$V = me^{-bt}$$

where: V = mean oil-in-ice concentration (in percent)
t = number of melt seasons after the oil discharge occurred

Constants for the above equation have been evaluated on the basis of the available data to determine upper and lower bound solutions using the following assumptions:

(a) mean oil-in-ice concentrations of 0.00001% will not be detected by a visual inspection; consequently, this value has been used as the endpoint value for the available data.

(b) The lower bound solution is based upon an observed oil-in-ice concentration of 0.007% (i.e., site 1 data) after two melt seasons had elapsed, and an assumed oil-in-ice concentration of (0.0001% after three melt seasons.

(c) The upper bound solution is based upon an observed oil-in-ice concentration of 0.25% (i.e., site 2 data) after two melt seasons had elapsed, and an assumed oil-in-ice concentration of 0.0001% after five melt seasons.

The following constants were obtained:

SOLUTION	m	b	r^2
Lower Bound	4.4	-3.5	0.994
Upper Bound	11.3	2.3	0.988

Figure 7 graphically shows the decay of the oil-in-ice concentration as predicted by the above lower and upper bound descriptors.

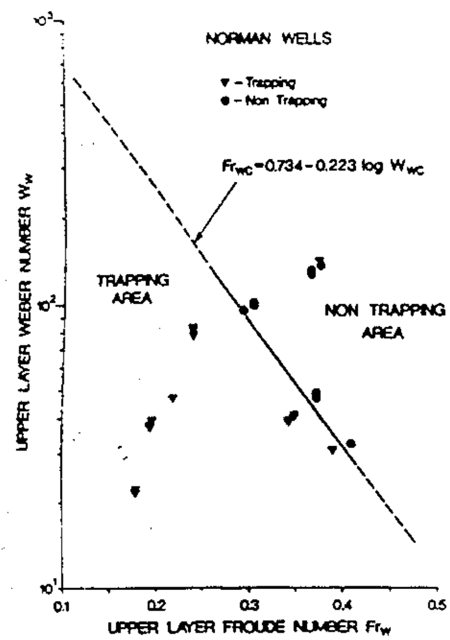


Figure 7 Decay of Oil-in-Ice Concentration

Dickins, D. and Buist, I. 1981. Oil and Gas Under Sea Ice. Prepared by Dome Petroleum Ltd. for COOSRA, Report CV-1, Volumes I and II.

This study is also reported in Dickins, Buist and Pistruzak, 1981 and Buist, Pistruzak and Dickins, 1981.

A field program was undertaken during the 1979-80 winter to investigate the fate and behaviour of oil and gas mixtures that are released under a static, continuous, sheet of first year sheet ice; and the cleanup of these materials by combustion.

Prudhoe Bay crude oil and compressed air were released under the ice at McKinley Bay, N.W.T., at flowrates intended to simulate a subsea blowout in 20m of water. Four discharges were conducted as summarized below:

Discharge Date	Phase No.	Total Volume of Oil Discharged (m^3)	Total Volume of Air Discharged (m^3- Ambient Conditions)
Dec. 17, 1979	1(Dry Run)	0	950
Dec. 18, 1979	1	5.85	1711
Apr. 10, 1980	2	6.56	435
May 2, 1980	2a	6.8	1219

An extensive monitoring program was carried out. The behaviour of the oil and gas during discharge was documented using divers and underwater photography. Subsequently, a coring program was carried out which provided information regarding the configuration of the oil and gas in the ice, and after analysis of the oiled ice samples, data to define the oil droplet size distribution. Measurements were made of many physical environment parameters including the ice thickness distribution, under-ice currents, the size and shape of the plume (using an echosounder), the temperature profile, the ablation of the snow and ice surface, the incident solar radiation and the surface albedo.

Results

Plume Dynamics and Under-Ice Spreading

Dickins, Buist and Pistruzak, 1981, describe the dynamics of the plume as follows:

> As the gas and oil mixture left the discharge pipe, the violent turbulence at the exit broke the oil into droplets. At the same time, the gas flow set up around the discharge pipe a inward current that drew in some silty sediments from the sea floor. The rising gas carried with it the oil droplets and entrained sediment as it rose in cylindrical "jet" towards the surface.
>
> Apprroximately 6 m above the discharge pipe, an upwards and outwards water current was generated by the rising gas "jet." This outward current, or plume, carried with it some of the oil particles and sediment. The sediment settled out of the plume and the oil droplets rose, due to their buoyancy.
>
> When the jet stream rose to within 7 m of the ice-water interface, it began to spread radially outwards, creating turbulent eddies that decayed within 15 to 20 m to a laminar outward flow. The gas quickly rose to the ice-water interface; the oil droplets floated up, but much more slowly, to impinge on the ice or collect in gas pockets. The entrained sediment "rained" out of the plume.

Figures 6 and 8 show the oil droplet distribution.

The interaction of the oil, gas, and ice was summarized by Dickins, Buist, and Pistruzak, 1981, as follows:

> As the gas rose out of the jet stream, it quickly collected in pockets under the ice. Once collected under the ice, the gas would flow "uphill," following natural under-ice contours and a slight tilt in the ice sheet until it reached a

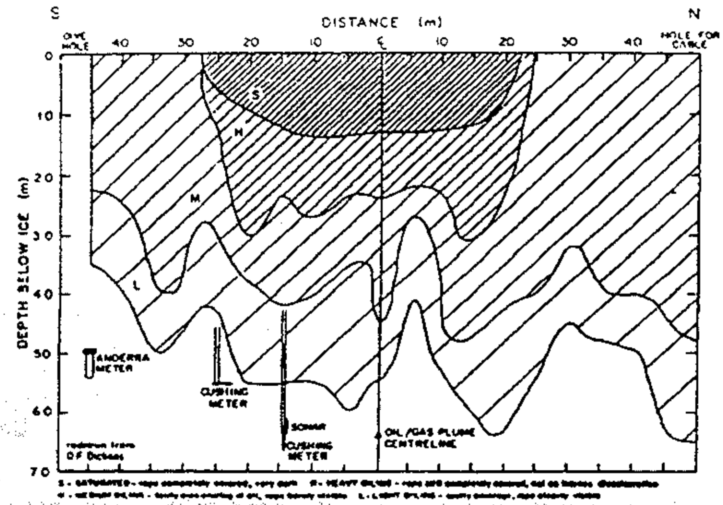


Figure 6. Distribution of oil droplets in a water column.

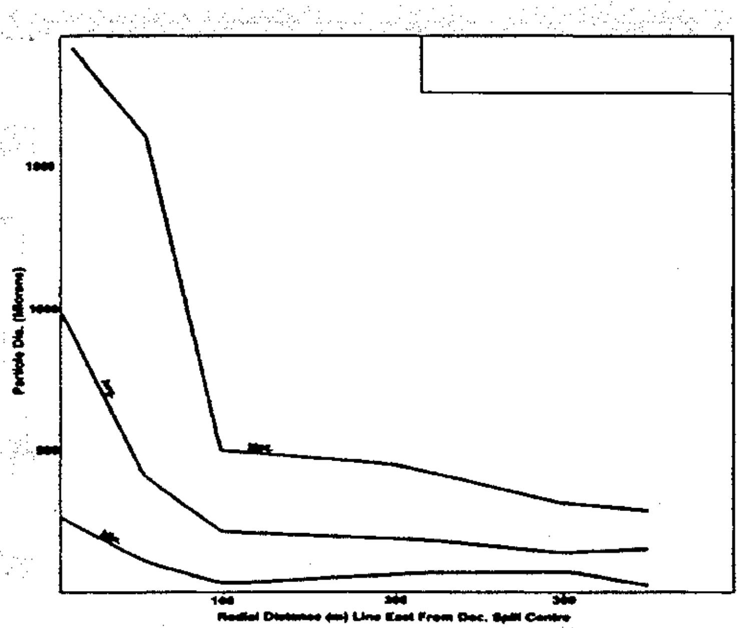


Figure 8. Oil particles size as radial distance.

> point of equilibrium . . .
>
> . . . During the Phase I dry run, when the ice was only some 65 cm thick, the gas pocket pushed the ice up in a dome some 50 m wide and 1 m high. The domed ice cracked and vented off the gas.
>
> During the Phase I discharge, an estimated 50 percent of the gas vented through the auger holes and carried with it water and some 0.5 m^3 of oil, which pooled on the surface and quickly froze. Since the Phase II discharge was performed at a reduced air flow rate, the area of oil contamination was much reduced over the Phase I discharge (30-m radius as opposed to 50-m, or one-third the area).
>
> The oil behaviour in the Phase II and II-A discharges was different from that in the Phase I discharge. In December, the under-ice surface was relatively smooth; thus, most of the oil was oserved as discrete particles, and a few pockets of oil and gas were found.
>
> In April and May, the under-ice surface was typically "wavy", as a result of differential freezing due to the insulating effects of snow drifts. Much of the oil collected in the "pockets" under the ice.

Editor's note: The gas did not vent through the ice for the April and May discharges.

Dickins and Buist, 1981, concluded that

> There were three basic configurations of oil and gas under the ice:
>
> 1. oil droplets;
> 2. gas bubbles with a coating of oil; and
> 3. large pools of oil underneath gas pockets.
>
> The oil droplet and gas bubble configuration predominated for the discharge under new flat ice [configurations 1 and 2] and oil pool configurations [configuration 3] predominated for the discharge under older ice with under-ice undulations.

Dickins and Buist, 1981, further observed that the presence of gas was an important factor affecting under-ice spreading. They stated that "The areal extent of contimination was reduced by 65% by reducing the gas flowrate and the GOR [gas-to-oil ratio] by 90%"

They also noted that the areal extent of contamination was not affected significantly by venting of the gas through the ice sheet.

Encapsulation

Dickins and Buist, 1981, observed that, for all tests, the oil was encapsulated by the growing ice sheet within 24 to 48 hours after being discharged. Encapsulation was "not adversely affected by the presence of gas".

Vertical Migration

The encapsulated oil surfaced during the spring melt as a result of two proceses (i.e., ablation of the ice surface down to the level where the oil lens was located in the sheet, and migration through the brine channels in the ice). The ablation "process was responsible for exposing the majority of the oil in the Phase I test site, since this discharge took place under relatively thin ice". Vertical migration through the brine channels was considered to be the main process responsible for releasing the oil spilled during the Phase 2 tests, particularly the April 10 test in which a reduced volume of air was released with the oil.

The observed oil behaviour (with respect to migration) was compared to that which occurred during the Balaena Bay oil spill program (conducted by NORCOR, 1975). Although ablation and vertical migration occurred during both field programs, it was concluded that the ablation process was responsible for releasing more of the oil spilled at McKinley Bay while the reverse was true for the Balaena Bay tests. The dominant factor responsible for this variation was considered to be differences in the under-ice oil distribution (and possibly, the oil viscosity).

Dickins and Buist, 1981, observed that

> Ice ablation accounted for the majority of the oil exposure at the discharge site under new, flat ice where the oil was present as discrete droplets. Migration accounted for the majority of the oil exposed at the discharge under older undulating ice where the oil was present in pools.

At Balaena Bay, most of the oil was present in pools rather than as discrete droplets. As effective oil migration cannot occur unless there is hydrostatic communication between the oil pools, the air and the seawater, less vertical migration is to be expected when the oil is distributed under the ice in discrete droplets.

The release timing was also investigated.

> Figure 9 illustrates the timing of the appearance of oil on the ice surface. Two facts were apparent: first, that the oil began to surface slowly and then, in a matter of days, the majority was exposed; and second, that the oil's surfacing seemed to be dependent on the time of year (i.e., ice thickness) that it was spilled under the ice: the earlier it was spilled, the earlier it appeared. Prior to breakup, approximately 85 percent of the oil had surfaced. None of the oil rising from the ice sheet was in an obvious emulsified (water-in-oil) form.

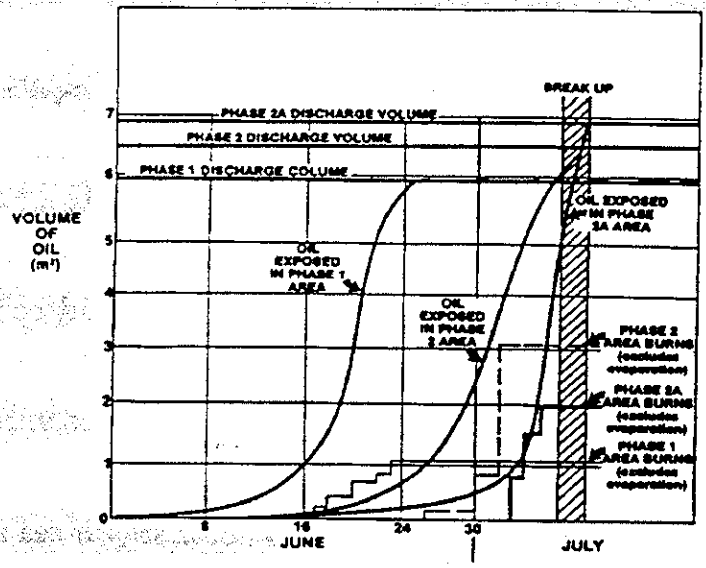


Figure 9. Preliminary mass balance on oil—burns only (no evaporation or manual cleanup included)

Buist, I. and Dickins, D. 1983. Fate and Behavior of Water-in-Oil Emulsions in Ice. prepared by Dome Petroleum Ltd. for the Canadian Offshore Oil Spill Research Association (COOSRA), Report No. CS 11, Calgary.

This study is also reported in Buist, Potter and Dickins, 1983.

A field project was conducted to investigate (a) the fate and behaviour of stable water-in-oil emulsions that are released under first year sea ice and (b) the cleanup of these materials. This experimental spill program was carried out at McKinley Bay, N.W.T. It was commenced on March 20-21, 1982, when 192 L of a 60% oil-in-water emulsion was released under a 1.65 m thick sheet of first year sea ice at each of two sites. An equal quantity of Kopoanoar crude oil only was discharged at a third site as a control.

Results

Buist, Potter and Dickins, 1983, made the following observations regarding oil fate and behaviour:

Discharge and Encapsulation

All discharges were characterized by the following general observations:

a) oil (emulsion and crude) broke onto discrete globules within 15.3 cm of the hose end;

b) these individual viscous globules floated slowly up against the ice and remained at the point of contact, with a distinctly irregular shape;

c) spreading laterally from the point of first contact was negligible for the emulsions and less than 61 cm for crude oil;

d) on completion of the discharge, the emulsion distribution remained static, with an irregular, "lumpy" texture; many highly viscous projections and globules of emulsion were visible, resulting in a rather grotesque appearance.

> The crude oil adopted a somewhat more uniform coating than the emulsion, as would be expected from the significant viscosity differences (26 vs 184 cSt @ 10^0C . . .)
>
> Within 24 hours of discharge, new ice crystals were observed forming within the emulsion itself. By 48 hours, both the emulsion and crude oil were almost completely incorporated within a thin skim of 2 to 3 mm new ice growing beneath the oil. The visual appearance and colour of the oil did not change during this incorporation process.

Buist, Potter and Dickins, 1983, found that by June 20 about 20 cm of new ice growth had occurred beneath the oil and the water-in-oil emulsion layers. A similar increase was observed for natural ice over this same period. They note that these results agree with previous field studies (conducted by Norcor, 1975, and Dickins and Buist, 1981) which also found that the presence of oil layers within the ice had no measurable effect on the maximum ice thickness reached.

Vertical Migration

The water-in-oil emulsions and the crude oil both migrated to the ice surface in the spring as the ice sheet deteriorated.

Buist and Dickins, 1983, observed that the crude oil began to appear on surface melt pools by mid-June whereas significant quantities of water-in-oil emulsions did not surface until July 5. They attributed this delay to the high viscosity of the water-in-oil emulsions (in comparison to the oil) which prevented them from flowing up the open brine channels. The release of the emulsions was effected by other processes. The dominant ones were considered to be ablation of the ice surface and "en masse" melting of the emulsion layer up through the ice (due to the absorption of incoming solar energy by the black emulsion layer).

Buist and Dickins, 1983, found that most (about 90%) of both the oil and the water-in-oil emulsions were released from the sheet by July 8 (which was one day prior to the breakup of the sheet).

Effect of Physical Behaviour of the Oil

Buist and Dickins, 1983, found that "the emulsion did not "break" during its encapsulation in the ice sheet or during its exposure on the ice surface".

Nelson, W.G., and Allen, A. 1981. Oil Migration and Modification Processes in Solid Sea Ice. Proceedings, 1981 Oil Spill Conference, American Petroleum Institute.

Small scale field tests were conducted over the 1979/1980 winter at Prudhoe Bay, Alaska, to investigate "the migration of Prudhoe Bay crude oil and diesel fuel within sea ice, and the effect of oil inclusions on ice growth rates." A total of 18 tests were conducted by discharging small quantities (i.e., 1.5 to 18 gal.) of diesel, Prudhoe Bay crude oil and emulsions under first year sea ice at various stages of its growth. The ice thickness at the time of discharge ranged from 15 to 57 cm.

Results

Migration

Only surface observations were made during the winter months. Nelson and Allen, 1981, report that "surface migration of the injected diesel fuel and crude oil was observed".

The tests were terminated on March 25, 1980 when the oiled ice at each site was removed from the parent ice.

For the diesel fuel tests, no lenses were observed in the ice. Nelson and Allen, 1981, report that this indicates that "the diesel fuel had migrated rapidly before the ice could form below the diesel fuel". They further report that diesel fuel inclusions, ranging in size from those just visible to the eye to 1 cm, were observed at the injection sites and along the diesel fuel migration paths.

For the crude oil tests, Nelson and Allen, 1981, report that "significant vertical migration of crude oil was observed at all hot oil injection sites." The authors compare their results qualitatively with observations that were made by NORCOR, 1975, during field tests conducted at Balaena Bay, N.W.T. Their results seem to indicate that significant vertical migration occured earlier than was the case at Balaena Bay, N.W.T., where oil migration was observed to be most significant during spring when the brine channels had enlarged. However, the authors point out that, at times, the sites were covered by abnormally deep snowdrifts. This could have resulted in warmer ice temperatures that would be more representative of spring conditions and the authors postulated that the observed vertical migration occurred during those time periods.

For the emulsified oil tests, Nelson and Allen, 1981, report that "the injected emulsions did not migrate in the vertical direction to any extent."

Thermal Resistance of Included Oil Layers

"The thermal resistance of included oil layers was computed on the basis of temperature and ice growth measurements by comparing the growth rates of surrounding unoiled experimental sites with those of the sites in question." At sites 2 and 3, the thermal conductivity of the oil layer was found to be "lower than the thermal conductivity of sea ice by a factor of at least 20."

Nelson and Allen, 1981, present preliminary results obtained from a laboratory cold room study that was conducted to determine the thermal conductivity of Prudhoe Bay crude oil encapsulated in an ice sheet. These results are summarized in Table 2.

Table 2. Laboratory Measurement of the Thermal Conductivity of Prudhoe Bay Crude Oil Layers

Crude oil layer thickness cm	Temperature of layer bottom °C	Temperature of upper surface °C	Thermal conductivity W/m-°C
12.5	-0.1	- 3	0.78
12.5	0.1	-28	0.29

A lower conductivity was measured for the case where the oil layer had a lower average temperature. This trend was attributed to the "higher viscosity of the oil and thus lower convective motion".

4.2 Associated Field Studies of Under Ice Roughness - Literature Review

Kovacs, A. 1977. Sea Ice Thickness Profiling and Under-ice Oil Entrapment. Paper 2949, Proceedings of the 9th Annual Offshore Technology Conference.

Field studies were conducted to measure the thickness profile of continuous sheets of first year sea ice and multi-year sea ice near Prudhoe Bay, Alaska. An electromagnetic impulse radar system was used to obtain a continuous record of the ice thickness profile.

Results

The under-ice storage capacity was computed by determining the area of the cavities in the profiles that were above the level of the mean ice thickness. The results are summarized below:

Ice Type	Length of Profile (m)	Mean Ice Thickness (m)	Computed Under-Ice Storage Capacity (m^3/m^2)
First year sea ice	382.5	1.91	.027
Multiyear sea ice	930	Not given in paper	.293

Barnes, P., E. Reimnitz, L. Toimil, and H. Hill. 1979a. Fast Ice Thickness and Snow Depth in Relation to Oil Entrapment Potential, Prudhoe Bay, Alaska. USCG Open File Report 79-537, Menlo Park, CA.

This study is also reported in Barnes, et al., 1979b.

Field studies were conducted to document the under-ice relief at three sites in the landfast ice near Prudhoe Bay, Alaska. The relationship between the under-ice topography and the surface snow cover was investigated and an assessment of the under-ice oil storage capacity was made.

The field work was carried out over the April 29 to May 15, 1978, period at sites "representing three different fast-ice environments - protected bay, deep, open lagoon, and narrow tidal channel".

One hundred metre long trenches were cut at each site parallel to and perpendicular to the predominant snow ridge direction. The ice thickness was measured at 2 m intervals and observations of the under-ice morphology were made using an upward-looking side-scan sonar, underwater television and divers. A time-lapse camera was also used to monitor changes in snowdrift patterns at one of the sites.

Results

Barnes et al., 1979a, summarize the under-ice morphology as follows:

> Snow depth and ice thickness vary 30-40 cm along the trench transects and exhibit a negative correlation - thin ice coinciding with a thicker insulating snow cover . . . . Elongate ridge and trough patterns on the ice bottom parallel the surface snow ridge patterns with wavelengths of typically 10 m. . . . Diving observations indicate a smaller set of depressions 5 cm or less in depth, oriented parallel to the ice crystal fabric, and show rapid release of exhaust air through the ice canopy at the ice surface.

Barnes et al., 1979a, observed that the surficial snow was mobile while the underlying snow ridges were stable. They suggest that "the oriented snow ridges and troughs form early in the ice growth season, to allow sufficient time for the development of ice thickness variations" and that the transport of surficial snow has little effect on the further development of under-ice roughnesses. They state that "the results imply a seasonal stability for the snow ridge pattern."

The under-ice storage capacity was determined based on the following rationale and description of the spreading process:

> Oil rising to the ice bottom will spread laterally, equalizing at some level beneath the ice, depending on the elevation of "passes" between adjoining ridges and troughs. Intuitively, "passes" in the under-ice ridge and trough pattern should exist near the mean draft computed for the ice. Thus the potential oil collecting pools, determined from our calculations, are based on the relief above a computed mean draft at each site. . . .

The computed storage volumes are summarized below:

Site No. and Location	General Site Description (after Barnes et al. 1979a)	Measured Average Ice Thickness (m)	Measured Average Snow Depth (cm)	Volume of Sub-ice Pools Above Average Draft
1-Prudhoe Bay	Protected bay	134	24	47,000 m^3/km^2
2-Stefansson Sound	Deep, open lagoon	157	15	25,400 m^3/km^2
3-Tidal inlet	Narrow tidal channel	153	24	36,200 m^3/km^2

Barnes et al., 1979a, compare their results and approach with that of Kovacs, 1977, who determined an under-ice storage volume of 27,500 m^3/km^2 for the fast ice based on ice thicknesses measured along a linear profile using electromagnetic techniques. Barnes et al., 1979a, point out that they estimated the under-ice storage capacity based on the area of the under-ice pockets that were above the level of the mean draft while Kovacs' 1977 analyses were based on the under-ice cavity areas above the level of the mean ice thickness. Barnes et al., 1979a, state that " draft values take into account the isostatic effects and result in lower volume estimates".

Kovacs, A., R.M. Morey, D.F. Cundy, and G. Decoff. 1981. Pooling of Oil Under Sea Ice. Proceedings, POAC 81: Sixth International Conference on Port and Ocean Engineering under Arctic Conditions, Quebec, pp 912-922.

The objective of this study was to assess the volume of oil that could be stored in the roughnesses that are present beneath a continuous, undeformed, sea ice sheet. Kovacs et al. (1981) note that "oil released under fast ice will spread, systematically filling up depressions or pockets" and that "the under-ice relief will govern which directions the oil will advance in, which pockets it will accumulate in, and the depth to which it will pool up in the pockets".

Field measurements of under-ice relief were made at six sites near Prudhoe Bay, Alaska. The measurements were made using an impulse radar sounding system which provided a continuous record of the ice thickness profile. Contour maps of the under-ice relief were produced at one site while linear profiles were obtained at the other sites.

Results

Kovacs et al., 1981, observed that

> The sounding data revealed in detail the undulating relief of the bottom of the sea ice in which oil could pool up if released under the ice. In general. ice bottom morphology was found to reflect variation of the surface snow cover thickness and ice deformation. However, at several sites the ice bottom relief could not be correlated with these factors. Slush ice accumulations of up to 0.5 m were apparently the cause of this bottom roughness. . .

The under-ice storage volume was computed by assuming that all cavities above the level of the mean ice thickness were filled. The reported results are summarized below:

Site	Measured Mean Ice Thickness (m)	Measured Ice Thickness Standard Deviation (m)	Computed Storage Volume (m^3/km^2)	Data Basis for Storage Volume Estimate
Tigvariak Island	1.546	.031	32,000	Average of 18 linear profiles, each 150m long spaced 1.1 m. apart.
Reindeer Island	1.33	0.01	10,000	Estimated based on an expected minimum oil slick thickness of 1 cm. The ice thickness data were not used to produce this estimate.
West Dock Site	1.83	0.15	60,500	Mapping over a 127m X 165m area with lines spaced 1.65m apart. The ice was reported to have undergone "minor pressuring" during early fall freezeup as uplifted ice blocks 15 cm thick were observed.
Site A	1.52-1.53 Avg. 1.523	Not Reported	23,700-25400 Avg. 24,800	Range of values for three 220 m long linear profiles that were configured in a triangle
Site B	1.57-1.61 Avg. 1.59	Not Reported	20,900-26,400 Avg. 23,900	Range of values for three 220 m long linear profiles that were configured in a triangle
Site C	1.57; 1.60	Not Reported	45,200; 57,400	Two 220 m long linear profiles. Kovacs et al. 1981, report that "slush keels" were present and caution that "the effect of slush ice relief and structure on potential under-ice pooling is for the most part unknown".

Comfort, G. 1986. Under-Ice Roughness Measurements, ARCTEC Canada Ltd. For the Environmental Studies Revolving Funds, ESRF No. 265-26-04.

The objective of the work was to obtain data on under-ice roughness for a continuous ice sheet and to assess the under-ice storage capacity.

Measurements of the ice thickness were made along six profiles over an approximate 60 m X 60 m grid by drilling the ice at intervals of one to two metres. Ice thickness data were collected for a 1.2 m thick sheet of first year sea ice at Seal Island, Alaska, (which is located in the Beaufort Sea) and for a 0.8 m thick freshwater ice sheet at Thunder Bay, Ontario.

Results

Under-Ice Storage Capacity

The under-ice storage capacity was computed for each of the measured thickness profiles for a range of fill depths. For the case where the under-ice depressions are only filled to the level of the mean ice thickness, the average under-ice storage capacity was determined to be 0.023 m^3/m^2 and 0.022 m^3/m^2 for the Seal Island and the Thunder Bay sites respectively. If the under-ice roughnesses are filled to the level of the maximum ice thickness, the average storage capacity was increased to 0.13 m^3/m^2 and 0.092 m^3/m^2 for the Seal Island and the Thunder Bay sites, respectively.

The following power curve was fitted to the data:

$$s = a F_d^x$$

where:

s = storage capacity

a = a dimensional constant

$$F_d = \frac{\text{depth of oil and/or gas in the under-ice depression}}{\text{maximum variation in ice thickness}}$$

The above constants were evaluated for the Seal Island and Thunder Bay data sets as follows:

Table 4.2 Power Curve Constants

Measurement Locations	a (m^3/m^2)	x	Correlation Coefficient $-r^2$
Seal Island	0.140	2.67	0.93
Thunder Bay	0.083	2.70	0.94

The calculated storage volumes were compared with values determined by Kovacs, 1981, on the basis of ice thickness mapping and profiling that was carried out near Prudhoe Bay, Alaska. Kovacs, 1981, computed values ranging from 0.021 m^3/m^2 to 0.061 m^3/m^2 for the case where the under-ice depressions are filled only to the level of the mean ice thickness.

Goodman, R., and and Holoboff, A.G. 1987. The Use of Polysulphide Rubber Molds to Measure Oil Storage Volumes, Proceedings of the Tenth Arctic Marine Oilspill Program Technical Seminar, Edmonton, pp 459-467.

This study is also reported in Goodman et al., 1987.

The objective of this work was to obtain information regarding the under-ice oil storage capacity of continuous, undeformed sheets of first year sea ice. This study examined the under-ice oil storage capacity for small scale roughnesses (i.e., roughnesses that occur "at a scale of a few centimetres with an amplitude of a few millimetres").

The work was conducted by making molds of the under-ice surface which were analyzed subsequently using stereo photography and by making volumetric measurement using progressive flooding techniques. A total of 12 molds, each with an area of about 1 m^2, of the under-ice surface were obtained. The field work was carried out at ARNAK, an artificial island in the Beaufort Sea, where the ice cover consisted of a landfast ice sheet. At the time of the field program, the ice cover was "at its maximum thickness, (about 2 m)" and "there was little ablation".

Results

Table 1 summarizes the storage volumes that were measured when the molds were fully-covered with oil.

Goodman and Holoboff, 1987, show that the under-ice storage volume increases greatly as the under-ice voids become filled more completely. Their data, and visual observations of the mold, indicate that "the surface roughness of the ice does not have a continuous spectrum, but rather consists of a few large features which occur on a generally flat surface."

TABLE 1 Average Ice Roughness Values		
Location	Average Roughness Photogrammetric m^3/m^2	Average Roughness Volumetric m^3/m^2
Site A		
Hole 1	0.009	0.008
2	0.013	0.014
3	0.010	0.010
4	0.011	0.012
Site B		
Hole 1	0.012	0.011
2	0.013	0.014
3	0.014	0.013
4	0.011	0.010
Site C		
Hole 1	0.010	0.011
2	0.011	0.010
3	0.018	0.016
4	0.010	0.011

Goodman and Holoboff, 1987, compare the average under-ice storage volume measured during their experiments (i.e., 0.012 m^3/m^2) with other values in the literature. Kovacs, 1981, and Comfort, 1986, determined storage volumes ranging from 0.010 m^3/m to 0.130 m^3/m.

Goodman and Holoboff, 1987, conclude that

> Initial observations in the field showed that there was a significant structure at a length scale of several centimeters, with a roughness of a few centimeters.
>
> This roughness contributes to the ability of ice to store oil spilled under the ice.

4.3 Laboratory Tests of Spreading, Encapsulation and Release - Literature Review

Wolfe, L.S., and Hoult, D.P., 1972. Effects of Oil Under Sea Ice, Fluid Mechanics Laboratory Publication No. 72-10, Department of Mechanical Engineering, M.I.T., Cambridge, MA.

This study is also reported in Wolfe and Hoult, 1974

The objective of this study was to observe, at laboratory scale, "the mode by which oil that is released beneath a sheet of sea ice becomes entrapped in the ice."

The tests were conducted in a 30.4 cm X 30.4 cm tank using a sheet of laboratory-grown saline ice. Two oil types (No. 2 diesel and North slope crude) were released under the ice during the test program.

Results

<u>Encapsulation</u>

It was found that the bulk of the oil was deposited under the ice and encapsulated as a lens in the ice by the subsequent ice growth which occured beneath it. A small amount of oil was observed to rise up into the skeletal layer of the ice.

Keevil, B.E. and R. Ramseier. 1975. Behaviour of Oil Spilled Under Floating Ice. Proceedings, 1975 Conference on Prevention and Control of Oil Pollution, American Petroleum Institute, pp 497-501.

This study is also reported in Chen, Keevil and Ramseier, 1976a and 1976b.

Laboratory tests were carried out to provide an "understanding of the mechanisms involved" when oil is spilled under floating ice.

> The objectives of the study are. . . to (1) conduct cold room experiments to determine the fate and behaviour of spilled crude oil under floating ice; (2) correlate the behaviour of spilled crude oil in cold room tests with accidental spills in the field.

The tests were conducted in a cylindrical basin, 1.5 m in diameter by 0.7 m deep, that was installed in a cold room.

Results

Under-ice Spreading

When released from the injection pipe, the oil was observed to separate into "hundreds of small globs or particles 0.1 to 2.0 cm in diameter". The particles rose up to the under-ice surface where they assumed a "flattened" shape due to the presence of the under-ice boundary and the action of buoyancy forces. Slicks with a thickness of about 1 cm were produced under the ice. Keevil and Ramseier, 1975, observed that the "oil particles spread in fairly uniform circular rings" under the "smooth planar ice" that was present in the tank.

The following spreading model was developed based on a spreading coefficient, S, which reflects the "energy expended in forming the ice-oil interface":

$$\gamma_{IW} = \gamma_{IO} + \gamma_{OW} \cos \theta$$

$$S = \gamma_{IW} - \gamma_{OW} - \gamma_{IO} = \gamma_{ow} (\cos \theta - 1)$$

For spreading, S is positive and for non-spreading, S is negative.

where: $\gamma_{IW}, \gamma_{IO}, \gamma_{OW}$ = interfacial tension at the ice-water, the ice-oil, and the oil-water interfaces, respectively.

θ = oil-ice contact angle

Keevil and Ramseier, 1975, caution that

> The spreading rate of oil under ice depends on interfacial tension forces and hydrostatic forces derived from density differences between oil, ice, and water. In addition, the spreading rate depends on the injection rate, particle formation, ice roughness, and the ability of the oil to fractionate according to different solubilities of some components. As a result, the spreading mechanism is complicated and there is no simple realistic equation to predict spreading rate.

<u>Encapsulation</u>

Keevil and Ramseier, 1975, observed that

> While the oil particles spread under the ice, coalesce, and form an oil lens, the ice continues to grow. First, the ice grows down around the sides of a lens and then underneath, sandwiching the lens betwen ice layers. Even with a slow ice growth rate (0.5 cm/day) or when the oil covers the whole ice-water interface, the oil is not pushed ahead by the growing ice. During one experiment, 5 litres of oil was sandwiched under 10 cm of ice.

Keevil and Ramseier, 1975, observed a large temperature drop across the oil lens and attributed this to the added thermal resistance of the oil in comparison to the surrounding ice. However, the ice growth rate was not significantly altered by the presence of an oil lens.

Purves, F. 1978. The Interaction of Crude Oil and Natural Gas with Laboratory-grown Saline Ice. Prepared by Arctec Canada Limited for the Environmental Protection Service, Environment Canada, Report No. EPS-4-EC-78-9.

The objective of the work was to observe, at laboratory scale, the behaviour of oil and gas bubbles released under a static, continuous sheet of saline ice. The test program examined the resulting configuration of oil and gas bubbles under the ice, and vertical migration of the oil and gas.

The tests were conducted in 1.2 m X 1.2 m tanks in a cold room. Droplets of Norman Wells crude oil and bubbles of methane gas were injected under the ice at a gas/oil ratio of 100:1.

Results

Configuration of the Oil and Gas Under the Ice and Under-Ice Spreading

Gas bubbles were released initially. These spread and coalesced to form a large bubble which underlaid most of the sheet. Oil droplets were then released which rose up and impinged upon the bottom of the gas bubble. The oil droplets formed a large sessile pool and spread over the bottom of the gas bubble. However, the oil volume was insufficient to fully coat the bottom of the gas bubble. The final configuration consisted of a gas bubble under the ice with oil beneath it which coated an estimated 80% of its bottom surface.

Purves, 1978, concludes that "at gas to oil ratios of 60:1 or greater, the pool of Norman Wells [crude oil] will not coat the entire bubble surface" and that "oil layers as thin as 0.2 cm will probably be encountered when well blowout products accumulate under ice". He further concludes that "the presence of gas greatly increases the area contaminated by oil spilled under the ice."

Encapsulation

The experiment was extended by allowing the ice to continue to grow. Purves, 1978, reports that "the gas/oil bi-layer will freeze in, as has been observed with pure oil lenses, and will be stable until (in first year ice) the minimum temperature in the sheet profile reaches -3.6^{0}C".

Vertical Migration and Release Timing of the Oil and Gas

After the oil and gas had been encapsulated into the sheet by the growing ice, the air temperature was gradually raised and the release of the oil and gas was observed.

It was found that release of the gas and oil did not occur until the minimum temperature in the sheet profile reached -3.6^0 C. The gas was released first through the brine channels. The gas release rate was small initially, but it became greater with increasing thawing-degree hours. The gas release rate was estimated at about 10^{-5} cc/cm^2-min when the ice had been exposed to about 70% of the total thawing degree hours required to fully release the gas. Although a few drops of oil were drawn to the surface with the gas, the bulk of the oil surfaced later.

Purves, 1978, concluded that "gas will be released much earlier than oil in the course of thawing a contaminated sheet" and that "the presence of gas has little or no effect on the release timing of oil trapped under first year ice."

Kisil, C.A., 1981. A Study of Oil and Gas in Fresh and Salt Water-ice Systems. University of Toronto, M.Sc Thesis, Toronto, Ontario.

The objective of the work was to examine the behaviour of oil and gas bubbles under a static, continuous ice cover. The following were investigated:

(a) the configuration of oil and gas bubbles released under an ice cover.
(b) the effect of the oil and gas on ice growth rates.
(c) migration and release of the oil and gas in the ice.

Analytical models were developed to predict the oil and gas bubble configuration, the effect of the oil and gas on the ice growth rate, and migration.

Experiments were carried out in an 11 litre aquarium which produced results that were compared with the analytical predictions. Tests were conducted in fresh and salt water by first releasing air under ice sheets that were grown in the tank and then adding oil. Norman Wells crude oil and pure hydrocarbons (toluene, mineral oil, cumene, and n-hexane) were used during the tests.

Results

For a description of under-ice spreading see the review of Kisil (1981) in Section 4.4.

Encapsulation: Effect of Oil and Gas on Ice Growth Rate

Experiments were conducted by releasing oil under an ice sheet after gas bubbles had already been injected beneath it.

Analyses were carried out by considering heat flow across the trapped oil and gas layer to occur by conduction only, and by a combination of conduction and convection, driven by buoyancy forces. These results were compared to the ice thicknesses observed during the laboratory experiments.

For all tests, the injection of oil and gas resulted in a reduction in the rate of subsequent ice growth. For all the freshwater ice tests and for the saltwater tests with oil only, the predicted ice thicknesses were within 10% of the measured values. It was found that the inclusion of convection-induced heat transfer "did not provide predicted values of ice depth closer to the experimental values than those obtained by considering heat transfer by conduction only".

For tests in which oil and gas were injected under saline ice at an oil-to-gas ratio of 0.06, the predicted values were "much lower" than the measured ice thicknesses. For tests in which relatively more oil was released (i.e., an oil-to-gas ratio of 0.24), the predicted results "agreed well" with the measured data. This variation was attributed to convective heat transfer resulting from surface tension gradients at the interfaces which was not modelled.

Kisil, 1981, recommended that future studies be conducted in a larger tank.

Migration and Release of the Oil and Gas

Kisil, 1981, proposed that the oil migration rate is controlled by melting of the ice, which acts to open up the brine channels and allows the oil to rise due to buoyancy forces.

The following expression was developed to predict the oil migration rate, U:

$$U = \frac{Ki}{\rho_i H_f} \left[\frac{T_s - T_o}{Z_o}\right]$$

where: K_i = thermal conductivity of the ice

T_s, T_o	=	temperatures at the ice surface and the oil location, respectively
Z_o	=	distance from the ice surface to the oil lens
H_f	=	latent heat of fusion of the ice
ρ_i	=	ice density

Kisil's experiments (described previously) were continued by thawing the ice, which had oil and gas trapped in it. The gas and oil migrated to the surface. Kisil, 1981, found that the gas escaped when the minimum ice temperature reached a range of values from -2.2° C to -6.0° C.

The results given by the above model were compared to the observed elapsed times for appearance of the oil and gas. For tests conducted with oil only, the predicted and the measured elapsed times agree within about 10%. The variation was significantly greater (i.e., up to about 50%) for the tests in which gas, and gas and oil, were released. This discrepancy was attributed to gas migration into the brine channels during the encapsulation process, which thus reduced the distance that the gas had to travel before escaping.

Payne, J.R., McNabb, G.D., Kirstein, B.E., Redding, R., Lambach, J. L., Phillips, C.R., Hachmeister, L.E. and Martin, S. 1984. Development of a Predictive Model for the Weathering of Oil in the Presence of Sea Ice. for NOAA/OCSEAP Office, Research Unit No. 640, Anchorage, Alaska

The overall objective of the work was to develop a model "to predict the chemical and physical weathering behaviour of oil released in the presence of first year sea ice." A number of studies were conducted to assist in the development of the model. These included tests in a refrigerated seawater tank about 0.8 m X 0.9 m X 3.5 m in size, which are summarized in this review.

The experiments were commenced by growing a thin sheet, consisting of about 8 cm of grease ice underlain by about 8 cm of columnar ice of simulated first year sea ice. About 5 L of fresh Prudhoe Bay crude oil was then injected under the ice and the ice sheet was allowed to continue to grow.

Results

The authors report that "within 23 hours, the spilled oil was completely encapsulated by a 5 mm (minimum) layer of columnar ice. . ."

Oil Migration

A thaw cycle was initiated subsequently. Oil flow rates through the brine channels were measured and compared to the brine channel migration equations developed by Cox et al. (1980).

The expression, given by Cox et al. (1980), for the minimum brine channel diameter, d, that will allow oil migration is

$$d = \frac{4\ \sigma_{ow}}{\delta} \cdot \frac{\cos\ \alpha}{(L_w - L_o)}$$

where: σ_{ow} = oil/water interfacial tension

α = angle of contact

δ = under-ice oil lens thickness

L_w, L_o = water and oil density, respectively

g = acceleration due to gravity

For the parameter values in Payne et al.'s experiment, the above expression yields a value for the minimum brine channel diameter of 3.6 mm, which the authors consider to be "reasonable".

The rise rate velocity, U_Z, is given by:

$$U_z = \frac{(L_w - L_o)\ g\ \delta\ d^2}{32\ L\ \mu}$$

where: L is the ice thickness and μ is the oil viscosity.

Payne et al., 1984, determined the rise rate velocity, U_z, for their experiment to be 0.35 mm/sec which "seems appropriate and is also in good agreement with the rise rate velocity of 0.7 mm/sec experimentally determined by Martin (1979)."

Finally, the volume flow rate to the surface, V, can be expressed by

$$v = \frac{\pi d^2}{4} U_z N'A$$

where: N' is the number of brine channels per unit area and A is the area of the spill.

Payne et al., 1984, determined a value of 27 mL/hr for the volume flow rate, for their experiment. They comment that

> . . . When compared to experimentally determined values, presented in Table 4, this value is somewhat higher yet not extremely excessive. [The average flow rates for the experiment, that are listed in table 4, range from 0.09 to 6.2 mL/hr]. Obviously, additional refinement of the modelling of oil migration in brine channels appears warranted; however, to our knowledge, this is the first comparison of measured data with predictions based on Cox's approach.

Oil In Broken Ice

An ice cover consisting of grease ice and test floes was produced by continuing to thaw the ice sheet described previously. At this time, "an estimated 90% of the oil was present on the ice/water interface".

Wave turbulence was produced in the tank. Payne et al., 1984 report that

> . . . The micro-scale turbulence introduced by the grinding action of the frazil ice and grease ice crystals between the major floes, significantly enhanced the formation of a stable water-in-oil emulsion. . . . This grinding action also led to lead matrix pumping, as described by Lee et al. (1974), causing oil to surface on the ice floes and around the rims. Subsurface observations and water sampling . . . illustrated that elevated levels of dispersed oil in the water column also resulted from this lead matrix pumping which causes oil droplets to disperse. This enhanced dispersion quickly became self-limiting, however, due to the enhanced water- in-oil emulsification behaviour.

4.4 Laboratory Tests of Spreading - Literature Review

Moir, J.R., and Y.L. Lau. 1975. Some Observations of Oil Slick Containment by Simulated Ice Ridge Keels. Project Report by Environment Canada (CCIW) to the Frozen Seas Research Group, Department of Fisheries and Oceans, Government of Canada.

The objective of the work was to observe the mechanism(s) and the conditions by which an ice ridge keel may contain oil in the presence of a current. The study was of limited scope and was exploratory in nature.

Tests were carried out in a tilting flume with a length, width, and depth of 15m, 0.06m, and 0.06 to 0.6 m, respectively. The tests were conducted by releasing oil upstream of a plexiglass barrier with a triangular cross-section that was intended to simulate an ice ridge keel. Three "keel" angles (30, 45, and 90 degrees to the horizontal) were tested. Some tests were conducted with a simulated ice cover (by placing sheets of vinyl-wrapped foam on top of the water) while the others were carried out in open water conditions. No information is given to describe the oil that was used.

Initially, tests were conducted with a single "keel". Subsequently, tests were undertaken with two "keels" in series.

Results

Single Keels

Moir and Lau, 1975, report that two types of containment failures occurred as follows:

> . . . 1) Droplets formed at the leading edge of the slick, or droplets formed at the barrier, and carried under the barrier and (2) a "sheet" type failure. . . [ie., where the oil flowed under the barrier as a sheet].

The containment provided by the barriers was related to the densimetric Froude Number, F_Δ. The table below summarizes the maximum densimetric froude numbers observed before containment failures occurred.

Barrier Angle (Deg)	Test with Open Water Surface			Tests with Simulated Ice Cover		
	U (m/sec)	D (cm)	Maximum F_Δ	U (m/sec)	D (cm)	Maximum F_Δ
90	.234	15.0	0.477	.249	13.95	.527
45	.227	16.9	0.437	.243	15.7	.487
30	.225	17.0	0.431	.242	15.8	.480

where D = depth of flow

U = average flow velocity

Δ = $(P_w - P_o) / P_w$

G = acceleration due to gravity

P_o, P_w = densities of oil and water, respectively

$$F_\Delta = U / \sqrt{G D \Delta}$$

Moir and Lau, 1975, noted that the oil retention capability of the barrier is slightly sensitive to the barrier angle and that the available theories for slick failure do not include the barrier shape as a parameter. They concluded that "ice ridge keels will retain oil and conditions for containment are similar to oil slick retention in open water. However, slicks contained behind the sloping ridges are prone to longterm leakage".

With respect to the effect of the ice cover, Moir and Lau, 1975, concluded that "the presence of an ice sheet upstream of the barrier does not significantly alter the slick profile or the maximum volume of oil containable, in comparison to the open water case".

Series of Keels

Tests were conducted with two "45 deg." barriers in series to assess whether oil could be stored in between two closely-spaced ridges.

Only qualitative observations are presented for the case where the barriers were spaced at 10 times their draft. It was found that oil was only retained at the downstream face of the upstream barrier for high densimetric Froude Numbers for a larger spacing (of 21 times the barrier draft). Moir and Lau, 1975, observed that "oil was retained downstream of the first barrier and upstream of the second barrier". They found that a "separation point" occurred in the oil slick in this cavity "about 5 barrier drafts downstream of the first barrier".

Rosenegger, L.W. 1975. The Movement of Oil Under Sea Ice. Prepared by Imperial Oil Limited for the Beaufort Sea Project, Department of the Environment Canada, Victoria, Beaufort Sea Technical Report No. 28.

This report presents the results of laboratory tests to determine the interfacial tension and motion of crude oil bubbles under sea ice. Two different crude oils were used in these experiments (Swan Hills and Norman Wells). An assessment has also been made of a) the ability of oil to penetrate sea ice from beneath, b) the equilibrium thickness of crude oil film on water under arctic conditions, and c) the redistribution of solutes in the oil.

Objectives

The major objectives of this study can be summarized as follows:

1. To determine the interfacial tension between oil and water at the temperature of freezing water for Normal Wells and Swan Hills crude oils by the sessile drop method.

2. To study the movement and/or absorption of sessile drops at an interface between sea ice and water in response to gravitational and drag forces produced by ice sheet tilt.

3. To determine the movement of an oil film in a lead in response to continuous oil input at a given point in the lead.

4. To determine whether oil will penetrate from beneath into a growing sea ice sheet due to buoyancy forces and to assess the effects of the redistribution of solutes in the oil on the ice sheet.

Results

Conclusions

An evaluation of some of the parameters affecting the flow and areal distribution of crude oil under a sea ice canopy has been presented. It was found that the interfacial tensions between oil and brine ($12^0/_{00}$) for Swan Hills and Norman Wells crude oils were 24.5 and 23.8 dynes/cm respectively. Interfacial tensions at salinities other than $12^0/_{00}$ have also been presented. Effects of aging on the interfacial tension could not be determined due to the scatter in the measured data. The equilibrium thickness of these two crude oils under ice was found to be 0.80 and 0.88 cm for the Swan Hills and Norman Wells samples respectively.

Expressions relating the force required to initiate motion of an oil bubble have also been presented. For the Swan Hills crude, this force is given by $F = 48.5M^{0.486}$ while for Norman Wells crude it is given by $F = 23.4M^{0.659}$. In these expressions, the force, F, is in dynes and the mass, M, is in grams. Data relating the mass of oil to the shape of the bubble has also been presented. This will enable calculations of the minimum currents required to initiate motion of an oil bubble to be made.

When considering the spread of oil on water under arctic conditions, as would be the case of oil spreading in a lead, it was found that a minimum equilibrium film thickness of 0.25 cm should be expected for the two crudes tested. Taking into account the effects of evaporation and the leaching of natural surface active agents present in the oil into the water, it is reasonable to expect this figure to be conservative in most cases. A determination of the maximum areal spread of the oil, barring any external forces (e.g., effects of currents, etc.), is therefore possible.

It was also concluded that the presence of dissolved salt in the oil, if indeed it does exist as a dissolved species in the oil, would not cause the under-ice surface to rot. Penetration of the oil into the ice sheet is not normally expected. When the oil encounters an oversized brine drainage channel of approximately 0.7 mm radius, limited penetration will likely result. As melting proceeds in the spring, and the brine drainage channels open, a significant amount of oil penetration should be expected.

MacKay, D., Medir, M. and Thornton, D.E. 1976. Interfacial Behaviour of Oil Under Ice. The Canadian Journal of Chemical Engineering, Vol. 54, 1976, pp 72-74.

The objective of the work was to observe the interfacial behaviour of oil droplets under an ice surface.

Small scale tests were conducted using a 20 cm X 20 cm X 10 cm chamber. A freshwater ice sheet was grown on the surface of the tank and oil (Prudhoe Bay crude oil and Norman Wells crude oil) was injected under the ice.

Results

Under-ice Spreading

> It was concluded that large volumes of crude oil spilled under plane ice in water or sea water will adopt a thickness of 0.8 to 1.2 cm and have a contact angle of 140 to 170° thus displaying "non-wetting" behaviour .... Oil droplets of volume less than 1 cm^3 will behave as mobile non-wetting, nearly spherical, particles whereas large oil volumes will behave as lenses also with non-wetting behaviour.

The authors go on to discuss the implications of their observations.

> There are several important implications of the observed behaviour. First, since oil drops do not "wet" ice, they may tend to remain mobile and may be subject to movement by currents until restricted by the growing ice. There is a possibility that oil removal from under-ice may be facilitated by inducing a water current if the under-ice topography does not dominate the oil configuration. Second, surface tension forces will act to retard spreading of oil under ice and it is unlikely that oil films will be thinned appreciably below 1 cm. . . .

Malcolm, J.D. 1979. Studies of Oil Spill Behaviour Under Ice. Oil, Ice and Gas, Environment Canada, Toronto, pp 47-53.

This study is also reported in Malcolm and Dutton, 1979.

Results

Under-Ice Spreading: Wetting Behaviour

The objective of the work was to measure the interfacial tension and the contact angle of oil droplets under ice. These properties were determined by analyzing sessile drops that were observed during laboratory tests with two crude oils under ice in both fresh water and seawater. The tests were conducted using a 20 gallon aquarium. Two crude oil types (Guanipa Venezuelan crude and a blended sample consisting of Trinidad (24.8%), B.C.F. (56.2%) and Leona (19.0%)) were used in the test program.

An improved method for determining the interfacial tension and the contact angle was developed. A contact angle of 180° was measured during each test. Malcolm and Dutton, 1979, comment that "this is interpreted to mean that the oil is separated from the solid surface by a thin water film, so that the oil does not wet or coat the solid".

The measured interfacial tensions range from 19.09 dynes/cm to 24.75 dynes/cm and Malcolm and Dutton, 1979, conclude that "interfacial tensions of the various crude oil/water systems is in the range 20 $\pm$5 dynes/cm".

Malcolm, 1979, states that

> It has been established that pools of oil under solid horizontal ice or glass sheets possess a maximum thickness at an intermediate volume, and when

more oil volume is added, the pool thickness is reduced, approaching a limiting thickness which is smaller than the maximum thickness.

The limiting thickness for the Guanipa crude oil was found to be 10.5 mm and 6.7 mm for freshwater and seawater, respectively, and for the blended crude oil, 10.0 mm and 8.0 mm, respectively.

Under-Ice Spreading: Oil Droplet Behaviour

The objective of this work was to examine the behaviour of oil droplets before, during and after contact with the ice bottom.

Laboratory tests were conducted by releasing oil droplets in a 1.2 m high tank under plate glass.

Malcolm, 1979, reports that "the rising oil drop flattens out on impact with the submerged glass cover plate . . . and then recovers a more spherical shape as it attempts to rebound". The oil droplet behaviour then became transient. Malcolm, 1979, reports that

> . . .After about two cycles of the flattening and rebounding oscillation, the drop shape fluctuations are damped out and the familiar sessile shape of the stationary drop is achieved. Subsequent drop motion depends on whether the surface supporting the drop is tilted to the horizontal, or whether there are currents present along the surface which can move the oil drop.
>
> Glass plate tilt angles as low as 2° to the horizon are found to be sufficient to cause oil drops to slide along the glass surface. . . .

Malcolm, 1979, observed that the oil droplets slid along the tilted glass after impact without leaving traces of oil. He states that "this shows that the thin water film remains intact during the impact and is not penetrated or removed by the impact process".

Mackay, D., Buist, I., Hossain, K., Kisil, I., Mascarenhas, R., and Paterson, S. 1979. A Laboratory Study of the Behaviour of Oil and Gas Under Ice. Proceedings of the Arctic Marine Oilspill Program Technical Seminar, Environment Canada, Ottawa, pp 101-109.

The objective of this work was to investigate the oil and gas configuration that occurs when they are released under a smooth ice sheet.

Tests were conducted in an 11 litre aquarium, which was located inside a cold chamber. Freshwater ice sheets, about 5 cm thick, were grown in the aquarium. First, gas bubbles were discharged under the sheet and then, oil droplets were released under it. "Norman Wells crude oil and pure hydrocarbons (toluene, cumene, n-hexane and mineral oil coloured with red Sudan IV dye were used in these experiments."

Results

Under-Ice Spreading: Spreading Oils

> The injected gas rose through the water column as bubbles which impacted on the ice surface. In a few seconds, the bubbles coalesced to form a single sessile bubble. . .
>
> The injected oil drops rose and impacted on the bubble. The first three or four drops quickly impacted and coalesced on the underside of the [gas] bubble to form a thin layer. Subsequent oil drops added impacted but tended not to coalesce. Rather, they travelled up to the ice surface and rested close to the edge of the gas bubble. After some time, the drop would coalesce with the oil layer around the bubble and flow to the bottom of the bubble. . .
>
> Further addition of oil tended to increase the thickness of this layer until it reached a maximum thickness of approximately 0.8 cm after which the oil tended to accumulate at the side of the bubble as a separate oil sessile drop.

Under-ice Spreading: Non-spreading Oils

> These oil drops tended to remain at the water-ice interface for some time then they coalesced with the gas bubble. They did not, however, spread out over

> the entire bubble area, rather they formed a floating lens under the bubble. . . . Addition of more oil resulted in the lens becoming larger until it completely enveloped the gas bubble.
>
> A theoretical analysis was undertaken which gave results entirely consistent with the experimental observations. The analysis suggests that a third regime may exist, non-coalescing behaviour in which the oil will remain entirely apart from the gas. This requires a combination of inter-facial tensions which we believe cannot be realised in practice.

The authors close by stating that

> In summary, the oil behaviour is dominated by its spreading tendency at the gas-water interface. This behaviour is influenced by coalescence time and oil rheology, neither effect being capable of easy characterisation.

Uzuner, M.S., Weiskopf, F.B., Cox, J.C., and Schultz, L.A., 1979. Transport of Oil under Smooth Ice. Environmental Protection Agency, NTIS Report No. PB 299235.

This study is also reported in Weiskopf and Uzuner, 1977.

The objective of the study was

> . . . to develop a model for predicting the behaviour of an oil slick in a straight stream or river of uniform depth, covered with a consolidated ice cover of uniform thickness.

The work was comprised of analytical studies and laboratory testing. Experiments were conducted in a refrigerated flume with dimensions of 0.61 m X 0.94 m X 13.7 m. Oil was injected under an ice sheet that was produced on the flume and observations were made of its transport under a range of currents. Two oil types (ie. No. 2 fuel oil and crude oil) were used during the test program.

Results

Uzuner et al. 1979, state that

> . . . The experimental results indicate that the slick movement depends on whether the slick aligns itself longitudinally or transversely to the current.
>
> The analytical treatments developed have not been successful in defining the distinguishing characteristics for the two types of behaviour, however, the proper relationship can be selected for field application after observing the orientation of the slick relative to the flow.
>
> The conclusions which can be drawn from the work . . . are as follows:
>
> 1. For an oil slick beneath a smooth uniform ice sheet, the slick velocity is related to the current velocity as follows:

Oil Type	Viscosity cp	Threshold Velocity cm/sec	Relationship of Slick Velocity, U_s, to Water Velocity, U_w cm/sec	Range of Applicability cm/sec
No. 2 Fuel	7	4	$U_s = 0.38\ U_w - 1.26$	0 - 36
Crude	24,500	8	$U_s = 8.6 \times 10^{-6}\ U_w^{4.29}$	8 - 28
			$U_s = 1.10\ U_w - 16.60$	28 - 36

2. For current velocities significantly greater than the range of applicability specified above, the tests indicate that the oil slick will become entrained in and distributed throughout the water column. The oil will then be transported in suspension with the water flow in this distributed manner, rather than along the underside of the ice surface in well-behaved slicks. Further investigation of this type of oil spill transport is beyond the scope of this study.

3. For oils other than the No. 2 fuel oil and crude oil used in the test program a theoretical analysis of the forces controlling slick transport and a comparison with the data yields a first approximation for predicting the relationship between slick velocity and water velocity for oil slicks transported beneath smooth uniform ice cover as follows:

$$(1 - U)^2 = \frac{0.146}{N_F^2} + 0.450$$

for slicks oriented parallel to the flow direction.

$$(1 - U)^2 = 2.15 \left(\frac{1}{N_F^2}\right)^{1.15}$$

for slicks oriented transverse to the flow direction.

where: U = non-dimensional velocity = U_s/U_w
where: N_F = densimetric Froude Number

$$\frac{U_w}{\sqrt{\Delta\, g\, h}}$$

g = acceleration due to gravity
h = oil slick thickness
Δ = relative density difference

$$\frac{\rho_w - \rho_o}{\rho_w}$$

ρ_w, ρ_o = water and oil density, respectively

4. . . .

5. Significant differences were observed in the behaviour of the crude oil slicks and the No. 2 fuel oil slicks. Crude oil slicks typically became shorter and wider as they moved downstream, with some thickening of the upstream portion at higher velocities. The crude oil slicks appeared to slide along the undersurface of the ice. Additional analysis beyond the scope of this study would be required to explain the reasons for these differences in behaviour.

6. A single test performed using plexiglass as a simulated ice sheet revealed that the behaviour of the oil slick beneath such a simulated ice cover was completely different. The crude oil used in this test adhered to the plexiglass, leaving a stationary 0.25 to 0.50 cm thick coating on the plexiglass. Neither crude oil nor No. 2 fuel oil adhered to either fresh water or salt water ice in these tests.

7. Any significant discontinuities in the ice cover, such as an open water ice edge or a slot, provided a region of containment and retention for the oil slick.

8. It should be noted that the results of these tests apply to unbounded underice oil slicks. Any contact between the slick and a boundary, such as the shores of rivers or streams, would be expected to result in the retardation of slick movement.

Cox, J.C., Schultz, L.A., Johnson, R.P., and Shelsby, R.A. 1980. The Transport and Behavior of Oil Spilled in and under Sea Ice. Arctec Incorporated for NOAA/OCSEAP, Research Unit 568, Final Report, 170 p.

This study is also reported in Cox and Schultz, 1980; Cox and Schultz, 1981a and 1981b.

The objective of the work was to study the transport and behaviour of oil that is released beneath an ice sheet. The project was mainly focussed on current-driven transport. An analytical predictor for vertical oil migration was also developed.

Tests were conducted in a 0.9 m X 0.6 m X 13.7 m long refrigerated flume. Freshwater ice sheets were produced with a range of roughnesses and oil was injected upstream. Four different oil types (No. 2, No. 4, No. 5 light and No. 5 heavy fuel oil) were tested.

Results

Smooth and Small Roughness Ice

The study was commenced by observing the equilibrium sheet thicknesses of the oils under smooth ice. The following empirical expression was found to fit the test data:

$$\delta_{eq} = 1.67 - 8.5\ (\Delta\ \rho_w) \tag{14}$$

where: δ_{eq} = static equilibrium slick thickness, cm
Δ = relative density difference = $(\rho_w - \rho_o) / \rho_w$
ρ_w = water density, g/cm^3
ρ_o = oil density, g/cm^3.

The smooth ice equilibrium thickness was determined to range from 0. 52 cm for No.

2 oil to 1. 16 cm for No. 5 heavy oil.

Next, the threshold velocity (i.e., the current at which under-ice slicks start to move) was observed for smooth ice. For the four oils tested, the threshold velocity was found to be related to the oil viscosity as follows:

$$U_{th} = 305.79 / 88.68 - \mu_o \qquad (2)$$

where: U_{th} = threshold current speed for slick movement, cm/sec
μ_o = viscosity of oil, g/cm-sec.

The relationship between the slick velocity and the current velocity was also investigated. The following expressions were found to fit the test data:

$$U_s = 0.15\, U_w - 0.60 \qquad \text{for } U_w < 18 \text{ cm/sec} \qquad (3)$$
$$U_s = U_w - 15.6 \qquad \text{for } U_w > 18 \text{ cm/sec}$$

where U_s = slick speed, cm/sec
U_s = mean current speed, cm/sec

Tests were then conducted using ice sheets with small roughnesses. A small roughness was defined as one that was less than the smooth ice equilibrium slick thickness of the oil. This was found to increase the threshold velocity substantially. Equation (15) below summarizes the observed slick velocity relationship for both the smooth ice and the small ice roughness tests.

$$\left(1-\frac{U_s}{U_w}\right)^2=\frac{K}{0.155F_\delta^{\,2}+1.105} \qquad (15)$$

where: K = friction amplification factor for rough ice, (which was determined experimentally)

F_δ = *slick densimetric Froude Number,* $U_w/\sqrt{\Delta g \delta}$

δ = local slick thickness

g = acceleration due to gravity

Single Large Ice Roughness Elements

The next series of tests were conducted using ice sheets that contained single large roughness elements (i.e., a roughness that was larger than the equilibrium slick thickness of the oil). For the four oil tested, it was observed that "oil trapped upstream of a single large roughness element can typically be flushed out at a current velocity in the range of 15 to 25 cm/sec.". This failure velocity was found to be related to the oil properties as follows:

$$U_{fail}=1.5\left\{2\left(\frac{\rho_o+\rho_w}{\rho_o\rho_w}\right)\left[\sigma_{o/w}g(\rho_o-\rho_w)\right]^{1/2}\right\}^{1/2} \qquad (17)$$

where: U_{fail} = freestream velocity when containment failure occurs, cm/sec

$\sigma_{o/w}$ = interfacial tension, dynes/cm

g = gravitational constant, cm/sec^2.

The volume of oil per unit width trapped upstream of a large roughness element could be approximated by the following relationship:

$$V'_{frontal} = \frac{[\eta + (U_w^2/4\Delta g)]}{2}\left(\frac{4\Delta g}{f_s U_w^2}\right)\left[\eta^2 - \left(\frac{U_w^2}{4\delta g}\right)^2\right] \qquad (22)$$

where: $V'_{frontal}$ = slick volume per unit width contained upstream 6 a large roughness element, cm^3/cm

η = ice roughness height, cm

f_s = interfacial friction factor.

However, after flushing events, some oil was found to remain in the wake of the roughness. This oil volume was approximated as follows:

$$V'_{wake} = 6 C_D \eta \delta_{eq} \qquad (23)$$

where V'_{wake} = slick volume per unit width contained downstream 6 a large roughness element in the wake region, cm^3/cm,

C_D = roughness form drag coefficient.

Ice Cavities

Tests were then conducted with ice sheets that contained a series of large roughness elements. A vortex zone was observed to occur immediately downstream of the roughness element while a shear zone developed beyond the vortex zone. See figure 3. This produced an offset behind the roughness element which grew in size with increasing current velocity, until oil drained from the cavity.

In the vortex zone, the depth of the offset was determined to be given by the empirical relation

$$\epsilon_1 = \frac{0.29 U_w^2}{\Delta g} \qquad (8)$$

where: ε_1 = offset of the oil-water interface in the vortex zone, cm and the length of the offset by the empirical relation:

$$l = 4\ U_w \tag{18}$$

where: l = vortex cell length, cm.

The shear zone will develop with an initial offset of

$$\epsilon_2 = 0.15 \frac{U_w^{\ 2}}{\Delta g} \tag{10}$$

where: ε_2 = offset of the oil-water interface at the stagnation point, cm.

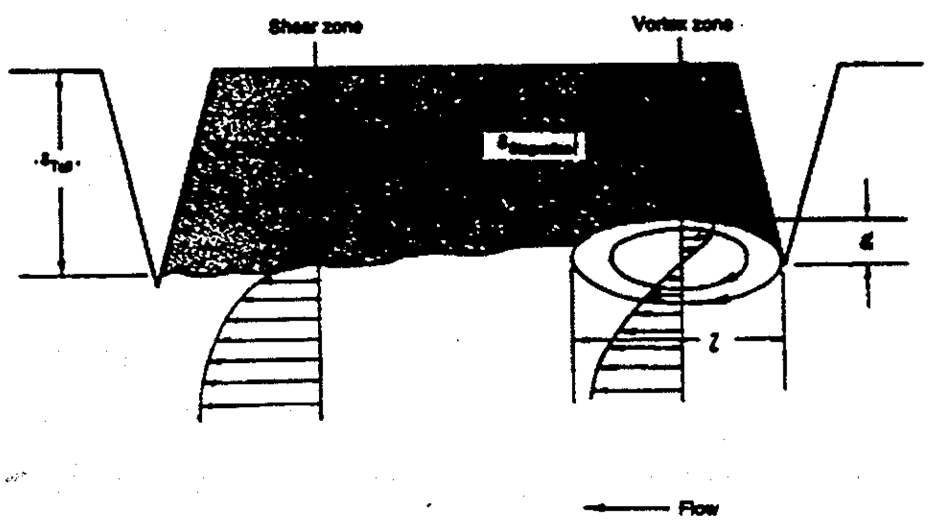


Figure 3 Generalized Description of Oil Contained in an Ice Roughness Cavity under the Influence of a Current

It will continue to grow parabolically to the back wall of the cavity according to

$$X = 250\frac{\Delta g}{U_w^2}(\delta^2_{tail} - \delta^2_{stag}) \qquad (11)$$

where: X = slick length, cm

$$\delta^2_{tail} = \frac{(\lambda - 1)f_s U_w^2}{4\Delta g} + (\eta - \frac{\epsilon_1}{2})^2, cm^2 \qquad (12)$$

(21)

$$\delta^2_{stag} = \eta^2 - \frac{(\lambda - 1)f_s U_w^2}{4\Delta g}, cm^2$$

λ = ice roughness spacing, cm
δ_{tail} = thickness of contained slick tail, cm
δ_{stag} = thickness of contained slick at point of flow reattachment, cm.

Application of Results

Cox and Schultz, 1981a developed the following methodology for utilizing the study's results to predict oil spill behaviour:

Equations in Fig. 5 Not Already Listed in Text

$$\varepsilon = \frac{U_w^2}{3.46\ \Delta g} \qquad (16)$$

$$X_{shear} = \frac{4\ \Delta g}{f_s\ U_w^2}[\eta^2 - (\eta - \frac{\varepsilon}{2})^2] \qquad (19)$$

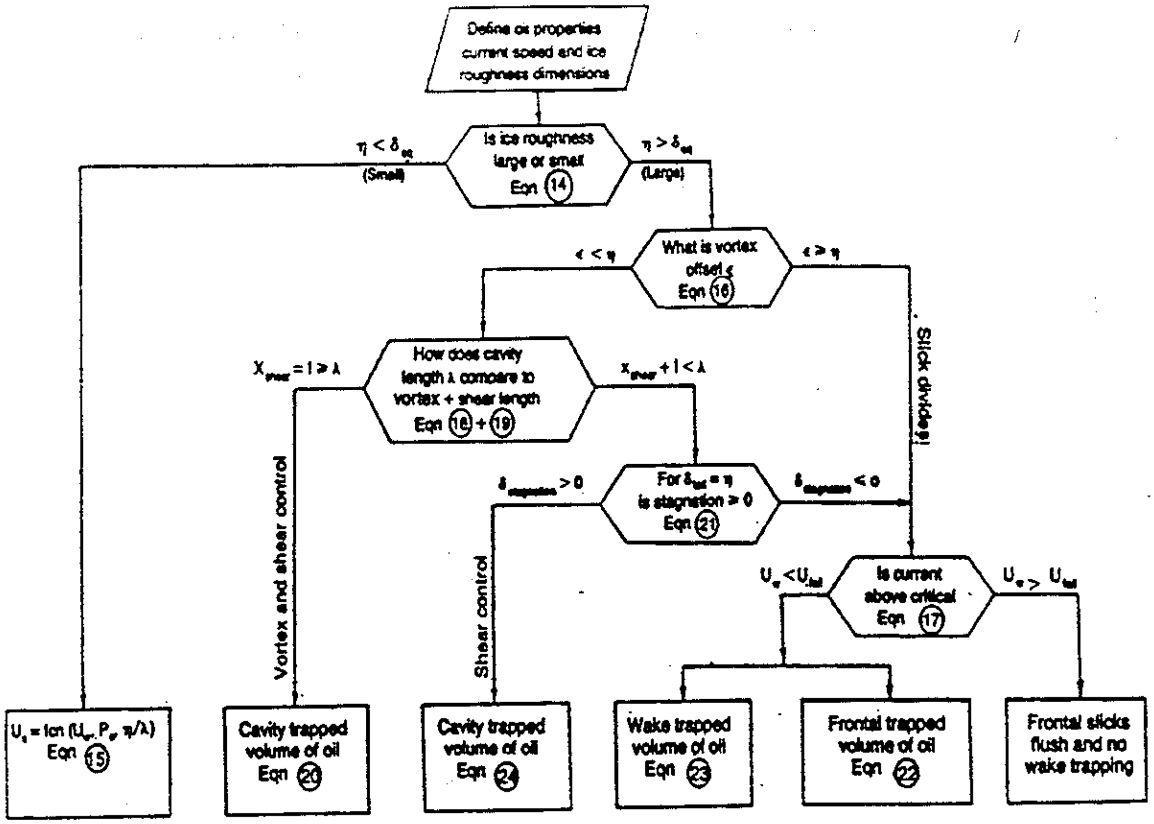


Figure 5: Flow chart of the procedure for calculating the transport or containment of oil beneath ice in the presence of a current.

$$V' = 1\ (\eta - \varepsilon) + \left[\frac{\delta_{tail} + (\eta - \frac{\varepsilon}{2})}{2}\right] (\lambda - 1) \qquad (20)$$

$$V' = \frac{1}{2}\left[\eta + (\eta^2 - \lambda \frac{f_s\, U_w^2}{4 \Delta g})^{\frac{1}{2}}\right] \lambda \qquad (24)$$

where:

- ε = vortex zone offset in a cavity, cm
- X_{shear} = length of the shear zone, cm
- λ = cavity length, cm

Vertical Migration

Cox et al., 1980, developed the following expression to predict the minimum diameter of a brine channel, d, to allow oil migration by balancing the buoyancy and the interfacial tension forces:

$$d = \frac{4\,\sigma_{o/w}}{\delta} \; \frac{\cos \alpha}{(\rho_w - \rho_o)\, g}$$

where: ρ_w, ρ_o = densities of water and oil, respectively

$\sigma_{o/w}$ = interfacial tension between oil and water

δ = thickness of the oil slick

α = contact angle of the oil with the ice

The rise rate, U_z, was predicted as follows:

$$U_z = \frac{(\rho_w - \rho_o)\, g\, \delta\, d^2}{32\, L\, u_o}$$

where: u_o = oil viscosity

L = ice thickness

Kisil, C.A., 1981. A Study of Oil and Gas in Fresh and Salt Water-ice Systems. University of Toronto, M.Sc Thesis, Toronto, Ontario.

The objective of the work was to examine the behaviour of oil and gas bubbles under a static, continuous ice cover. The following were investigated:

(a) the configuration of oil and gas bubbles released under an ice cover.
(b) the effect of the oil and gas on ice growth rates.
(c) migration and release of the oil and gas in the ice.

Analytical models were developed to predict the oil and gas bubble configuration, the effect of the oil and gas on the ice growth rate, and migration.

Experiments were carried out in an 11 litre aquarium which produced results that were compared with the analytical predictions. Tests were conducted in fresh and salt water by first releasing air under ice sheets that were grown in the tank and then adding oil. Norman Wells crude oil and pure hydrocarbons (toluene, mineral oil, cumene, and n-hexane) were used during the tests.

Results

Under-Ice Spreading: Configuration of the Oil and Gas

The behaviour of a gas bubble under the ice was analyzed and observed. The following theoretical predictor was developed to determine the gas bubble depth, h, based on the configuration which minimized the energy of the system:

$$h^2 = 2\,\Delta\sigma / g\,\Delta\rho$$

where: $\Delta\rho$ = density difference between the water and the gas

$\Delta\sigma$ = interfacial energy per unit horizontal area of the bubble

g = acceleration due to gravity

The above expression predicts bubble depths that correlate well with the laboratory test data when the value used for $\Delta\sigma$ is close to twice the air-water interfacial tension. Kisil, 1981, concludes that this indicates that "the gas bubble is enveloped by water, as has been suggested by Malcolm, 1979".

The addition of oil to the system was next considered and observed. For the case where a large area of gas is underlain by an equal area of oil, the following expression was developed to predict the optimal depth, h, for the gas bubble:

$$h^2 = v \, \Delta \sigma / g \, [0.5 \, v \, \rho_w + V \, (1 + V/2v)(\rho_w - \rho_o)]$$

where: V,v = oil and gas bubble volume, respectively

ρ_w, ρ_o = densities of water and oil, respectively

For the case where the gas bubble is "completely engulfed by spreading oil", Kisil, 1981, developed the following expression to predict the gas bubble depth:

$$h^2 = 2 \, \Delta \sigma \, / \, g \, (\rho_o - \rho_g)$$

These analyses led Kisil, 1981, to conclude that "oil will generally accumulate at the bottom of gas bubbles when volumes are large and edge effects can be ignored."

Experiments were conducted by releasing oil under an ice sheet after gas bubbles had already been injected beneath it.

For spreading oils (i.e., toluene and Norman Wells crude oils), it was observed that the gas bubble "tended to flatten and spread . . . until an "equilibrium" configuration was reached when the gas was totally enclosed in oil". Kisil observed that

> . . . at oil to gas volume ratios below 0.1 there is a regime in which the dominant effect of the oil is to envelope the gas . . . . When the ratio is in the range 0.1 to 1.3 the oil accumulates at the bottom of the gas bubble . . . . At higher oil to gas ratios the oil tends to form adjacent sessile drops, the depths remaining constant. . . .

For non-spreading oils (e.g. mineral oil), the depth of the gas bubble was unchanged when the oil was added.

Kisil, 1981, made the following comments regarding the oil and gas configuration to be expected for the case of a blowout:

> Since gas to oil volumetric ratios in blowouts are typically 100 and most fresh oils tend to spread on water it appears that the predominant regime will be that of oil covered bubbles. A major factor will be the under ice topography which typically varies by about 20% of the ice thickness, thus pockets of gas will probably form tens of cm thick underlain by oil films which may be up to a mm thick. The extent to which the gas vents through the ice and carries oil with it are unknown at present. An additional factor which will alter the behaviour is the crystalline and slushy character of the sea ice undersurface which will probably retard horizontal movement, especially of small bubbles or drops.

For a description of encapsulation and migration results, see the review of Kisil (1981) in Section 4.3.

Malcolm, J.D. and Cammaert, A.B. 1981b. Transport and Deposition of Oil and Gas Under Sea Ice. Proceedings of the Fourth Arctic Marine Oilspill Program, Environment Canada, Ottawa, pp 45-73.

This study is also reported in Malcolm and Cammaert, 1981a, and Cammaert, 1980.

Results

Under-Ice Spreading: Oil Pool Thickness Under Smooth Ice

Equations (1) and (2) were developed by a computer solution of the "nonlinear ordinary differential equation which governs the shapes of all axisymmetric interfaces" to predict the maximum oil drop thickness, H_{max}, and the thickness for drops of infinite volume, H_L.

$$H_{max} = 2.12953 \, (\sigma/\rho g)^{1/2} \quad (1)$$

$$H_L = 2.0 \, (\sigma/\rho g)^{1/2} \quad (2)$$

where: σ = interfacial tension
ρ = density difference between oil and water
g = gravitational acceleration

The predicted limiting thickness for API gravity 25 and API gravity 45 oils in seawater ranges from 5.81 mm to 10.06 mm and 4.27 mm to 7.40 mm, respectively for a range of interfacial tensions from 10 dynes/cm to 30 dynes/cm. The authors state that this range of interfacial tensions was selected based on work by Malcolm and Dutton, 1979.

Under-Ice Spreading: Potential for Fracture of a Smooth Ice Sheet by a Trapped Gas Bubble

The thickness of a gas bubble beneath a smooth horizontal ice sheet was calculated using equations (1) and (2) to be "no more than 6 mm". This value is less than the 40 to 50 mm bubble thickness predicted to be necessary to cause failure of an 0.5 m thick ice sheet by Topham's 1977 analysis. Malcolm and Cammaert, 1981b, conclude that "only gas bubbles trapped in very large undulations are capable of fracturing the ice".

Under-Ice Spreading: Configuration of Oil and Gas Bubbles

Photographic observations were made in the laboratory of the behaviour of oil and gas bubbles released under smooth plate glass which was selected to simulate a smooth ice sheet.

Air bubbles were released first, followed by oil droplets. It was found that individual oil drops" coalesce with the gas/water interface and spread over it to form either a very thin film extending to the edge of the bubble, or a thick lens of oil confined to the bottom of the gas bubble." Malcolm and Cammaert, 1981b, further observed that

> . . . the arrival of a successive train of oil drops at the gas bubble interface produces a growing oil lens in the gas bubble after each drop coalesces with the lens. Drops that land near the edge of the gas bubble slide upward along the bubble contour since the bubble surface is not horizontal, but curved. . . . Some drops slide off the gas bubble and onto the ice (or glass in our experiments) before coalescence takes place. . . .When a thick oil lens covers the bottom of the gas bubble, oil drops tend to slide off the bubble more readily, and in the process, drag oil from the lens up the side of the gas bubble. . . .

Under-Ice Spreading: Effect of Currents for a Continuous Ice Cover

A total of eight tests were conducted to investigate the effect of currents on crude oil motion under undulating ice covers when gas is trapped between the cavities. The tests were conducted in a 1.2 m high X 1.2 m wide X 12 m long refrigerated flame. A saline ice cover was grown and undulations were produced by selectively insulating the growing ice sheet with styrofoam. Undulations with respective depths and wavelengths of 15 cm and 1 m, 7.5 cm and 1.5 m, and 2 cm and 1.5 m were produced. Air and oil were injected at gas/oil ratios of 150:1 and 15:1.

Malcolm and Cammaert, 1981a, conclude that

> . . .the spreading of oil under an ice cover, when released in the presence of gas, depends on the effective configuration of the underside of the ice cover. The volume of gas and undulation geometry combine to determine the behaviour of the oil slick on the gas/water interface.
>
> For the meter-long undulations tested, if the gas volume is small or the undulation depth is large enough that the gas/water interface is more than about 5 cm above the bottom of the undulation of lower ice surface, the oil slick seemed to be fully protected from the flow. The only effect on the oil slick at velocities as high as 44 cm/s was herding or migration of the oil slick to the downstream limit of the gas/water interface below the gas pocket.
>
> However, when the ice extended only 1.5 cm below the gas/water interface, the oil slick was forced out of the undulation at a flow velocity of 44 cm/s and migrated under the ice cover. When the ice cover extended 0.5 cm to 1.0 cm below the gas/water interface, a flow velocity of 25 cm/s was able to force the oil out of the undulation. (It should be noted that the size of the ice lip was difficult to observe under a fluctuating water level.)

Under-Ice Spreading: Current-Induced Transport for a Broken Ice Cover

One test was conducted with a poorly-consolidated ice cover that consisted of blocks with dimensions of about 15 cm on each side. The released gas quickly vented through this ice cover. This test was conducted with currents up to a maximum of 34 cm/sec. The oil remained trapped in the under-ice surface for all currents tested. Cammaert, 1980, observed that

> Most of the oil was trapped in the slushy ice between blocks and was not carried away with the flow. When the thin film of ice on the surface [of the ice cover] was broken, the oil contained in the slush ice seeped to the surface.

Payne, J.R., McNabb, G.D., Hackmeister, L.E., Kirstein, B.E., Clayton, J.R., Phillips, C.R., Redding, R.T., Clary, C.L., Smith, G.S., and Farmer, G.H. 1987. Development of a Predictive Model for the Weathering of Oil in the Presence of Sea Ice. for NOAA/OCSEAP Office, Research Unit No. 664, Anchorage, Alaska.

Editor's note: Although results from laboratory tests in first year sea ice are also presented in this reference, they have not been included in this review. The first year ice test results are summarized in our review for the reference Payne et al., 1984, which describes these tests in more detail.

The objective of this program was "to develop a predictive model that describes the qualitative and quantitative weathering of spilled oil and refined petroleum products in the presence of first year and multiyear ice."

A number of studies were conducted to assist in the development of the model. These included tests in a refrigerated seawater tank about 0.8 m X 0.9 m X 3.5 m in size, which are summarized in this review.

Results

Payne et al.'s (1987) discussion of the laboratory program commences with a summary description of tests that were conducted in simulated sea ice (which are documented in Payne et al., 1984).

With respect to these oil migration data, Payne et al., 1987, note that the predicted oil flow rates (using Cox et al.'s, (1980) approach) is "somewhat high compared to the experimentally determined values". They suggest that "other factors may need to be taken into consideration" to explain the observed iscrepancies:

1) The depth of the oil pool in the ice, 2) the rate of temperature increase (totally controlled by laboratory conditions), 3) the fact that the laboratory ice was relatively thin (≤ 10 cm), 4) the fact that the oil lens was initially trapped in columar ice 4 cm below a 5 cm canopy of refrozen grease ice, 5) uncertainties in the number of brine channels/unit area in the laboratory and field studies, and 6) the influence of the oil after it had surfaced with additional ice ablation and melting.

Payne et al., 1987, observe that "obviously, additional refinement of the modelling of oil migration in brine channels appears warranted".

Puskas, J., McBean, E., and Kouwen, N. 1987. Behaviour and Transport of Oil Under Smooth Ice. Canadian Journal of Civil Engineering, Vol. 14, pp 510-518.

The current-driven transport of an oil slick under a smooth, continuous ice cover was investigated. An analytical model was developed and tests were carried out in the laboratory to verify the model.

Experiments were conducted in a 0.58 m X 0.67 m X 6.7 m flume located inside a refrigerated chamber. Three crude oils (Adgo, Itiyok and Norman Wells) were used during the test program.

Results

It was found that the light oil (Norman Wells) formed a long narrow slick that was aligned longitudinally with the direction of the current, while the heavier oils tended to form short, wide slicks transverse to the current. The authors note that these observations are in agreement with those of Uzuner et al., 1979.

The authors state that:

> For these analyses the slicks were separated into two groups:
>
> 1. Long, narrow slicks, whose primary driving force is the shear stress force.
>
> 2. Short, wide slicks, whose primary driving force is the form drag force.

<u>Long, narrow slicks oriented parallel to the flow direction:</u>
Analytical expressions were developed for this case by balancing the shear force at the oil-water interface with the oil-ice friction force and by assuming no-slip at the oil-ice interface. The authors note that the Reynolds number was less than 5×10^5 for all of these experiments and therefore, they have utilized the shear stress

coefficient for laminar flow. The following expression was developed to predict the mean slick velocity, U_s:

$$U_s = 0.332 \frac{h \rho_w}{\mu_o} R_1^{-1/2} (U_w - 2U_s)^2$$

where: h = oil slick thickness

ρ_w = water density

μ_o = dynamic viscosity of the oil

μ_w = water velocity

l = slick length

μ_1 = water velocity at oil-water interface

μ_w = viscosity of the water

Short, wide slicks oriented transversely to the flow:

The authors present analyses regarding the velocity profile, the results of which they summarize as follows:

> Oils with high viscosities move almost as solid masses, with the majority of the velocity variation taking place in the water film separating the oil and the ice. Through inference, the thickness of this film was determined to be several orders of magnitude larger than that expected for a static oil slick under quiescent conditions.

> Puskas et al., 1987, observed that "the oils with higher viscosities normally formed short, wide slicks oriented transverse to the water flow direction." For this case, Puskas et al., 1987, note that the dominant force acting to transport the oil slick under the ice is the form drag force, F_D. This motion is resisted by oil-ice friction, F_f, which was calculated by assuming a constant velocity in the oil slick:

$$F_D = C_D \rho_w (U_w - U_s)^2 wh^l$$

$$F_f = \mu_w \frac{U_s w l}{\lambda}$$

where: $h^{\prime}$ = oil slick thickness in the "head" region
C_d = drag coefficient
w = width of oil slick
μ_w = dynamic viscosity of the water
λ = thickness of the oil film between the oil slick and the ice

By setting the form drag force equal to the frictional force (which reflects the case when the slick is in equilibrium), the authors attempt to determine information regarding the drag coefficient of the slick, and its relationship to the dimensionless ratio $h^{\prime}/\delta$ (where δ is the boundary layer thickness in water). However, the authors note that "the uncertainty is large" for λ which produces inaccuracy in the calculated value of C_D. Also, the authors note that

> Due to the scatter of the measured velocities within the water boundary layer, it is impossible to predict the thickness of the boundary layer from the measured profiles with any degree of accuracy. This, coupled with the uncertainty associated with the calculated values for C_D, makes the relationship between C_D and $h^{\prime}/\lambda$ indeterminate from these data.

Yapa, P.D., and Chowdhury, T. 1990. Spreading of Oil Under Ice. in Journal of Hydraulic Engineering, Vol. 116., No. 12. pp 1468-1483.

This study is also reported in Yapa and Chowdhury, 1989a and 1989b.

The axi-symmetric spreading of oil under a smooth, continuous ice sheet was investigated during this work. Numerical predictors were developed using theoretical analyses. Experiments were carried out to verify the models and to obtain values for constants required for the models.

Results

Although expressions are presented to analyze the gravity (buoyancy)-inertia spreading phase, Yapa and Chowdhury, 1990, note that for typical field cases, the duration of this phase is of the "order of seconds" and that "the dominant spreading mechanism under ice covers is the buoyancy-viscous phase".

Equations were derived based on an analysis of the buoyancy-viscous phase. Two equations were developed, depending on whether the oil discharge rate, Q, is constant, or whether a constant volume of oil, V, is spilled, as listed below:

$$R = k_1 \left[\left(\frac{(\rho_w - \rho_o)\, g Q^3}{\mu_o}\right]^{1/8} t^{1/2} \qquad \text{(Constant Q)}$$

$$R = k_2 \left[\frac{(\rho_w - \rho_o)\, g V^3}{\mu_o}\right] t^{1/8} \qquad \text{(Constant Spill Volume)}$$

where: R = radius of slick

k_1, k_2 = dimensionless constants

ρ_w, ρ_o = density of water and oil, respectively

μ_o = oil viscosity

g = acceleration due to gravity

t = elapsed time

The following expression was developed to predict the final slick radius, R_f:

$$R_f = k_3 \left[g \frac{(\rho_w - \rho_o)}{\sigma_n} \right]^{1/4} V^{1/2}$$

where: V = the total volume of oil spilled

k_3 = a coefficient that must be found experimentally

Experiments were conducted in a 1.2 m X 1.2 m tank in which quantities (500 cm^3 to 1479 cm^3) of several different types of oils (ranging in viscosity from 60 cs to 700 cs) were released under ice sheets with a range of under-ice roughnesses from 0.00015 cm to 1.64 cm.

Yapa and Chowdhury, 1990, conclude that

> The equations agree closely with laboratory data. Discrepancies between theory and the experimental data can be attributed to the experimental difficulties and errors introduced from assumptions made in deriving the theory. These assumptions were needed to keep the equations in a manageable form for application to practical situations. The close agreement between the experimental data and the theory shows that the errors introduced from these assumptions were not critical. The calculated percent standard error estimate for all the experiments and for all data points is 6.24%.

The following values were determined from the laboratory test data for the dimensionless constants in the models:

Constant	Range	Value
k_1	$0 \leq Q^{0.4}/(g^{0.2}\varepsilon) \leq 11$ $Q^{0.4} / (g^{0.2}\varepsilon) > 11$	$k_1 = 10^{-.407} X\ 10^{.105 \log X_1}$ $k_1 = 0.495$
k_2	$0 \geq V^{1/3}\varepsilon \geq 100$	$k_2 = 10^{2.668} X\ 10^{3.566 \log X2}$
k_3	All tests	0.467

where: ε = mean ice roughness height
$X_1 = Q^{0.4}/(g^{0.2}\varepsilon)$
$X_2 = V^{1/3}/\varepsilon$

Yapa and Chowdhury, 1990, caution that

> In ice fields it is possible to have roughness heights much larger than the mean oil slick thickness. If there are a large number of such ice protrusions present, the spreading rate can become significantly different from what is described in this paper.

They also caution that

> At extremely high values of Q, the gravity-inertia phase would last much longer than mentioned here. The physical behaviour of the oil at these high values will differ vastly from the aspects considered in this paper. For example, the effects of the plunging oil jet would be so significant that its effects would need to be considered. This aspect is not addressed in this paper. Although some plunging of oil may occur even at moderate discharges, the resulting effects are dampened so quickly that the theory described here can still be used for practical purposes.

4.5 Analytical and Modelling Studies - Literature Review

NORCOR Engineering and Research Ltd. 1977. Probable Behavior and Fate of a Winter Spill in the Beaufort Sea. prepared for the Environmental Protection Service, Department of Fisheries and Environment Canada. Report No. EPS 4-EC-77-5.

This report describes a numerical model that was developed to predict the fate of oil and gas released from a well blowout in the transition zone of the Beaufort Sea. The model is applicable to cases where the ice cover consists of a continuous sheet which may or may not be moving. The model is not intended to handle broken ice conditions. The model was run for a number of cases. The report also presents field data that were collected over the November 1975 to July 1976 period to document ice conditions in the transition zone of the Beaufort Sea.

Results

<u>Modelling Approach</u>

The model provides a prediction of the large scale fate of oil and gas released under a continuous ice sheet. Local spreading and behaviour are not predicted. Oil and gas are assumed to collect in the undulations that are present under a continuous ice cover. The area of contamination, and the average thickness of the resulting layers of oil (and gas, if present) are determined using a volumetric analysis. This is based on the volume of the discharged oil and gas, the under-ice storage capacity (which was estimated based on available data to define ice thickness variations) and the residence time of the ice over the blowout site (which was based on an estimate of the plume diameter and available ice movement data). Key equations in the model (after NORCOR, 1977) are listed below:

- Mean Width of Saturated Area - W_s [15]

$$W_s = \frac{Q_o P_s}{L_s \overline{V}\ C_o}$$

- Minimum Width of Contaminated Area = Plume Width D [13]

$$D = 1.7\ Z\ [\frac{Q_1}{Z + 10.36}]^{1/3}$$

from Topham, 1975

- Mean Thickness of Oil Film $\bar{C}$ 0 [14]

$$C_0 = \frac{Q_0}{[W_s L_s) + D(1 - L_s)]\overline{V}}$$

- Percent Area Below a Given Average Oil Thickness d [15]

$$\%\ A(C < d) = \frac{\overline{C_0}\ D(1 - L)\overline{V}}{Q_o}\ X\ 100\%$$

$$\frac{D\ (1 - L)}{[W_s L_s + D(1 - L_s)]}\ X\ 100\%$$

hence, L = proportion of distance travelled by the ice sheet below velocity V

where V = Q_o/dD m/min^{-1}

- Percent Volume Below a Given Oil Thickness d

[16]

$$\% \; Vol \; (c<d) = e^{-0.60d/dD}$$

Note: Equation [16] only applies when the average thickness of oil, d, is less than that required for saturation.

Where:

Q_o = rate of discharge of oil (m^3/min^{-1})

Q_t = total flow of oil and gas (m^3/min^{-1}) ($Q_t = Q_oK_1$)

V_s = ice velocity necessary to achieve saturation (m/min^{-1})

P_s = probability of ice velocities less than V_s

L_s = probability of distance travelled by the ice at velocities less than V_s

$\bar{V}$ = mean ice velocity (1.5 m/min^{-1} from NORCOR camp movement) (m/min^{-1})

$C_{m,f}$ = average combined oil and gas film thickness at saturation (governed for different ice types by formulae [8], [9]) (m)

C_o = average saturated oil film thickness (m)

Z = water depth (m)

The authors recognize that gas venting may occur and an arbitrary approach was used to include this possibility in the model in order to conduct a sensitivity analysis.

The oil (and the gas, if it is present and not vented) are assumed to be encapsulated and then released during the spring melt. Vertical migration is assumed to occur at the average rates observed during the Balaena Bay field tests (conducted by NORCOR, 1975) and weathering of the oil occurs (at rates observed for Norman Wells crude oil) after the oil reaches the surface.

The model was run for several cases. The results show that the movement of the ice is a significant factor as this increases the area of contamination and reduces the average film thickness. The under-ice cavities were predicted to be only partially-filled. The presence of gas is predicted to increase the area of contamination greatly (unless venting occurs) as gas is expected to be released in much greater quantities than oil during a blowout.

Conclusions

NORCOR, 1977, cautions that the available information base is scant and that the results are sensitive to a number of critical assumptions (e.g., percent venting, percent multiyear ice). They state that "the resulting range of possible winter oil volumes represents a combination of several extreme cases."

However, they conclude that

> Several major conclusions can be made regarding the probable behaviour and fate of a winter oil spill in the Beaufort Sea. Evaporation in the first summer will likely be extremely effective in quickly reducing the volume of contaminant (by up to 50%) and the level of toxicity. Unless ice in the spill area is stationary for more than a third of the time, less than 20% of the oil will form films greater than 0.5 cm on the ice surface in the spring. With evaporation and varying amounts of multi-year ice the final volume in thick films will likely be even less. Therefore, possibilities for any significant cleanup using conventional burning techniques appear extremely limited.
>
> During the following summer opportunities for effective cleanup would be even less with weathered, thin films spread over a large area.
>
> In spite of these rather grim conclusions, the end result even without human intervention would be a very small oil loading/km^2 expressed in terms of the Beaufort Sea area. If burning techniques could be developed to cope with thin films, then the impact could be reduced further. Further studies will hopefully allow a safe estimate which could be made of oil spillage to be tolerated in the Beaufort Sea.

Topham, D.R. 1977. The Deflection of an Ice Sheet by a Submerged Gas Source, Journal of Applied Mechanics, June, 1977, pp 279-284.

The deflection of an infinite ice sheet by a submerged gas source, as would result from an undersea gas or oil well blowout is analysed utilizing an elastic thin plate model. . . .

Results

The results show that fracture may occur either at the bubble center or just beyond the bubble edge, depending upon the bubble depth, the ice thickness, and the material properties assumed for the ice sheet. For ice one meter in thickness and a trapped gas depth greater than 100 mm, fracture at the bubble edge is probable. The critical bubble radius for failure varies rapidly with ice thickness, bubble depth, and the ice properties, which in view of the variability of the latter, makes the prediction of actual bubble radii to cause failure subject to a large degree of uncertainty.

Topham, D.R. 1979. The Disposition of Gas/Oil Mixtures Trapped Under Ice. in Oil, Ice and Gas, Environment Canada, Toronto, pp 55-65.

This study is also reported in Topham, 1980.

The objective of this work was to investigate the probable configuration of oil and gas droplets that are released under an ice sheet.

Results

The following possible gas-oil configurations were considered:

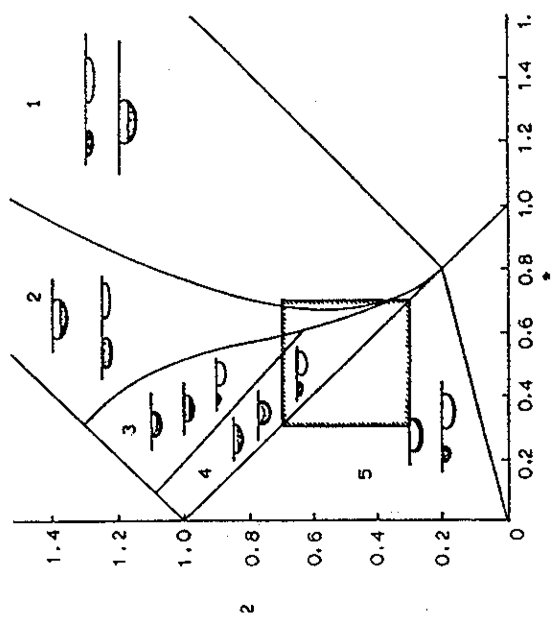
(a) oil coating the bottom part of a gas bubble (which was termed the sessile drop/lens configuration)

(b) a gas bubble inside a sessile drop of oil (which was termed the double sessile drop configuration)

(c) separate sessile drops of oil and gas.

The energies of the various systems were compared and the most probable configurations are shown in Figure 8.

Figure 8 Existence Diagram for an Oil Specific Gravity of 0.8



Note: The lowest configuration shown for each region is the one with the minimum energy. The upper ones show "the most likely configurations which would result form a finite disturbance of the system or from "a further addition of oil".

where:

$\overset{*}{\gamma}_{12}$ = $\dfrac{\text{surface tension of oil with respect to gas}}{\text{surface tension of water with respect to gas}}$

$\overset{*}{\gamma}_{2}$ = $\dfrac{\text{oil/water interfacial tension}}{\text{surface tension of water with respect to gas}}$

Topham, 1979, points out that "the probable range of normalized interfacial tensions for crude oils is between 0.3 and 0.7 (Malcolm and Dutton, 1979, Rosenegger, 1975)", which are shown in the shaded area of Figure 8. Topham, 1979, notes that little information is available to verify the analyses presented although the observations made by Purves, 1978 provide some guidance. Purves, 1978, found that all three of the configurations can exist when oil and gas are released beneath an ice sheet.

Topham, 1979, continues by considering the probable behaviour for the case of an oil well blowout. He concludes that "in the case of a blowout in which large quantities of gas are trapped beneath the ice, oil would tend to accumulate at the edge of the gas, and that gas bubbles would advance through the accumulated oil, pushing it aside."

Topham, 1979, cautions that

> . . . the analysis is only valid for infinitely large bubbles and that the energies of finite bubbles may change the preferred configuration."

Wotherspoon, P., Swiss, J., Kowalchuk, R., and Armstrong, J. 1985. Oil in Ice Computer Model. for the Environmental Studies Research Fund, Report No. 019.

A numerical model was developed to predict the spread of oil and gas released under a static, continuous ice sheet. Wotherspoon et al., 1985, state that the model

- considers the case of oil released under ice;
- deals with finite and continuous spills;
- allows for the effect of admixed gas on the spreading of the oil;
- includes the effects of ocean current on the net movement of the slick; and
- models the effect of roughness of the undersurface of the ice.

Results

The model is set up to analyze a total of 16 case types, which are delineated by the following conditions:

- whether or not the ice bottom is smooth or rough
- whether or not under-ice currents are present
- whether or not gas is released with the oil
- whether the spill is finite or continuous

Figure 2, and Tables 1 and 2, show the approach used with respect to the treatment of oil transport by currents under rough ice and smooth ice. The Wotherspoon et al., 1985, model is based on the laboratory tests and analyses conducted by Cox et al., 1980. Equation [5] (Table 1) is a quadratic approximation that was fitted by Wotherspoon et al., 1985, to the laboratory test data of Cox et al., 1980.

Wotherspoon et al., 1985, found that Cox et al.'s (1980) formulation (see Equation [15]), which is listed in Table 1 as equation [6], "yields values of the friction amplification factor [K] that are too great when the ratio of cavity depth to cavity length exceeds the domain originally investigated by Cox et al., 1980. To keep the value resonable, the program restricts the value of K to a maximum of 3.0".

The model conducts a volumetric analysis to determine the area of contamination taking into account slick transport under the ice for the cases where this occurs. The under-ice storage capacity is determined from the under-ice profile, which is an input to the model. The model assumes that the under-ice cavities are completely filled.

The spread of combined gas and oil spills is analyzed by first computing the area of contamination that would result for an oil-only spill in which the same oil volume is discharged. This area is then increased by an empirically-derived spread factor to account for the presence of the gas. Spread factors of 6.3 and 7.0 are stored in the model as default values for spills with gas-to-oil ratios of 150:1 and 200:1, respectively, based on the observations made at McKinley Bay, N.W.T., by Dickins and Buist, 1981. The model is set up such that other values may be entered by the user. The calculation procedure for determining the area of the spill is summarized in Tables 3 and 4.

The model is written in FORTRAN and was run for a number of cases. The results are sensitive to many factors including the under-ice profile, the presence or absence of gas, and the magnitude of under-ice currents (if they exceed about 15 cm/s).

The authors conclude by stating that

> The development of this computer model has relied on a number of assumptions and predictions. However, the program does provide a method by which to define the possible location of oil under or in an ice cover. Whether or not the assumed methodology is proven erroneous by others, the authors feel that the program provides a supportive base from which alterations can be made. The software package has been designed to allow for future alterations.

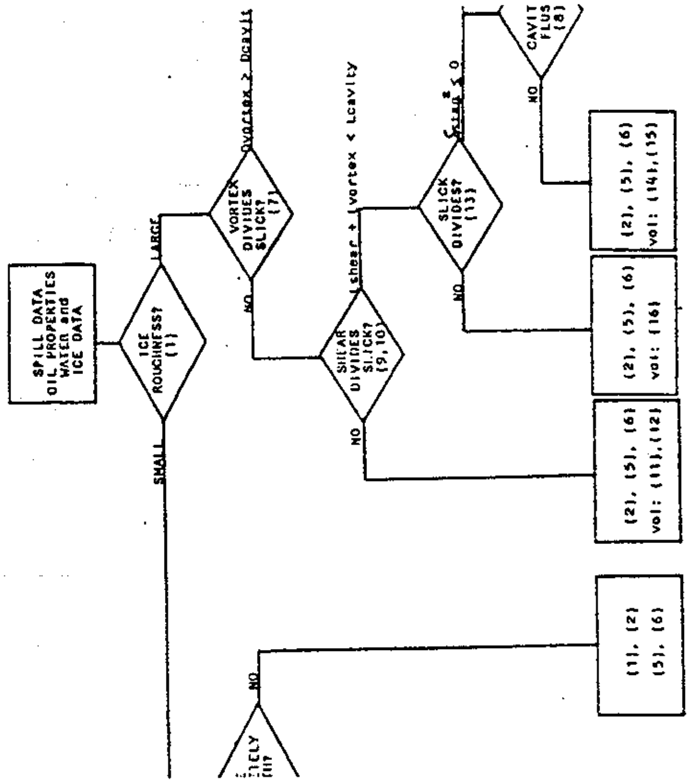


Figure 2 Flow Chart to Determine the Calculation Regime

Note: The numbers in brackets refer to equations which are listed in Table 1.

Table 1 Equations Referred to in Figure 2

$$\delta_{eq} = 1.67 - 8.50\ (\rho_w - \rho_o) \tag{1}$$

$$S_{tk} = 305.79/(88.68 - \mu_o) \tag{2}$$

$$S_s = 0.155\ S_w - 0.60 \quad for\ S_w < 18\ cm/sec \tag{3}$$

$$S_s = S_w - 15.6 \quad for\ S_w > 18\ cm/sec \tag{4}$$

$$S_s = S_w[1 - \sqrt{(K/\ (0.115\ F_\delta^{\ 2} + 1.105))}\ ] \tag{5}$$

$$K = 1 + 1.96(D_{cavity}/L_{cavity}) + 2.22\sqrt{(D_{cavity}/L_{cavity})} \tag{6}$$

$$D_{vortex} = S_w^{\ 2}/(3.46\Delta g) \tag{7}$$

$$S_{fall} = 1.5\sqrt{(2((\rho_w + \rho_o)\ /\ (\rho_w\rho_o))\ \sqrt{(\sigma_{ofw}(\rho_w - \rho_o))})} \tag{8}$$

$$L_{vortex} = 4S_w \tag{9}$$

$$L_{shear} = 4\Delta g\ (D_{cavity}^{\ 2} - (D_{cavity} - D_{vortex}/2)^{\ 2})\ /\ (f_s S_w^2) \tag{10}$$

$$V_{width} = L_{vortex}(D_{cavity} - D_{vortex}) + (L_{cavity} - L_{vortex})\ (\delta_{tail} + (D_{cavity} - D_{vortex}/2))\ /2 \tag{11}$$

$$\delta_{tail} = \sqrt{(f_s S_w^{\ 2}\ (L_{cavity} - L_{vortex})\ /\ (4\Delta g) + (D_{cavity} - D_{vortex}/2)^{\ 2})} \tag{12}$$

$$\delta_{stagnation}^{\ \ 2} = D_{cavity}^{\ 2} - f_s\ S_w^{\ 2}\ (L_{cavity} - L_{vortex})\ /\ (4pg) \tag{13}$$

$$V_{width} = (D_{cavity} + S_w^{\ 2}\ /\ (4\Delta g))\ (4\Delta g/(f_s S_w^{\ 2}))\ (D_{cavity}^{\ 2} - (S_w^{\ 2}/(4\Delta g))^2)/2 \tag{14}$$

$$v_{width} = 6C_D \, D_{cavity} \delta_{eq} \tag{15}$$

$$V_{width} = L_{cavity}(D_{cavity} + \sqrt{(D_{cavity}^{2} - L_{cavity} f_s S_w^{2} / (4\Delta g)}\,)/2 \tag{16}$$

Note: See table 2 for a listing of the above nomenclature.

Table 2 Terms Used in Equations in Table 1

Symbol	Definition	Units
A_s	Area of slick with current	m^2
A^1_s	Area of slick with current	m^2
C_D	Roughness form drag coefficient $C_D = 1.98$ for rectangular prism $C_D = 1.55$ for triangular prism	Dimensionless
δ	Local slick thickness	cm
δ_{eq}	Equilibrium oil slick thickness beneath smooth ice	cm
$\delta_{stagnation}$	Thickness of slick in a cavity at the end of the vortex zone	cm
δ_{sil}	Thickness of contained slick at the downstream cavity wall	cm
D_{vortex}	Vortex zone offset into a cavity	cm
D_{cavity}	Ice roughness height or cavity depth	cm
F_δ	Densimetric Froude number $F_\delta = S_w/\sqrt{(\Delta g \delta)}$ For this case, $\delta = \delta_{eq}$	Dimensionless
f_s	Oil/Water interfacial friction factor (Empirically $\simeq$ 0.016)	Dimensionless
g	Gravitational acceleration	cm/sec^2
K	Ice friction amplification factor	Dimensionless
L_{shear}	Length of the shear-dominated portion of the oil in a cavity	cm
L_{vortex}	Length of vortex cell	cm
L_{cavity}	Cavity length	cm
μ_o	Viscosity of oil	g/cm-sec
Δ	Relative density ratio $\Delta = (\rho_w - \rho_o) / \rho_w$	Dimensionless
ρ_o	Density of oil	g/cm^3
ρ_w	Density of water	g/cm^3
$\sigma_{o/w}$	Interfacial tension between oil and water typically 30 - 35 dynes/cm for crude oils	dynes/cm
R_s	Rate of spill	$m^3/hour$
S_e	Speed of edge of slick	cm/sec
S_{fail}	Current speed for containment failure	cm/sec
S_s	Oil slick speed	cm/sec
S_{th}	Threshold current speed for slick movement	cm/sec
S_w	Water current speed	cm/sec
T	Time	hours
T_{end}	Duration of spill	hours
V_s	Volume of slick	m^3
V_{area}	Volume per unit area without current	m^3
V'_{area}	Volume per unit area with current	m^3
V_{width}	Approximate volume of oil trapped per unit width of cavity	cm^3/cm
W_s	Width of slick	m

Table 3 Calculation Procedures for Determining the Area of Contamination for Spills Under Smooth Ice (i.e., No Roughness)

	Case	Calculation Procedure
A: B:	No current, no gas, finite spill and; No current, no gas, continuous spill	$$A_s = \frac{V_{oil}}{\delta_{eq}}$$ where: A_s = area of slick, m^2 V_{oil} = volume of oil spilled, m_3 δ_{eq} = equilibrium oil slick thickness, m, (from equation [1]-see table 1)
C: D:	No current, gas finite spill and; No current, gas, continuous spill	$$A_s = F_{gas} [\frac{V_{oil}}{\delta_{eq}}]$$ where: F_{gas} = a spread factor which accounts for the additional area of a gas/oil spill.
E:	Current, no gas, finite spill	$Sw < S_{th}$: same as for no-current case above $Sw > S_{th}$: the slick area is computed as above and "the entire slick is assumed to move uniformly downstream at a speed given by either equation (3) or (4)".
F:	Current, no gas, continuous spill	Similar to E above except that fresh oil is added at each time step $S_w < S_{th}$: Same as for case E. The model assumes that the slick will be circular. $Sw > S_{th}$: The model assumes that the slick shape will be oval which is approximated by a rectangle with semi-circular ends. The width of the slick, W_s, is determined as follows: $W_s = R_s / (S_s \cdot \delta_{eq})$ where: R_s = rate of spill, m^3/hour S_s = speed of slick, m/hour (defined by eq'n. (3) or (4) - see table 1). δ_{eq} = equilibrium thickness of slick, m (defined by eq'n. (1) - see table 1).
G: H:	Current, gas, finite spill and; Current, gas, continuous spill	Same as for cases E and F above except that the spill area in increased by the factor, F_{gas}, as for cases C and D above.

Table 4 Calculation Procedures for Determining the Area of Contamination for Spills Under Rough Ice

Case		Calculation Procedure
I:	No current, no gas, finite spill and;	$$A_s = \frac{V_{oil}}{\delta_{eq} + V_{stor}}$$ where: A_s = area of slick, m^2 V_{oil} = volume of oil spilled, m_3 δ_{eq} = equilibrium oil slick thickness, m (from eq'n.[1] - see table 1) V_{stor} = unit under-ice storage volume, m^3/m^2
J:	No current, no gas, continuous spill	
K:	No current, gas, finite spill and;	$$A_s = F_{gas} \left[\frac{V_{oil}}{\delta_{eq} + V_{stor}}\right]$$ Note: See table 3 for a definition of F_{gas}
L:	No current, gas, continuous spill	
M:	Current, no gas, finite spill	$S_w > S_{th}$ K: (a) determine the slick speed, S_s (from eq'n. [5] - table 1). If $S_s \leq$ O, then branch to case I (b) determine the oil volume, that wil be trapped in the under-ice cavities. See figure 2 for approach. (c) if $S_w < S_{fail}$ (ie. $V'_{stor} > 0$): $$A_s = \frac{V_{oil}}{V'_{stor}}$$ where: V'_{stor} = unit under-ice storage volume (m^3/m^2) determined in (b) above. (d) If $S_w > S_{fail}$ (ie. $V'_{stor} \leq 0$), which indicates that the under-ice cavities will be flushed out: same as for case E - see table 3 $S_w \leq S_{th}$ K: same as for case I

Table 4 Cont'd.

N:	Current, no gas, continuous spill	$S_w > S_{th}$ K: S_s is checked and V'_{stor} is calculated as described above for case M. (a) If $S_w < S_{fail}$, the width of the slick is determined using the same procedure as for case F (table 3). "The slick is then assumed to be in the form of an oval. the upstream end of which is centred on the release point, and the downstream edge of which advances continuously at an effective speed, S_e (m/hr): $S_e = S_s \delta eq / (\delta_{eq} + V'_{stor})$ where: S_s = speed of body of slick, m/hr "When the spill ceases, the downstream edge continues to advance at the same effective speed until all the oil in the equilibrium thickness layer is trapped. The final length is given by": $L'^{s} = L_S (\delta_{eq} (\delta_{eq} + V'_{stor})/V'_{stor}$ where: L'_s = length of slick with no equilibrium layer (which is the final length) L_s = length of slick with equilibrim layer (which is the length at the instant the spill ceases) Wotherspoon et al. 1985, state that "these calculations assume a rectangular shape, and the results must be modified for the oval shape actually used in the model output." (b) If $S_w > S_{fail}$, calculations are done as for case M, but S_e is equal to S_s. "If the spill ceases, the length remains fixd, but the entire slick moves bodily downstream at S_s". $S_w \leq S_{th}$ K: same as for case J
0:	Current, gas, finite spill	$S_w < S_{th}$ K: same as for case K $S_w > S_{th}$ K: same as for case M, except that the spill area is increased in the same manner as for case K
P.	Current, gas, continuous spill	Similar to case N, except that the spill area is increased as for case L and "if the current is sufficient to cause the oil to move, the width of the advancing front will be greater in proportion to the increase in area caused by the gas".

Comfort, G. 1987. Analytical Modelling of Oil and Gas Spreading Under Ice. Arctec Canada Ltd. for the Environmental Studies Research Fund, ESRF Report No. 077.

An analytical model was developed to predict the area of contamination resulting from discharges of oil and gas under a static, continuous ice sheet, at locations where under-ice currents are negligible. The model was run for a number of cases. The modelling approaches and the results obtained were compared to those used in another model that was previously developed by Wotherspoon et al., 1985.

Editor's note: As the Wotherspoon et al., 1985 model has been reviewed separately, this summary will be limited to a description of the Comfort, 1987, model.

Results

Modelling of Under-Ice Spreading

A volumetric analysis is performed. The under-ice storage capacity is predicted based on the ice thickness, the ice thickness standard deviation, and the depth to which the under-ice cavities are filled with oil and gas. Based on review of the available field data, the following expression was developed and used to predict the under-ice storage volume, S_v (m^3/m^2) for Arctic locations where the ice thickness is greater than 0.5 m:

$$S_v = \left(\frac{F_D}{0.5}\right)^{2.7} \cdot \left[\frac{0.3\ h_{sD}\ h_i}{100}\right]$$

where: h_i = mean ice thickness

h_{sd} = ice thickness standard deviation (expressed as a percentage of the mean ice thickness)

F_D = Fill depth ratio (which is defined as the oil pool depth/maximum ice thickness variation)

Editor's note: The above equation is not listed directly in Comfort, 1987. It was produced by the editors based on the approach used in Comfort, 1987 to predict the under-ice storage volume. The model assumes that the under-ice depressions are filled systematically, starting with the ones nearest to the oil and gas plume. The under-ice depressions are initially filled to the level of the mean ice thickness.

Based on observations of field spills, an ice lip is assumed to form around the oil and gas at a faster rate than the unoiled ice growth rate. This effectively increases the under-ice storage capacity as oil and gas must pool to greater depth in the under-ice cavities before further lateral spreading is possible. Based on laboratory test results, the ice lip is assumed to grow at twice the unoiled ice growth rate.

The volume of gas and oil discharged is an input to the model. Checks are made by the model to determine whether or not failure of the ice, and hence, venting of the gas, will occur using the analyses of Topham, 1977. If venting occurs, the volume of gas is reduced. Comfort, 1987, assumed that only 80% of the gas would be vented when ice rupture occurs as the cracks produced in the ice sheet might not intersect all of the under-ice pockets where gas was stored.

Gas is assumed to dissipate through the ice during the spring melt period at a rate of 1.5×10^{-4} m^3/m^2 per day (which is based on laboratory measurements of gas dissipation rates made by Purves, 1978). Gas dissipation is commenced when ice thickness exceeds a user-input value.

The model was run for a number of cases.

The predicted area of contamination is sensitive to the under-ice storage capacity, the presence or absence of gas, and whether or not venting occurs.

In closing, the author notes that "the results of this study are limited by gaps in our understanding in a number of important factors." These uncertainties include the under-ice storage capacity, the effect of currents on large oil pool depths, the effects of a continuous spill on the formation of a confining ice lip, and gas venting due to rupture of the ice sheet.

Venkatesh, S., El-Tahan, H., Comfort, G., and Abdelnour, R. 1990a. Modelling the Behaviour of Oil Spills in Ice-Infested Waters, Atmosphere-Ocean 28 (3), pp 303-329.

This study is also reported in Venkatesh, El-Tahan, Comfort, Abdelnour, 1990b; and El-Tahan, Comfort and Abdelnour, 1988.

The objective of the work was to develop methodologies for computing the drift and spread of oil spills in broken ice. The model is limited to oil-only spills and it does not include oil property changes during the spill (e.g., weathering).

Results

Oil Drift in an Ice Field

The available data were reviewed in an effort to assess the conditions under which relative oil motion will and will not occur in an ice field. Venkatesh et al., 1990a, note that the information base is scant, and use the following approach:

> . . . oil and ice will move together in ice concentrations greater than about 30%. For ice concentrations less than 30%, the oil will behave in a manner similar to a spill on open water. Since the present study is mainly concerned with medium and high ice concentrations, it is assumed that under steady-state conditions, the oil and ice will move together...

The motion of spills 1 and 2 (of the tests conducted by S.L. Ross and DF Dickins, 1987) was simulated using both kinematic and dynamic modelling. Both models provide a reasonable prediction of the observed drift (Figure 3). However, the dynamic model produced a slightly better fit. The authors caution that the duration of the available field data is only 5 hours and recommend that additional field data with a longer duration be acquired to provide a better verification.

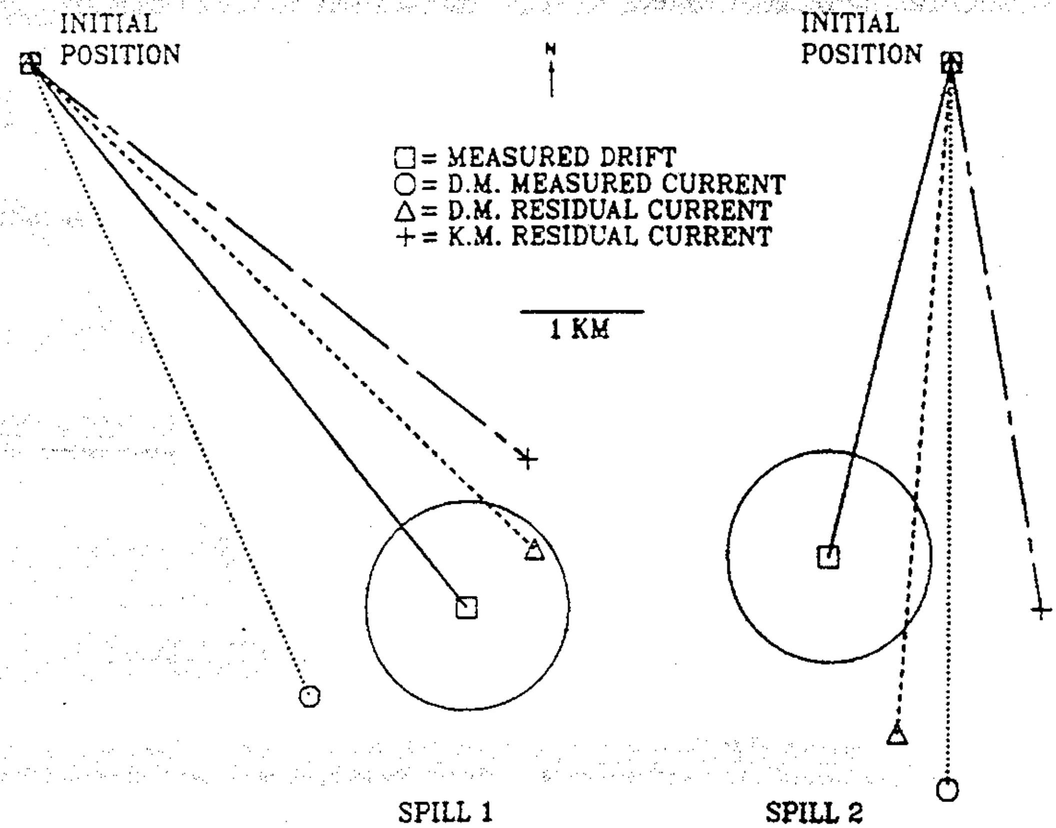


Figure 3: **Comparison of model-simulated oil drift (over 5 h) with observations from the S.L. Ross and DF Dickins (1987) study. D.M. refers to the Dynamic Model of El-Tahan and Warbanski (1987) and K.M. refers to the Kinematic Model used by S.L. Ross and DF Dickins (1987). The circles represent measurement errors in the observed final locations.**

<u>Oil Spreading in Broken Ice</u>

Present methodologies for predicting the spread of oil on cold water and in particle ice were reviewed. Venkatesh et al., 1990a, note that there is considerable scatter between the predicted values and the available field and laboratory observations. Based on most of the field and laboratory test data, the following empirical expressions were developed:

Oil spreading on cold water: $T_w = \mu/125$ [5]

Oil spreading in particle ice: $T_s = 0.0316\ \mu$ [7]

where: T_w, T_s = equilibrium thickness (mm) of oil on cold water and in particle ice, respectively

μ = oil viscosity (MPa s)

The area of contamination, A, was computed as follows for low, medium and high ice concentrations:

Low ice concentrations (C< 30%)

$$A = V/[T_w(1\text{-}C)] \qquad [8]$$

where: V = volume of oil spilled

Medium ice concentratioins (30% ≤ C ≤ 80%). The volume of oil trapped under the ice, V_{ui}, is determined as follows:

$$V_{ui} = A_{fl}\, T_{ui}\, C \qquad [9]$$

where: A_{fl} = horizontal area of an average floe

T_{ui} = the under-ice storage volume per unit area which was defined as 0.021 X (ice thickness)

The volume of oil trapped by slush or brash ice, V_s, was determined as follows:

$$V_s = T_s\, A_s \qquad [11]$$

where: A_s = area covered by slush or brash ice

The remaining oil, V_r, is then available for spreading and thus is computed as follows: [12]

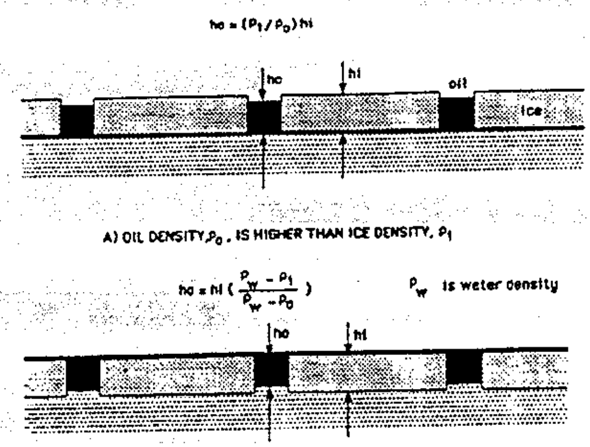
$$V_r = V_t - (V_{ui} + V_s) \qquad \text{where: } V_t = \text{total volume of oil spilled}$$

The area of contamination is then computed by substituting V_r into equation [8].

High ice concentrations (C > 80%). The model computes the oil-volume stored under the ice (using equation [9]) and between the floes, V_{fl}, within an area, A, using the following expression:

$$V_{fl} = (1 - C)\ A\ h_o$$

where: h_o = the oil thickness filling the closed gaps (see below)



A) OIL DENSITY, ρ_o, IS HIGHER THAN ICE DENSITY, ρ_i

B) OIL DENSITY, ρ_o, LOWER THAN ICE DENSITY, ρ_i

The model's results were compared with field observations made by S.L. Ross and DF Dickins, 1987 during an experimental spill in pack ice that was conducted. The model predicts an area of contamination of 42 m^2, in comparison to measured values of 36 m^2 and 35 m^2 at sites 1 and 2. The authors consider this comparison to be a "fairly good but limited validation" of the model. They caution that "additional data sets are required for a more complete and accurate evaluation of the model."

Some sensitivity studies were done. The model's results are sensitive to several factors including the ice concentration (Figure 9), the floe size (Figure 10), and the presence of slush (Figure 11).

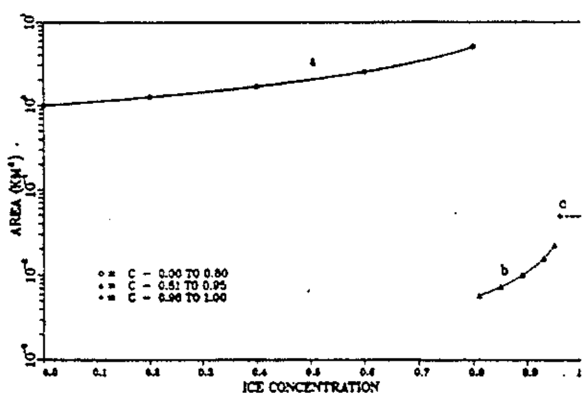


Figure 9 **Oil-contaminated Area as a Function of Ice Concentration for a 1000-m^3 Spill and 10-m Average Floe Size**

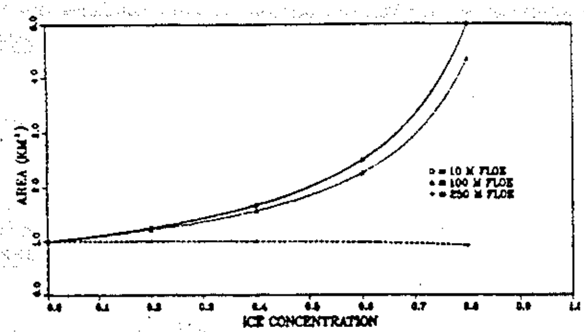


Figure 10 Effect of Ice-floe on an Oil-contaminated Area for a 100-m³ Spill

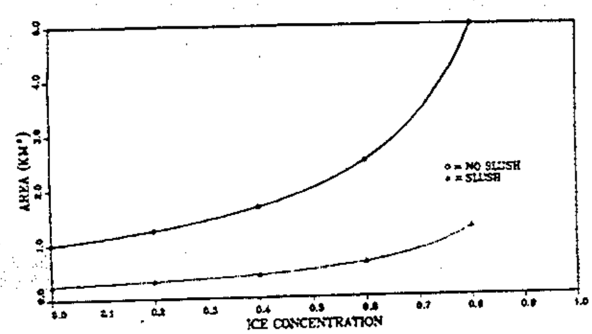


Figure 11 Effect of the Presence of Slush Ice on an Oil-contaminated Area for a 1000-m³ Spill and a 10-m Average Floe Size.

4.6 Discussion: Key Processes and Modelling

The research described in Section 4.1 has provided an understanding of the processes that will probably occur when large volumes of oil, and oil and gas mixtures, are discharged under a static, continuous sheet of sea ice. This section provides a discussion of the key processes and a review of the modelling approaches that have been used to date. This section has been organized into subsections based on the following main processes:

(1) Under-ice spreading of the oil and gas;

(2) Encapsulation of the oil and gas in the ice;

(3) Migration and release of the oil and gas.

4.6.1 Under-Ice Spreading

4.6.1.1 Configuration of the Oil and Gas

Extensive research, consisting of a combination of analytical studies, laboratory tests, and field spills, has been conducted to develop an understanding of the spread of oil, and gas if present, under an ice sheet. Laboratory tests have aided in understanding the processes involved and have produced data to define key spreading parameters (e.g., contact angle, interfacial tension). Field spills have provided information at large scale which has helped to develop an overall understanding of the expected spreading behaviour.

Oil Spilled Under an Ice Sheet

The basic case of oil spreading under a smooth ice surface in calm water has been investigated by several researchers. Numerical models have been developed by Hoult, 1975, Chen et al, 1976, and Yapa and Chowdhury, 1990, to analyze this case. Of these, the Yapa and Chowdhury, 1990, model is the most general one in that it can handle spills in which either a constant discharge rate is maintained or a fixed volume is spilled.

However, the under-surface of an ice sheet is rarely smooth and field spills have shown that the final under-ice configuration of the spilled oil is dominated by the under-ice topography. During the largest field spills conducted to date (at Balaena Bay, N.W.T.), NORCOR, 1975, observed that the oil flowed along under-ice troughs in rivulets to the nearest dome under the ice where it pooled. Little oil was entrapped in the skeletal layer and in the immediate vicinity of the plane. The oil appeared to etch a channel in the skeletal layer and repeatedly followed the same course. Most of the oil was deposited in relatively thick pools (i.e., in excess of 2 cm) and few sessile drops were present. The oil appeared to fill the under-ice depressions systematically. Therefore, the under-ice topography is a very important factor. The available information to describe and model this is discussed in the next section.

General spreading models have been developed by NORCOR, 1977; Wotherspoon et al., 1985; Comfort, 1987; and Venkatesh et al., 1990, to analyze the fate and behaviour of oil spilled under an ice sheet. For each of these models, the area of contamination is computed using a volumetric analysis, based on the volume of oil discharged and the available under-ice storage volume. Although none of these models have been verified with field data (as the required field data are not available), this is considered to be a reliable approach for predicting the spread of large spills under an ice sheet.

A Combined Oil and Gas Spill Under an Ice Sheet

Laboratory tests have been conducted to investigate the resulting configuration when oil and gas are released together under an ice sheet. The observed configurations include an oil-coated gas bubble, gas bubbles with oil on their sides and bottom, and separate sessile drops of oil and gas.

When oil and gas were released under the ice in the field (at McKinley Bay, N.W.T.), the following configurations were observed (Dickins and Buist, 1981):

(1) oil droplets;
(2) gas bubbles with a coating of oil; and
(3) large pools of oil underneath gas pockets.

Dickins and Buist, 1981, observed that most of the oil was distributed as oil droplets and gas bubbles (i.e., configurations 1 and 2) for the case when the oil was released under relatively thin ice (which was relatively flat). For spills carried out later on during the winter when the ice was relatively thick and rough, most of the oil and gas were contained in the under-ice pockets (i.e., configuration 3). These observations show the importance of the under-ice topography on the spread and configuration of the oil and gas.

Three general spreading models have been developed to date to predict the fate and behaviour of oil and gas released beneath an ice sheet (by NORCOR, 1977; Wotherspoon et al, 1985; and Comfort, 1987). The NORCOR, 1977, and Comfort, 1987, models assume that the oil and gas will fill the under-ice depressions uniformly with pockets of gas underlain by an oil film. The area of contamination is computed based on the volume of the spilled oil and gas, and the available under-ice storage volume.

The Wotherspoon et al., 1985, model predicts the area of a combined oil and gas spill by multiplying the area of an oil-only spill (with the same oil volume) by a constant spread factor. The default values for the spread factors in the Wotherspoon et al., 1985, model were developed based on the field observations made by Dickins and Buist, 1981, at the McKinley Bay spill.

The volumetric approach adopted by NORCOR, 1977, and Comfort, 1987, is considered to be preferable as it is more general and physically-based. Comfort, 1987, found that this approach produced results which were in general agreement with the McKinley Bay data (on which the spread factors of the Wotherspoon et al. model are based).

4.6.1.2 Under-Ice Morphology and Storage Volume

It is well known that ice thickness variations occur in a continuous sheet of undeformed sea ice. The morphology and size of the under-ice relief has an important effect on the spread of oil and gas as it will accumulate in the under-ice depressions. For cases where the under-ice currents are insufficient to strip oil from the under-ice cavities, the area of contamination will be governed by the volume of the released oil and gas and the available under-ice storage volume.

Under-ice roughnesses have been observed on a number of scales. Small scale roughnesses in the skeletal layer of the growing ice sheet occur with a depth of up to a few centimetres and up to a wavelength of 5 to 10 centimetres. The only available data to define the storage volume in these roughnesses were obtained by Goodman et al. (1987a, 1987b) for a thick sheet of first year ice in the Beaufort Sea. They measured an average storage volume of 0.012 m^3/m^2 for the case where these voids are completely filled.

There is some uncertainty regarding the role of these skeletal layer voids during a spill. During under-ice oil spills that were conducted at Balaena Bay, N.W.T., NORCOR, 1975, observed that the skeletal layer was eroded by the oil which tended to flow in rivulets that cut a path and meandered through the skeletal layer roughnesses. Little oil was trapped in these voids during the spreading of the oil.

NORCOR, 1975, observed that the majority of the oil was contained in larger scale under-ice depressions that occur as a result of variations in snow cover. Other investigators (e.g., Dickins et al, 1981) have also observed that the under-ice configuration of the spilled oil and gas was effectively controlled by large scale under-ice cavities in the sheet. The morphology and magnitude of these larger-scale under-ice roughnesses has been studied by several investigators, as summarized in Table 4.2.

Table 4.2 Summary of Computed Storage Volumes for First Year Sea Ice

REFERENCE	COMPUTED STORAGE VOLUME (m^3/m^2)
Kovacs, 1977	.027
Barnes, 1979a; 1979b	.025 to .047
Kovacs et al, 1981	.010 to .061
Comfort, 1986	.023

Each of the above references has been reviewed in Section 4.1. It should be noted that Barnes et al., 1979a; 1979b; determined the storage volume by assuming that cavities with drafts less than the mean draft were filled while the other investigators based their estimates on under-ice pockets that were above the level of the mean ice thickness. Therefore, lower storage volumes are to be expected from the work of

Barnes et al., 1979a; 1979b.

The under-ice storage volume depends on a number of factors, including the mean ice thickness, the ice thickness variation and the depth to which the under-ice pools are filled.

The under-ice storage capacity may also be affected by the encapsulation process as an ice lip has been observed to form rapidly around the edges of the oil and gas lens. Depending upon the relative rates of ice formation and oil and gas discharge, this ice lip may increase the available storage as the under-ice pools must fill to greater depth before further lateral spreading is possible. Unfortunately, there is little information available to assess this possibility quantitatively. All of the experimental field spills conducted to date have been of relatively short duration (i.e., less than one hour) which makes it difficult to extrapolate to the case of a continuous spill.

For a combined oil and gas spill under relatively thick ice (i.e., sufficiently thick that failure of the ice sheet does not occur), the under-ice storage may be increased by uplift of the sheet.

Table 4.3 summarizes the approaches that have been used to date to predict the storage volume. The predictors of NORCOR, 1977, and Comfort, 1987, are empirical and are intended to predict the storage volume resulting from the larger scale under-ice roughnesses (discussed previously). Wotherspoon et al.'s (1985) approach is applicable to under-ice roughnesses on a range of scales.

The Comfort, 1987, predictor is considered to have the most general applicability as it allows the user to predict the storage volume as a function of time during a continuous spill for a range of ice conditions.

However, there are uncertainties associated with using each of the predictors. The

Table 4.3 Modelling Approaches Used to Predict Under-Ice Storage Volume

Reference	Modelling Approach and Assumptions	Predictors Developed
NORCOR, 1977	Estimated by assuming that the under-ice depressions are filled completely and that: (a) the under-ice surface is sinusoidal and; (b) the average oil-gas film thickness is 10% of the mean ice thickness, and; (c) the mean ice thickness increases at a rate of 1 cm/day, and; (d) multi-year ice has an initial thickness of 3 m.	Multi-year ice: $C_m = (300 + n)\ 10^{-3}m$ First year ice: $C_f = n\ 10^{-3}\ m$ where: C_f, C_m = saturated oil and gas film thicknesses for first year and multi-year ice, respectively n = number of days after freezeup
Wotherspoon et al, 1985	Determined based on the shape and size of the under-ice roughness profile, which are input by the user.	• Volumetric analysis of under-ice roughness profile. • Under-ice roughnesses assumed to be filled completely.
Comfort, 1987	Determined based on the mean ice thickness, the ice thickness standard deviation, and the depth to which the under-ice pools are filled. The model assumes that the under-ice depressions are filled initially to the level of the mean ice thickness. An ice lip is assumed to form around the oil and gas lens (at twice the growth rate of the unoiled ice) which causes the storage volume to increase as the under-ice pools are filled to greater depth.	$V_s = \left(\frac{F_d}{0.5}\right)^{2.7} \left[\frac{0.3\, h_{sd} h_i}{100}\right]$ where: V_s = storage volume (m^3/m^2) h_i = mean ice thickness (m) h_{sd} = ice thickness std dev. (expressed as a percentage of the ice thickness) F_D = fill depth ratio = oil pool depth / ice thickness variation

NORCOR, 1977, provides an estimate of the maximum available storage volume as it assumes that the under-ice depressions are fully-filled. This may overestimate the available storage volume. The Wotherspoon et al., 1985, model relies on a knowledge of the under-ice profile, which may be difficult to define accurately. It also assumes that the under-ice depressions are filled completely. The Comfort, 1987, model has a number of assumptions (e.g., that the under-ice pools are initially filled to the level of the mean ice thickness and that the under-ice pools fill to greater depth subsequently due to the formation of an ice lip around the oil and gas lens) which should be verified before it is used as a general predictor.

4.6.1.3 Interaction of Gas with the Ice Sheet: Gas Venting

The spread area of a combined oil and gas spill will be greatly affected by whether or not the gas is vented through the ice sheet. Gas venting can occur by a number of mechanisms which include:

(a) rupture of the ice sheet due to the buoyancy forces exerted by the trapped gas bubble;

(b) release of the trapped gas to the ice surface through brine channels in the ice and through other flaws that may be present in the ice sheet. For this discussion, this process has been termed dissipation.

Rupture of the Ice Sheet

Many investigators have suggested that the ice sheet may rupture when a large gas bubble is trapped beneath it.

Dickins and Buist, 1981, conducted the only experimental field spill to date in which oil and gas (compressed air was used in their study) were released together under a continuous sheet of first year sea ice. These tests were carried out at McKinley Bay, N.W.T. The ice sheet did not rupture for the tests conducted in late April and early May (when the ice was about 1.8 m thick). Tests were also conducted in mid-December, when the ice was about 0.6 m thick; however, for these tests, the ice sheet was drilled to allow the gas to escape.

The only available numerical model to analyze the deflection and failure of an ice sheet due to a trapped gas bubble was developed by Topham, 1977. His analysis treats the ice sheet as an infinite, elastic, thin plate. Based on a review of the Topham, 1977, model and its results, and the field experience gained at McKinley Bay, N.W.T., Dickins and Buist, 1981 predicted that ice sheets thinner than about 1 metre would probably rupture.

A number of modelling approaches have been used to date to include the effect of ice sheet rupture on the spread of oil and gas under a continuous ice sheet, as summarized in Table 4.4.

The most realistic approach is considered to be that used in the Comfort, 1987, model. In this model, ice rupture is treated as a separate event which then affects the area covered by the oil and gas. However, this model relies on Topham's analyses to predict failure of the ice sheet. This may be questioned as the Topham model assumes that the rheological behaviour of the ice sheet is linear-elastic, whereas creep deflections of the ice are known to be significant for long term loadings. NORCOR's (1977) model is arbitrary, although it is a simple and useful approach for investigating extreme cases and for conducting sensitivity analyses. The Wotherspoon et al., 1985, model is empirical. As it is based on a single field spill program in which the individual discharges were of short duration (i.e., about 30 minutes), its applicability to spills of long duration may be questionable.

In summary, there are uncertainties associated with each of the above approaches and further work is required to develop a proven, reliable model.

Table 4.4 Summary of Modelling Approaches Used to Date to Include the Effect of Ice Sheet Rupture on the Spread of Oil and Gas Beneath an Ice Sheet

REFERENCE	MODELLING APPROACH
NORCOR, 1977	NORCOR, 1977 assumed that all of the gas would be vented for first year ice while all of the gas would remain trapped under multi-year ice.
Wotherspoon et al., 1985	The area of a combined oil and gas spill, $A_{gas \& oil}$ is determined as follows: $A_{gas \& oil} = F_{gas} \cdot A_{oil}$ where: A_{oil} = area predicted to be covered by only the oil volume released during the gas/oil spill. F_{gas} = a spread factor that is intended to account for the increased area of a combined gas and oil spill, based on observations made at the McKinley Bay spill by Dickins and Buist, 1981. The Wotherspoon et al, 1985, model has default values of 6.3 and 7.0 for F_{gas} for gas-to-oil ratios of 150:1 and 200:1, respectively. The Wotherspoon et al, 1985, model predicts that the area of a continuous gas and oil spill will increase linearly with time over the duration of the spill. This model uses Topham's, 1977, analysis to check whether or not rupture of the sheet will occur.
Comfort, 1987	For a continuous spill, the trapped gas bubble increases in size depending on the volume and the rate of discharge of the oil and gas, and the lateral spreading that occurs, which is dependent upon the under-ice stroage capacity. If Topham's, 1977, failure criteria for rupture of the ice sheet are exceeded, then the gas is assumed to vent. Comfort, 1987, assumed that only 80% of the gas would vent to account for gas volumes that could be located far away from the cracks produced in the ice sheet and which might not be released. With this approach, the spill size is predicted to increase with time until venting occurs. The area of the spill is then greatly reduced.

Gas Dissipation

Gas trapped in an ice sheet, and pooled under it, may rise to the surface through brine channels in the sheet and other flaws (e.g., cracks). Laboratory tests have been conducted by Purves, 1978, and Kisil, 1981, which provide information regarding this process. During both test programs, it was found that the gas remained trapped in and under the ice until the sheet had become relatively warm. Gas migration commenced when the minimum ice temperature reached -3.6° C, and -2.2° C to -6.0° C, in Purves's and Kisil's tests, respectively. The gas was released in advance of the oil during both test programs.

These results are supported qualitatively by observations made at McKinley Bay, N.W.T., by Dickins and Buist, 1981. They observed that the gas remained trapped in the ice until early spring when it was released in advance of the oil.

The only under-ice spreading model that is known to include gas dissipation is that of Comfort, 1987. This model assumes that gas will vent during spring conditions at 1.5×10^{-4} m^3/m^2/day, which is the rate observed by Purves, 1978, during his laboratory tests. This model allows gas dissipation to commence once the ice thickness exceeds 1.75 m.

It is of interest to compare the above gas dissipation rate with the gas volume that might be expected for a blowout. Assuming an oil discharge rate of 1900 m^3/day and a gas-to-oil ratio of 150:1, a gas volume of 285,000 m^3 would be released under the ice in one day. In order to dissipate this volume in one day at the above rate, the gas must be spread over an area with a diameter of about 50 km, which is believed to be a large area in the context of a blowout. This exploratory calculation indicates that gas dissipation is unlikely to affect the under-ice spread of oil and gas significantly.

4.6.1.4 Under-Ice Spreading: Transport by Currents

The spread of oil and gas beneath an ice sheet may be affected significantly by the presence of under-ice currents.

Relatively little information is available for assessing current-driven oil transport under an ice sheet. Most of it is based on tests conducted in laboratory flumes where the oil spread mainly in one direction only.

One experimental spill was conducted in the field (near Cape Parry, N.W.T.) where currents up to about 10 cm/sec were present (by NORCOR, 1975). This current was found to produce a directional bias in the under-ice area covered by the oil, but it was insufficient to strip oil from the under-ice depressions after the oil had ceased to spread.

The current-driven transport of oil under smooth ice has been investigated by Uzuner et al., 1979, and by Puskas et al., 1987. The transport of the slick was found to depend greatly on whether it was aligned with the direction of the current, or transverse to it. Models were produced by each of these investigators for these two cases; however, the developed models are incapable of determining the direction of the slick, which presents difficulties for general application.

However, the transport of oil slicks beneath a rough ice surface is considered to be a more practical case for sea ice sheets. Tests have been conducted in the laboratory by Cammaert, 1980, and Cox et al., 1980, which provide information for this case. These tests indicate that currents in excess of about 15 to 25 cm/sec are required to strip oil from the under-ice depressions, which would affect the spread area of a spill. For smaller currents, the location of the oil deposited under the ice is likely to be affected by the presence of currents, as the oil will be transported "downstream" of the release point until it ceases to spread. However, this is unlikely to increase the total area of contamination.

The only available numerical model for current-driven oil transport under a rough ice surface was developed by Cox et al., 1980. Only one general spreading model has been developed which includes the effect of under-ice currents (i.e., the Wotherspoon et al. 1985 model). Cox et al.'s (1980) predictors and approach were implemented by Wotherspoon et al. in their model.

The Cox et al., 1980, has not been verified independently with field or other laboratory data (as these data are not available). Therefore, its reliability cannot be assessed at present. However, as the model is relatively comprehensive, and as it is the only available predictor, it is recommended for use during future modelling studies with the proviso that these results be interpreted carefully.

4.6.1.5 Under-Ice Spreading: Effect of Ice Movement

The area of contamination for oil, and combined oil and gas, spills under an ice sheet may be increased should ice movements occur during the spill.

The only model available to analyze this scenario was developed by NORCOR, 1977. The area of contamination and the resulting oil film thickness are predicted using a volumetric analysis taking into account the oil and gas discharge rate, whether or not the gas is vented, the available under-ice storage volume, and the ice movement rate.

Although this model has not been verified with field data (as these data are not available), this approach is expected to provide reliable results provided that realistic parameter values are used.

4.6.2 Encapsulation

For cases where the oil, and gas if present, are discharged under the ice while the sheet is still growing, the oil and gas will be encapsulated in the ice by subsequent growth beneath it. This has been observed to occur during all of the field and laboratory tests conducted to date.

The first step in the encapsulation process is the formation of an ice lip around the oil and gas. Subsequently, the oil and gas becomes fully-encapsulated, either by lateral ice growth from the sides of the lens, and/or by vertical heat flow, depending on the geometry and size of the lens and the temperature gradients.

Encapsulation is an important process as it effectively immobilizes the oil and gas, thereby preventing further spreading. There are two aspects of this process that need to be considered in a model of oil-ice interaction

(1) the time required for the ice lip to form and for the oil and gas to become encapsulated;

(2) the effect of the encapsulated oil and gas on subsequent ice growth.

The time required for the formation of an ice lip and for encapsulation has not been analyzed numerically. An empirical approach is recommended for present modelling studies, as this is a simple approach and a relatively large information base is available.

With respect to the effect of the encapsulated oil and gas on subsequent ice growth, several investigators (e.g., NORCOR, 1975; Chen, Keevil and Ramseier, 1976; Kisil, 1981) have considered this problem. Heat flow across the oil lens has been assumed to occur either by conduction only, or by a combination of conduction and convection. As the thermal conductivity of oil and gas is significantly less than that of ice (by a factor of more than 10), these models typically predict that ice growth will be reduced by the presence of an oil lens. In extreme cases (i.e., thick oil lenses), convective heat transfer across the oil layer could result in increased ice growth (NORCOR, 1975). However, for typical cases, these analyses suggest that conduction will be the dominant heat transfer mechanism, and thus, the models predict that subsequent ice growth will be retarded.

Reasonable agreement has been obtained in the laboratory between the measured and the predicted values (by assuming that heat transfer occurs either by conduction only, or by a combination of conduction and convection). However, field conditions are more complex (e.g., due to the presence of snow cover variations) and thus, care should be taken in applying these models to field cases.

The most extensive work on this subject was conducted by NORCOR, 1975, using data collected during a large field spill at Balaena Bay, N.W.T. Their analyses showed that the overall effect of the encapsulated oil was small in comparison to natural variations in ice thickness which occur (as a result of snow cover variations). This result is corroborated by data collected during large field spills of oil and gas under sea ice at McKinley Bay, N.W.T., (conducted by Dickins and Buist, 1981) in which the presence of the oil and gas was not observed to effect the maximum ice thickness.

Therefore, care should be taken in applying these numerical models to the problem of ice growth beneath the oil lens. An empirical approach is recommended as it is relatively simple and as a relatively large database of field experience is available.

4.6.3 Vertical Migration and Release of the Oil and Gas

4.6.3.1 First Year Sea Ice

The available field and laboratory test data show that oil, and gas if present, which is trapped in the ice will be released in the spring as the sheet deteriorates. This is an important aspect of oil-in-ice behaviour as it results in a situation where the oil is present on the ice surface, allowing oil cleanup operations to be carried out.

The release of the oil and gas results from the combination of two general processes:

(1) vertical rise of the oil through the brine channels in the ice (which is hereafter referred to as vertical migration);
(2) ablation of the ice surface down to the oil lens in the ice.

Laboratory test results (i.e., Purves, 1978, Kisil, 1981) and field observations (Dickins and Buist, 1981) show that, for a combined oil and gas spill, the gas will be released in advance of the oil. See Section 4.6.1.3 for a discussion of gas dissipation. The oil in the ice sheet will be released subsequently, which is discussed in this section.

Both vertical migration and surface ablation have been observed to occur in the field (NORCOR, 1975; Dickins and Buist, 1981). In practice, the two processes are interrelated to some degree. Ice with a trapped oil layer tends to absorb more solar radiation than unoiled ice which enhances surface ablation. This also serves to increase oil transport by vertical migration as it warms the ice sheet and it reduces the travel distance necessary for the oil to reach the ice surface.

Dickins and Buist, 1981, provide an assessment of the relative oil volumes that were released by the two processes during field spills at Balaena Bay, N.W.T. (conducted by NORCOR, 1975) and at McKinley Bay, N.W.T. (conducted by Dickins and Buist, 1981). The relative amounts depend on several factors including the depth of the oil lens in the ice and the configuration of the oil in the ice (i.e., discrete droplets vs. pools of oil).

No theoretical models have been developed to describe oil release by surface ablation while two theoretical models are available in the literature for oil transport and release by vertical migration. Cox et al., 1980, developed a model by balancing the buoyancy and the interfacial tension forces acting on the oil slick. Kisil, 1981, utilized an alternative approach by considering that the oil migration rate was controlled by the rate of melting of the ice above the oil.

Neither model has been conclusively verified although the results produced by each have been compared to laboratory test data. Kisil, 1981, conducted laboratory tests which she compared with to model's predictions while the model results of Cox et al. (1980) were compared by Payne et al., 1984, to their laboratory test results. In each case, the models were in reasonable agreement with the test data. However, further work is required to develop a general theoretical model capable of describing the vertical migration process.

An empirical approach was utilized by NORCOR, 1977, based on the Balaena Bay field data to predict the large scale fate and behaviour of oil released under a continuous ice cover.

As proven models are not available to describe the ablation and vertical migration processes, and their interaction, an empirical approach is considered to be the most reliable modelling method at present.

4.6.3.2 Multi-Year Sea Ice

The release of oil and gas trapped in multi-year ice may occur more slowly than for first year ice as for the following reasons:

(1) the brine channels in multi-year ice are likely to be discontinuous, which will reduce oil transport by vertical migration.

(2) multi-year ice is thicker than first year ice which will reduce the amount of oil released by surface ablation.

Only a small amount of information is available to assess this case. Three small-scale field spills of oil under multi-year ice were conducted at Griper Bay, N.W.T., (Comfort et al., 1983) which showed that some oil (i.e., up to 10% of the volume spilled), remained in the ice after two melt seasons. Thus, these tests indicate that oil is likely to persist longer in multi-year ice than first year ice (for which all of the oil has been observed to surface during one melt season).

No theoretically-based numerical models are available to describe oil release for multi-year ice; however, an empirical predictor was developed by Comfort et al., 1983 based on observations made over a five-year period at the Griper Bay spills. This provides an approach for estimating the long term persistence of oil spilled under multi-year ice. However, as the available information is based on small-scale spills, this approach should be applied with care.

5.0 OIL IN LEADS AND BROKEN ICE

This section provides a summary of the key literature that relates to the behavior and fate of oil in leads and broken ice covers. The reviewed papers are divided into four subtopics:

1. spills of opportunity in broken ice
2. oil behavior in developing ice covers
3. oil behavior in broken ice (spreading and containment)
4. oil behavior during lead closure to examine the phenomenon of "lead pumping"

Within each subtopic, the papers are organized by date, starting with the earliest. The papers reviewed include analytical studies, laboratory tests, and field spills. A discussion of the key findings and important process equations is included in Section 5.5 at the end of the literature reviews.

5.1 Spills of Opportunity in Broken Ice - Literature Review

McLean, A.Y. 1972. The Behavior of Oil Spilled in a Cold Water Environment. OTC Paper No. 1522. Fourth Annual Offshore Technology Conference, Houston, Texas, May 1-3, 1972.

The tanker *Arrow*, carrying a cargo of 16,000 tons of Bunker C oil, hit Cerberus Rock at the entrance to Chedobucto Bay, Nova Scotia, on February 4, 1970.

Observations

McLean (1972) made the following observations:

> At the time of the spill there were considerable quantities of shore fast ice which increased and reached a maximum about March 1st.
>
> . . . .
>
> Oil was seen to congregate in heavy pools against the ice front, and as the ice grew, these pools became trapped in the ice. . . .
>
> One interesting feature was that ice grew on top of oil trapped in lagoons. The oil did not mix with the ice and if the lagoon had been ice covered before the oil entered, ice-oil-ice "sandwiches" were formed with layers of oil up to six inches thick. Samples of this oil showed that extensive emulsification had taken place, presumably before the oil entered the lagoon. The very viscosity of the emulsified oil perhaps explains the lack of interaction of the oil with the ice.
>
> Many sections of the coastline had shore fast ice of floating ice slurries which were held against the shore by wind. Oil was driven into this ice and the oil contaminated ice, which subsequently became snow covered and the oil-water-ice slurry presented insoluble clean up problems. . . . Much of the crystalline ice found on the shore was brown due to the coating of the oil . . . the oil content was low, about 1 - 3%.
>
> The most significant change in oil properties observed during the *Arrow* incident was the formation of extremely stable water-in-oil emulsions.

Ramseier, R.O., G.A. Gontcheff, and L. Colby. 1973. Oil Spill at Deception Bay, Hudson Strait. Canada Centre for Inland Waters Scientific Series, No. 29, Environment Canada, Ottawa, Ontario.

Ramseier et al. (1973) described the oil spill as follows:

> Approximately 427,000 gallons of Arctic diesel oil and gasoline were spilled over permafrost and sea ice at Deception Bay, Quebec, sometime between June 6 and 8, 1970, when a tank farm was destroyed by a slush avalanche. Deception Bay is located at the northern tip of Ungava. . . . At the time of the spill the entire bay was covered with a continuous ice sheet approximately 54 inches thick. A well-developed tidal crack system separated the sea-ice cover from the shore-fast ice. The mean diurnal tide varies between 12 and 19 feet. The tidal currents average approximately 0.9 knots.

Observations

> The spilled oil flowed up and down the crack system, and into the shore-fast ice, depending on the tide and prevailing wind.
>
> . . . .
>
> During tidal inflow most of the pools tended to move in a southeasterly direction, while during tidal outflow they moved in a northwesterly direction. The wind sweeping across the bay carried oil droplets over the ice surface spreading them at considerable distances, even as far as the other side of the bay. Small spherical potholes (less than one inch diameter) were created and filled with oil and wide irregular water ponds were covered with a thin film of oil.
>
> . . . .
>
> The tides . . . made the surface and bottom of the shore-fast ice very irregular; and an ideal place for absorption and pooling of oil.
>
> . . . .
>
> . . . most of the oil was stored in and under the shore-fast ice, i.e., the intertidal region. Tunnels three to four feet high were discovered under the shore-fast ice. These contained large pools of oil and gasoline.

Ramseier et al. (1973) noted that while an oil slick generally follows the tidal currents

> . . . ice booms are capable of partially or totally curtailing the movement of oil. . . . [and] . . . wind counter to the tidal current not only can slow down the

movement of the oil but can effectively entrain it in its own direction.

They also stated that, although the water in the tidal crack system was not as turbulent as open water, some emulsification of the oil did occur

> . . . through friction of the oil against ice caused by the tidal motion and by wind on top of the sea ice. This was evidenced by the discovery of a few oil globules which had escaped to the open sea.

<u>Oil Budget</u>

Ramseier et al. (1973) calculated the following oil budget on June 15, nine days after the spill occurred:

> 1) Oil retrieved . . . 5,000 gallons
> 2) Oil visible in open pools along tidal crack network. . . . 50,000 gallons
> 3) Oil in soil and snow. . . . The soil contained 2% of oil by weight; or approximately 45,000 gallons. The snow contained 5% of oil by weight; approximately 34,000 gallons.
> 4) Oil observed in shore-fast ice. . . . On the average a two-inch thick oil layer was found on top of the water. Assuming the drainage area of this hole to be one square foot in area and on the average three feet deep, the total amount of oil trapped in the pores would be 42,000 gallons.
> 5) Oil in water . . . 30,000 gallons. Although a reasonable value for the concentration of oil in the water can be obtained, the effect of tidal flushing is difficult to assess. According to Kenney et al. (1969) in a study on the effect of tidal flushing in Cook Inlet, Alaska, the amount of oil removed would amount to 3%, which is negligible. . . .
> 6) Loss of oil components by evaporation . . . the amount lost is estimated at about 4% of the Arctic diesel and possibly all of the gasoline. Arctic diesel: 15,000 gallons, gasoline 58,000 gallons.
> 7) Oil under shore-fast ice . . . 75,000 gallons . . . .
>
> From a total spill of 427,000 gallons, approximately 354,000 gallons can be accounted for . . . . The 73,000 gallons which have not been accounted for could easily be assumed to be included in 6) and 7). . . .

Deslauriers, P.C. and S. Martin. 1978. Behavior of the BOUCHARD #65 Oil Spill in the Ice-Covered Waters of Buzzards Bay. Proceedings of the Tenth Offshore Technology Conference, Dallas, Texas, pp 267-276.

Note: The chemical analyses and maps of the spill are contained in Deslauriers et al., 1977.

The barge *Bouchard #65* grounded in Buzzards Bay, Mass., on January 28, 1977, carrying 3.2 million gallons of No. 2 home-heating oil. Ice cover in the bay was half shorefast ice and half broken ice. The broken ice comprised about 75% ice floes and 25% hummocks, pressure ridges, and rafted ice. The ice had an average thickness of about 0.3 m and a low over-all salinity (surface salinity was nearly that of fresh water and the interior salinity was about 4 ppt).

About 4,000 gal of oil spilled off Cleveland Ledge where the barge grounded (an area of 2,800 sq m.). Oil also spilled along the broken ice track when the barge was towed to Wings Neck. "This oil was incorporated into hummocks and ridges as the ice field closed". Most of the oil (80%) was spilled at Wings Neck where some oil was offloaded. The strong tidal currents (0.5 m/s) controlled the oil spreading amongst the broken ice in this area. A total of 81,150 gal of No. 2 oil was spilled.

Observations

Oil Transport Under Ice

Deslauriers and Martin (1978) observed that oil leaking from the barge was initially transported under the ice by the strong tidal currents.

> Once under the ice, the currents transported the oil laterally to ridges, leads, hummocks, and rafted ice. Because of the oil's density, it rose into the openings in the ice where it was trapped and restrained from spreading further under the ice.

Current velocity was the most important factor controlling the oil spreading. Above the threshold current velocity of 0.035 m/s (for No. 2 oil under smooth ice), Deslauriers and Martin (1978) stated that the oil velocity (V_o in m/s) depended on the current velocity (V_c in m/s) according to the following equation:

$$V_o = 0.38V_c - 0.0133, \text{ up to a current velocity of } 0.3 \text{ ms}^{-1}.$$

They concluded that most of the under ice transport occurred within the first two days of the spill due to the strong currents (0.5 m/s), the static appearance of the spill area after two days, and that ice cores from floes collected several days after the spill were oil free.

Oil in Rafted Ice, Pressure Ridges, and Hummocks

Deslauriers and Martin (1978) found that

> . . . approximately 30 percent of the spilled oil was contained in deep pools on the ice surface with depths of about 0.12 m, which were formed by rafted ice. . . .

Figure 3 shows how these pools likely form in the rafted ice. Oil pools formed by the rafted ice were estimated to contain about 200 gal of oil; some very large pools

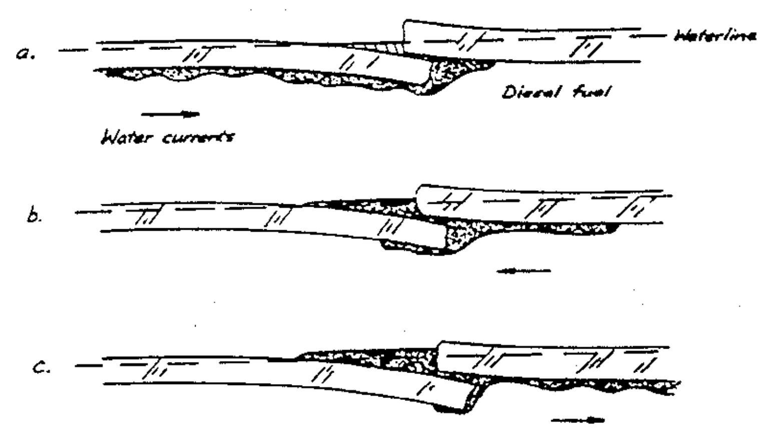


FIG. 3 - FLOW OF OIL IN RAFTED ICE A) OIL FLOWING UNDERNEATH THE ICE COMES IN CONTACT WITH RAFTED ICE, B) CURRENT REVERSAL ENCOURAGES OIL FILLING INTO RAFTED ICE POCKET C) REVERSAL OF CURRENT SWEEPS UNSHELTERED OIL AWAY.

contained up to 2,000 gal of oil.

Pressure ridges and hummocks in the broken ice areas between Cleveland Ledge and Wings Neck and at Wings Neck were also found to effectively contain the oil. However, oil that was incorporated into ridges and hummocks was not as concentrated as the pooled oil in the rafted ice.

> A core taken through a pressure ridge revealed no flow of oil into the core hole. No pooling was observed; rather the ridge consisted primarily of oily ice. Also, there was no concentrated oil underneath the ice along the ice keel for the ridges investigated. In many cases, the hummocks, being more porous, allowed heavier concentrations of oil to form. . . . However, oil pooling in hummocks was not as extensive as that observed in the rafted ice.

Spreading of Oil on Top of Ice

Deslauriers and Martin (1978) suggested that the major source of oil observed on the ice surface was windblown oil from the rafted pools as

> . . . the ice floes had a smooth surface and a low porosity. The oil had a low viscosity and the wind velocities were rather substantial, reaching 30 knots (15 ms^{-1}) on Jan. 29. Also, the rafted ice configuration consisted of a gradual rise from oil pools to the ice surface presenting little resistance to oil spreading on top of the ice.
>
> It was estimated that approximately 6,000 gal of oil spread onto the ice surface in this manner. . . .

Spreading of Oil on Open Water and in Leads

Oil spilled in the lead at Wings Neck flowed under the ice edge.

> The ice failed to contain the oil because of wind and current stresses, the water velocity being approximately 0.5 ms^{-1} and the wind averaging 12 ms^{-1}. Oil sheen later detected on several occasions in leads did not build up along the ice edge; rather the sheen tended to flow underneath the ice. . . .

Transport of Oil by Ice Floes

Once the ice floes began to break up about February 8, the oil contained in the deformed ice was transported over a much greater area than the original spill area. The oil was released from the floes in the form of a thin sheen. Oily ice floes were transported by the tidal currents NNE into Cape Cod Bay where they subsequently melted.

Oil Migration into Ice

Deslauriers and Martin (1978) recorded the following variations in oil absorption into the ice:

1. The oil mixed with the slush ice at the edges of the pools in rafted ice contained 30% oil by volume.
2. Brash ice and small ice pieces was often heavily oil stained and contained 3 to 5% oil by volume. Lightly stained ice contained about 0.5% oil by volume. Oil penetration into the ice surface on both heavily and lightly stained ice was between 25 to 60 mm.
3. The windblown oil usually penetrated only the upper 3 mm of the ice surface as there were few brine channels or pores. This upper ice layer contained 50% oil by volume.
4. While there was no visible oil on the under side of the ice in both the shorefast and broken ice areas affected by the spill, oil concentrations in the lower 80 mm of the ice averaged 310 ppb.

They concluded that the variations in the small scale migration of oil into ice were largely due to the volume and duration of the oil's exposure to the ice.

Oil Absorption by Snow

On February 5, 12 cm of snow fell and covered the spill area.

> Areas that had heavy concentrations of oil, such as the rafted pools, were saturated with the snow, forming an oil/snow mulch. This slush-like mixture was determined to be approximately 30 percent oil by volume. . . . In addition, oiled ice, which was covered by snow with no oil absorption, formed an ice/oil/ice sandwich. . . .

Oil Weathering

Deslauriers and Martin (1978) found that the rate of oil weathering ranged between 6 and 47% volume loss, depending on the amount of air exposure the oil had. They also noted that even the most weathered oil did not sink due to hydrostatic forces.

Oil Mass Balance

The oil mass balance, shown in Table 2, was calculated before the snowfall when the oil was stable in the broken ice area.

Table 2 Oil Budget for *Bouchard* #65 Oil Spill, January, 1977

Type of Oil/Ice Configuration	Area Encompassed by Spill from Mashnee Island to Wings Neck Tower (m^2)	Area Encompassed by Spill from Wings Neck Tower to Cleveland Ledge (m^2)	Total area (m^2)	% Oil Saturation	Depth of Saturation (m)	Volume (litres)	Volume (gallons)	Weathered Losses (gallons)
Deep Oil Pools	400	300	700	100	0.13	91,000	24,000	3,100
Shallow Oil Pools	1,500	300	1,800	100	0.025	45,000	12,000	1,400
Heavily Stained Ice	7,400	2,400	9,800	5	0.05	49,000	13,000	2,00
Medium Stained Ice	26,500	3,200	29,700	1	0.05	30,000	8,000	1,500
Lightly Stained Ice	28,700	3,800	32,500	0.5	0.05	16,000	4,000	1,900
Windblown Oil	2,100	12,600	14,700	50	0.003	22,000	6,000	1,800
Burn Site (heavily stained ice and shallow oil pools)	—	—	5,600	5	0.05	14,000	4,000	500
Weathered Evaporation Losses	—	—	—	—	—	46,000	12,000	—
Totals	≈66,600	≈22,600	≈94,800			≈313,000	≈83,000	≈12,000

Deslauriers and Martin (1978) concluded that, of the 81,150 gal (309 m^3) of oil spilled, approximately 45% was held in pools and capable of being pumped. The rest of the oil was in the form of contaminated ice and was spread over an area of about 95,000 m^2, with an average concentration of one gallon per 1.2 m^2.

Welsh, J.P., I.M. Lissauer, G.L. Hufford, T.S. Ellis, B.D. Thompson, L.D. Farmer, and R.T. Hiltabrand. 1977. Some Dynamics of Spilled Oil in a Fractured Ice Field in Buzzards Bay, Massachusetts. in Ocean Engineering, Vol. 4, pp 197-203.

Ruby, C.H., L.G. Ward, L.A. Fischer and P.J. Brown. 1977. Buzzards Bay Oil Spill - An Arctic Analogue. Proceedings, Port and Ocean Engineering Under Arctic Conditions 1977, St. Johns, Nfld.

These two papers also discuss oil and ice interactions during the Buzzards Bay oil spill.

In their conclusions Welsh et al. (1977) noted that

1. Approximately 60% of the oil was contained in the ice within four days of the spill.
2. The dispersion of the oil was determined by oil and water density differences, and the ice deformation.
3. The oil was transported under the ice by tidal and surface currents. Winds were significant in transporting pooled oil over the ice surface.
4. When leads opened oil was released from under the ice and became incorporated into the deformed ice in the leads as they closed. Thus the opening and closing of leads tended to disperse the oil.
5. No oil pancakes or tarballs were observed as the oil remained less dense than the water.
6. The shorefast ice acted as an effective barrier to oil contamination of the beaches.

Ruby et al. (1977) discussed successful and unsuccessful methods used during clean-up of the Buzzards Bay spill. They also presented some observations of oil and ice interactions. They noted that the shorefast ice generally protected the the beaches from oil contamination (until melt occurred). The beach profiles showed that oil

> . . . was concentrated in the brash ice between the bottom fast ice and the May 15, 1992, floating fast ice. Oil moving under the ice surfaced in these areas. . . . oil-water mixtures were seen rising onto the ice blocks with the flooding tides, exposing the mixture to the southwest winds which blew the oil across the ice blocks, leaving a coating of oil on them.

Deslauriers, P.C. 1979. Observations of Oil Behavior in Ice Floes and the 1977 *Ethel H* Spill. Oil, Ice and Gas, Environment Canada, Toronto, Ontario, pp 87-94.

Deslauriers (1979) described the oil spill as follows:

> On 4 February 1977, the barge *Ethel H*, with 2.7 million gallons of high-pour No. 6 fuel oil, ran aground on Con Hook Rock, two miles north of the Bear Mountain Bridge in the Hudson River. The barge leaked oil into the river for three days, until offloading operations were complete. By that time 420,000 gallons of oil had been spilled into the icy waters of the Hudson.
>
> At the time of the spill, ice covered up to 80% of the river surface, and averaged 15-25 cm in thickness. Icing conditions do not often occur here, except in unusually cold winters. By February 4 the low saline ice was deteriorating rapidly. Ice formations consisted of both shorefast ice and ice floes. . . . Ice floes . . . averaged 7 m in diameter, with some floes as large as 90 m. Transport and breakup of these floes was influenced primarily by strong river currents, and to some extent by shipping traffic and winds.

Observations

According to Deslauriers (1979), one of the main objectives

> . . . was to determine if large amounts of oil were present in the shorefast ice region. Shorefast ice along the river had a very smooth underside. Several transects were made along the remaining shorefast ice areas. While the ice was not visibly stained with oil, chemical analyses of the ice samples revealed the oil concentration in the ice to be from 0.7 to 0.8 ppm. The only oil detected under the ice was in the form of a very thin sheen. No evidence of heavy pooling was found.
>
> The oil from the *Ethel H* became intermixed with the ice floes, while both were transported down river by the currents. It was observed that the black tarry oil adhered to many of the ice floes and, in some instances, the ice floe surface was as much as 60% covered with this oil. . . .
>
> Ice floes appeared to flow down the river in bands of closely packed floes stretching across the river. These bands were up to 100 m wide with up to 1 km separating each strip. The black tarry oil tended to stay within these

bands while moving downriver. Concentrations of oil were much higher within these packs of ice than in the ice free areas, although sheen was often visible covering most of the river surface. . . .

Conclusions

Deslauriers (1979) made the following conclusions on the behavior of oil spilled in broken ice from observations of this spill, the Buzzards Bay spill (Deslauriers and Martin, 1978), and from laboratory experiments:

> The more porous the ice the greater the probability that oil will adhere to its surface. Therefore more oil will remain on the water for a spill in hard fresh water ice floes compared to a spill in decaying saline ice floes.
>
> Heavy ends of oil tend to adhere to porous ice floes while lighter ends are released on the surrounding water in a thin sheen. If there is enough interaction between the oil and ice, all of the heavy fractions of the spilled oil may adhere to the porous ice surfaces. This may have a great effect on cleanup procedures.
>
> Melt holes are formed in decaying ice where oil has come in contact with the ice. Therefore, the oil cannot easily be removed from the ice surface.
>
> When the ice is growing the oil which has adhered to the ice will become enclosed by ice.
>
> When the ice concentration is low, oil and ice tend to move in different directions and speeds. Also, at some increased ice concentration oil and ice movement occur together. It is not known at what ice concentration this transition of oil and ice movement occurs. This may be important for spill trajectory.
>
> When ice floes are very close together and stationary, high viscosity oil tends to accumulate to great thickness. The thickness of the oil appears to be dependent upon ice concentration, ice movement, oil viscosity, oil volume, and ice thickness. . . .
>
> When ice floes are very close together and moving, the oil is spread amongst the ice. If there are waves present, the ice field will periodically compress and expand so that the oil will be progressively pumped along channels. If a channel is restricted and the film is sufficiently thick, the oil

will be found on the ice surface.

After ice breakup, oil in rafts, rubble fields, and ridges will travel with the moving ice floes until those ice formations decay.

Oil incorporated in ice floes can travel considerable distances before being released. If those floes are beached or settle in sensitive areas the relatively fresh oil will be released in these areas, possibly increasing the environmental impact on these areas.

Reimer, E.M. 1980a. Oil in Pack Ice: the *Kurdistan* Spill. Proceedings of the Third Arctic Marine Oilspill Program Technical Seminar, Ottawa, pp 529-544.

C-CORE. 1980. An Oilspill in Pack Ice. Prepared by Centre for Cold Ocean Resources Engineering, Memorial University of Newfoundland for Environmental Protection Service, Environment Canada, Report No. EE-15 or C-CORE Report No. 80-2.

Oil and ice interactions from the *Kurdistan* spill are also presented Reimer (1979), Reimer (1980b), Reimer (1981), and Vandermeulen and Buckley (1985).

The tanker *Kurdistan*, with a cargo of 29,000 tonnes of Bunker C, was damaged by ice in the Cabot Strait, Nova Scotia. The tanker returned to open water and broke in two on March 15, 1979. Approximately 7,000 tonnes of Bunker C was spilled into the pack ice. The offshore pack ice was mixed with large areas of brash ice. Reimer (1980a) observed that

> . . . The oil, with a pour point between 15 and 20 °C congealed rapidly in the cold water. It is not likely that an extensive surface slick formed.

Observations

The physical properties of the original oil and of field samples of the oil collected from various locations during March and April are shown in Table 3.1 (C-CORE, 1980).

> The positive buoyancy of the oil in seawater was only 0.04 gm/ml. This minimal difference was such that blobs and oil pancakes could easily be carried beneath the water surface by wave and wind induced turbulence or by currents. . . .

Table 3.1 Physical Properties of Bunker C Oil

Product Specifications Bunker 6C-3	Measured Properties of Samples from Ice
Specific Gravity: 0.96 @ 60 F	0.973 @ 20 C
Pour Point: 45 F (~6 C)	0.987 @ -2 C
Viscosity:	22 C to 28 C
Water Content:	5% to 20%

It was also observed that because the density of the oil was greater than that of the ice, oil could be carried under the ice.

Distribution of Oil

Reimer (1980a) observed that various processes resulted in oil being found on, in, and under floes.

a) Occasional floes (usually only a few metres in diameter) were seen to carry a total surface film of oil. In the few cases where those were directly examined the film was only a few millimetres thick, the ice surface was relatively smooth.

The only likely process which could account for this would be the direct deposition of hot oil. . . . It was concluded that deposits of this type would have been created at the original breakup site of the ship either from leakage during the splitting process prior to total breakup or at the final event.

b) Oil was distributed on floe surfaces as small blobs and spatters, usually with the highest concentrations within a few metres of the floe periphery. These spatters usually consisted of a few grams of oil and were often sunk into "melt pockets" as a result of solar heating. This oil was probably thrown initially onto the floe surface by wave action.

Circumferential dykes (or ridges) or oil-contaminated brash were frequently observed on floes in heavily contaminated areas. Some of these appeared to have a very high oil content - possibly due to the concentration of surface oil by melting of the brash.

Occasionally, large blobs were seen on floe surfaces, particularly late in the season when the ice had decayed considerably. These blobs may have originally been covered by a layer of snow or ice.

A substantial proportion of the oil present was distributed in the ice brash as small particles.

Oil Loading

The total oil loading is presented in both Reimer (1980a) and C-CORE (1980).

Taking the major areas and estimating the contamination level as roughly 200 ppm oil in ice to an average depth of 50 cm, the total loading works out as:

Pt. Michaud area:	1 km^2	100 tonnes
St. Esprit area:	1 km^2	100 tonnes
Gabarus to Scatarie:	9 km^2	900 tonnes
	TOTAL	1100 tonnes

It is estimated that, from the 900 tonnes in the Gabarus to Scatarie area on March 27, that by April 2, 260 tonnes would remain in Gabarus Bay and approximately 400 tonnes would be entrained in the ice off Framboise Cove. By April 7 an estimated 200 tonnes remained off Isle Madame.

In one offshore area, oil concentrations in the brash ice were about 200 ppm and it was estimated that half of the oil was on the floe surfaces and the other half was mixed in the brash ice to a depth of 1 metre. Approximately 20%, or 2 km^2, of the surface area of the ice was contaminated with oil. The oil content of the contaminated area was estimated to be 400 metric tons (C-CORE, 1980).

Large Scale Mixing

Reimer (1980a) observed that

. . . oil, initially present as concentrated bands or streaks in the ice, tended to become dispersed and diluted in the pack. Very little of that process can be detailed. Little mixing or movement occurred within ice fields which were held onshore by winds. Maximum mixing would have occurred when the pack was very loose and differential drift could occur.

Differential movement between brash and floes was observed, however, it did not appear to disperse the contaminated areas to any great extent. . . .

Small Scale Phenomena

In general, the effect of entrainment of this semi-solid oil in pack ice was a dispersion of the oil as progressively smaller particles. Although the primary events leading to the entrainment of the oil in the pack ice remain unknown, over the period of observation the trend seems to have been toward finer dispersion and dilution of the oil in pack ice. (This process may have been reversed to some extent during the final melting of the ice when ice tended to herd or contain small particles. Some reagglomeration may have occurred, especially with larger blobs.)

C-CORE (1980) indicated that

One of the primary dispersion processes was the grinding of oil in brash ice as a result of floe impact and differential movement. In the offshore pack which permitted only swell propagation, the grinding process . . . resulted in particles from a few centimetres in diameter down to micron sizes. For the brash samples taken a few "blobs" with dimensions in the order of 1 cm accounted for 80% of the oil present. . . .

Conclusions

C-CORE (1980) summarized the oil and ice interactions as follows:

The total loading for oil in ice for the Cape Breton shore was 1100 metric tonnes.

Initial shoreline deposits of oil (March 26) were in the order of 10 tonnes (at a loading of about 1/2 tonne per km of shoreline).

As oil-contaminated ice moved back and forth along the shoreline, considerable mixing and dilution occurred, however contaminated areas remained relatively coherent.

Oil contamination was held offshore by the ice cover.

The general trend was toward progressively smaller oil particles with mechanical grinding as a primary cause and "melt pocket" processes as a secondary cause.

The oil distribution in the pack took on all possible forms. The average oil in ice concentration was about 200 ppm.

Oil concentrations in the water column under the contaminated pack did not exceed 1 ppm.

Light hydrocarbons tended to be enriched in the ice (with respect to the surrounding water).

Payne, J.R., G.D. NcNabb, B.E. Kirstein, R. Redding, J.L. Lambach, C.R. Phillips, L.E. Hachmeister, and S. Martin. 1984. Development of a Predictive Model for the Weathering of Oil in the Presence of Sea Ice. for NOAA/OCSEAP Office, Research Unit No. 640, Anchorage, Alaska.

Part of this study includes a review of a spill of opportunity in Cook Inlet, Alaska. Payne et al. (1984) includes the following description:

> The M/V Cepheus grounded [on January 21, 1984]. . . on the shallow point on the western side of Knik Arm [Cook Inlet, Alaska]. An estimated 200,000 gal (~4800 bbls) of JP-5 (Jet A) aircraft fuel had been lost during both the grounding incident and movement of the ship to the dock. . . . At the time of grounding, ice coverage was estimated to be 60 - 80% and the the air temperature was in the -10 to -25 °F range.

Ice floes were 6-9 m across and were mixed with pancake, grease, and brash ice (Payne, pers. comm.).

Observations

> . . . JP-5 samples collected by the Coast Guard showed the material to be a clear, low-viscosity and low density (0.7 - 0.8 g/ml) fluid, which was quite similar in appearance to intermediate distillate cuts of Prudhoe Bay Crude. . . .
>
> With the ice cover pressing against the ship, no evidence of any spill product (JP-5) could be observed from a distance of 5 to 10 meters above the surface. With the outflow of the ebb tide current . . . several 10 - 20 meter wide leads opened adjacent to the hull and JP-5 could be observed bubbling to the surface. . . . With the outgoing tide the oil and broken ice moved parallel to and away form the vessel at an estimated speed of 1 -2 knots. The oil was not visible after a distance of 10 - 20 meters. Very little could be done to contain the spill in the presence of moving ice. . . .

Payne (pers. comm.) commented that when the ice moved away from the hull an oil sheen was visible but most of the JP-5 had evaporated. Frazil ice formed in the leads that developed, however, it was impossible to tell if the oil become entrained in the grease ice as JP-5 is clear. It seemed that no emulsions were formed as the JP-5 evaporated too quickly.

Wilson, D.G. and D. Mackay. 1987. The Behavior of Oil in Freezing Situations. Prepared at the University of Toronto for the Environmental Protection Directorate, Environment Canada, Report No. EE-92, Ottawa, Ontario.

This spill is also discussed in Wilson and Mackay (1986).

A spill of No. 6 fuel in the Gulf of St. Lawrence, near Matane, Quebec, occurred in December 1985. The ice cover included a mixture of grease and pancake ice extending five metres offshore and a mixture of frazil and grease ice extending for the next twenty metres offshore.

Observations

Wilson and Mackay (1987) made the following observations:

> The spill occurred about 100 m offshore and was blown into the grease/pancake ice mixture by the wind and current of the river. At the time of observation no oil was visible within or above the grease ice and the only visible oil was that washed up on shore. The oil washed up on shore was grease ice that had been compressed and had the water forced from between the individual ice particles by the pressure of the ice against the shore. The result was a porous crystalline ice oil mixture that contained up to 50% oil. . . .
>
> The specific gravity of the oil near freezing temperatures is quite close to that of sea water at the spill site which was estimated to be 1.02. This raises the possibility that although there was no oil visible from above the grease and frazil ice there may have been large quantities of oil below or within the ice. There was also a high level of turbulence in the water during the period of the spill and hence it is possible that water/oil emulsions may have been formed.

Conclusions

Wilson and Mackay (1987) concluded that much of the oil was incorporated in the grease ice.

While a grease ice field would dampen waves experimental observations showed that sufficient agitation to force oil particles downward may easily be created. Once the oil particles have been forced downwards in the ice field they may remain there because of the same driving force or because of the natures of the ice field and oil. . . . In this case the grease ice field failed to prevent breaking of the waves and hence failed to prevent the resulting downward driving force of the waves. In light of the analysis of the oil from the spill and the revelation of its high density it seems likely that much of the spill was in fact incorporated amongst the grease ice field.

Hirvi, J-P. 1990. The Oil Spill in the Gulf of Finland in 1987. Proceedings, IAHR 1990, the 10th International Symposium on Ice, Espoo, Finland.

On February 6, 1987, the Soviet tanker MT *Antonio Gramsci* grounded in the Gulf of Finland, spilling about 570 metric tons of Soviet Export Blend crude oil (density at 15° C is 849 kg/m^3, kinetic viscosity at 20° C is 9.6 mm^2/s, and pour point is -15° C). There was a small area of new ice in the area where the ship grounded and the rest of the sea was covered with close, ridged ice.

Observations

Hirvi (1990) observed that the oil mixed and drifted with the ice pack until early May when ice in the Gulf started to melt.

> Oil film, emulsion drops and clumps (tarballs) were widely observed at sea. No concentrated oil slicks were formed at sea, only oil film. In mid-May the oil started to drift ashore . . . in southern Finland. . . . It may be interesting to note that the oil was present under the water surface in the form of large emulsion drops (5 - 20 mm). This indicated the formation of near buoyant water-in-oil-in-water particles, consisting of large water spheres surrounded by a thin oil film. . . . the emulsion formations lasted for weeks and spread over a large sea-area. . . . .

The oil spread over an approximate area of 2,500 km^2. The oil budget was estimated from observations of the spill and from laboratory experiments designed to study the behavior of the Soviet crude oil in cold, brackish waters.

Conclusions

Hirvi (1990) concluded that the fate of the oil was controlled mainly by evaporation.

Table 2 Summary of the Fate of the *Antonio Gramsci* Oil Spill in the Gulf of Finland in 1987

Process	Loss (tons)	Comments
Evaporation		
February	114	20% x 570 tons
March-April	38	10% x 376 tons
May-June	34	10% x 338 tons
Sedimentation	1	winter
Dissolution	1	winter
Oil recovery		
sea	100	80 tons in February
shores	10	38 tons of oily waste
BULK LOSS	298 tons	
OIL REMAINING	272 tons	dispersed into the sea

5.2 Developing Ice - Literature Review

Scott, B.F. 1973. Investigation of the Weathering of a Selected Crude Oil in a Cold Environment. Department of the Environment, Ottawa. Also published in Water Quality Parameters, ASTM STP 573, American Society for Testing of Materials, 1975, pp 514-525.

The experiments was conducted in 1973 making it one of the first field tests of oil fate in a developing ice field (an initial step in understanding oil-in-ice behaviour. The program objective was to understand oil fate and oil weathering in arctic regions and in other Canadian areas with potential for cold weather.

Two tests were conducted in a manmade ponds, 15.6 by 7.2 m, located northwest of Ottawa. The first test investigated oil fate in a developing ice field and the second oil fate on the ice surface. Only the first describes oil behaviour in a developing ice field.

The first test started Nov 20, 1972 with the pumping of 90 L (0.09 m^3) of Norman Wells crude oil into a 3.6 x 3.6 m hole cut in the ice (augmented by an accidental triangular opening on one side). The oil spread to an initial thickness of 4 mm. The oil was observed for several months.

Results

Scott (1973) reports on the weather and oil fate:

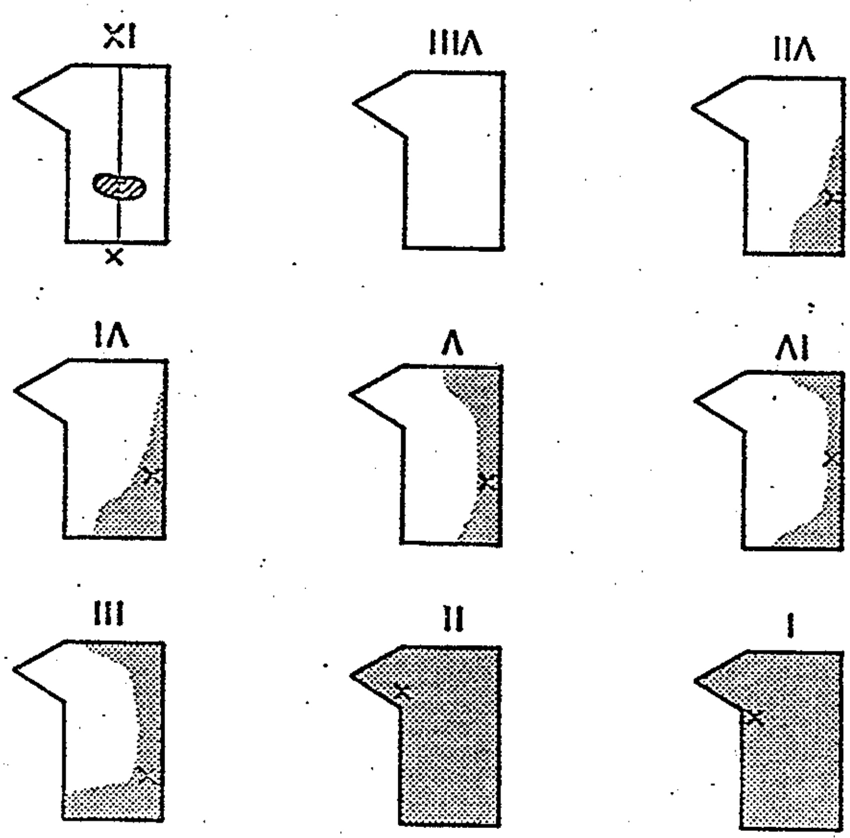
> Throughout November, the temperatures remained near freezing but turned much colder during the first few days of December. A few days of milder weather followed but colder weather returned. Wind speeds were relatively constant (2.0 m/s), but its direction often changed. Precipitation, mainly in the form of snow, was minimal until 2 December when snow completely covered

the oil to a depth of 200 mm. The oil did not reappear until 6 December, during a freezing rain storm. . .

. . .

During the period of observation of the spill, there was precipitation in the form of snow which was then melted by the oil, passed down through the oil because of its greater density and then formed additional ice on the ice surface under the oil. This was most noticeable in the triangular section of the exposed water surface where ice was removed just prior to the spill, shown in illustration I [Figure 4]. The increased ice height around this area allowed the oil to run off this section towards the centre of the pond. Prevailing winds than caused the oil to be concentrated in the northwest section. It was from this area, later in the winter, that oil was seen oozing from cracks in the ice, which were created by pressure on the ice surface.

Figure 4 Movement of Oil on Water Ice Surface (from Scott, 1973). I = Nov. 20; II = Nov. 21, 22 and 23; III = Nov. 24; IV = Nov. 25; V = Nov. 26 and 27; VI = Nov. 28; VII = Nov. 29, 30, Dec. 1 and 2; VII = Dec. 3, 4 and 5; IX = Dec. 6, 7 and 8; VIII = Dec. 9.



The same observation of snow passing through the oil was made during the second test.

Scott concluded that for oil spilled in a developing ice field,

> . . . the oil will influence its immediate environment and that there will be movement of the oil, once spilled, perhaps long distances away from the original spill area. Also, . . . [oil] may not disappear under subsequent snow falls.

Martin, S. P. Kauffman, and P.E. Welander. 1976. A Laboratory Study of the Dispersion of Crude Oil Within Sea Ice Growth in a Wave Field. University of Washington, Report No. 69, Seattle. WA.

Martin et al. (1976) were the first to document oil behaviour in a simulated grease ice field. Several experiments follow from their work because their observation of oil being pumped onto the ice floes and trapped by the raised edges of the floe has important implications for oil spill cleanup. Martin et al. note that "frazil and grease ice occur in all ice-covered seas" and that pancake ice is important in areas such as the Bering Sea, Chukchi Sea, and Gulf of St. Lawrence.

Two types of test were carried out. In the first series, ice development in a wave field is observed. In the second series, oil incorporation and behaviour in the ice is observed.

An insulated tank 2.2m long by 0.93m wide was filled with sea water to 0.41m depth and cooled to -2.1°C water temperature and -20°C air temperature. A wedge shaped paddle was used to produce waves up to 0.5m peak to peak amplitude and 0.6-1.0s period. Usually breaking waves of 0.2m peak to peak amplitude and 0.63s period were produced. Ice appearance was recorded photographically. Ice temperatures were profiled vertically with thermistors.

Results - Ice Growth

Martin et al. (1976) report on the development of frazil and grease ice:

> We observed that the individual frazil ice crystals, which were plate shaped with rough edges, had characteristic diameters of 1-3 mm and thicknesses of the order of 0.1 mm. When these crystals initially formed in the tank, they were transported away from the paddle, even if the fans were flowing

toward the paddle, by the phenomenon of wave herding - that grease ice damps out the small-scale waves. . . .

. . .

Grease ice has a number of interesting properties. First, it remained a fluid porous mass of frazil ice crystals up to a thickness of about 120 mm. . . . grease ice is compressed at the wave crest, and stretched at the trough. This observation supports the idea that the layer of grease ice behaves as a buoyant viscous fluid floating on the sea water.

Second, we found from several measurements that the ratio of the volume of ice to the total volume of sea water and ice ranged from 35-40% . . . . Third, the high grease ice porosity affected the heat transfer within the ice.

. . .

When the grease ice thickness reached 70-100 mm, the crystals at the surface began to join together into what we called 'proto'-pancakes. . . . these proto-pancakes consist of clumps of crystals, measuring 50-100 mm in the cross tank direction, 50 mm wide, and 3-5 mm thick, which although they had a much lower porosity than the surrounding and underlying grease ice, were still so soft that we could not pick them up.

These proto-pans quickly evolve into pancake ice. . . . The ice-induced decrease in wave amplitude permits the smaller pancakes to join together with out being broken apart by the wave field, so that as the experiment progresses, small pans join up into larger cakes.

. . . the pancakes have an average width of 0.2 m or about one-fifth of the driving wavelength. Further, over the two hours covered . . . the rims around the cakes grow from virtually nothing to a height of 20-40 mm. As with the proto-pans, the rims . . . appear to grow from grease ice which is pumped up onto the pancake surface. . . . Our movie films further show, when the rims come together, that grease ice is pumped up between the rims to a height above the pancake surface. . . .

In the experiment, the pancakes floated in a much thicker layer of grease ice, which . . . continued to increase in thickness even after the formation of pancakes. Besides supplying material for the rims, the grease ice affected the pancakes in three other ways; namely, it helped yield the dish-shaped bottom profile of the pancakes, determined the frazil crystal structure of the pancakes, and caused the ice to float such that the pancake center was below the water line. . . .

. . . Examination of the detailed photographs . . . show that the pancakes are made up of many small frazil ice crystals. . . . Our oil experiments suggest that these small crystal platelets, which are either randomly or horizontally-oriented, are less likely to capture oil flowing along the ice bottom than the parallel vertical crystals of columnar sea ice. . . . The combination of the dish-shaped bottom profiles of the pancakes and their crystal structure means that oil spilled under the pancakes is likely to come to the grease ice surface in the cracks between the cakes.

Third, the low buoyancy of the grease ice combined with the raised pancake rims means that the pancakes float so low in the water that the ice surface at the pancake center is slightly below the water line. . . .

The additional weight of the rims is even more important. Figure 13 is a schematic diagram of a pancake . . . . If we assume that the pancakes are two-dimensional bodies . . . the effect of this additional mass above the water line is that the pancake now floats such that the mean water level is 0.7 mm above the ice surface at the pancake center. . . .

Because of the lowered freeboard and the raised rims, we observed in all of our pancake experiments that the pancake surface was covered with a thin layer of highly-saline brine, which was probably formed from the water pumped over the rims and onto the ice. Once on the surface, because of the lowered freeboard, the brine remained there. . . . As we show later, this lowered freeboard makes the pancakes more vulnerable to oil spilled under the ice being pumped onto the surface.

Results - Diesel and Prudhoe Bay Crude Oil Tests

During the first test, 0.25 L of No. 2 diesel was released just as the pancakes started to form. A second test released 0.5 L of Prudhoe Bay crude (S.G. 0.893) later in the growth of the pancakes. For both tests, oil was discharged in a turbulent jet beneath the ice through a j-shaped tube.

Diesel Test

Martin et al. observed the following behaviour of diesel fuel:

The combination of the high porosity grease ice and the buoyancy of the diesel oil meant that the grease ice did not absorb the oil, rather the oil quickly appeared on the grease ice surface in the cracks surrounding the pancakes. The oscillatory motion of the pancakes then pumped the oil laterally from its original discharge point. . . . [A] photograph of the spill taken about 30 minutes after the discharge, shows that the oil affected an area measuring about 0.4 m x 0.4 m, so that the average thickness of the slick is about 1 mm.

Figure 13 Schematic of Pancake Cross Section (from Martin et al., 1976)

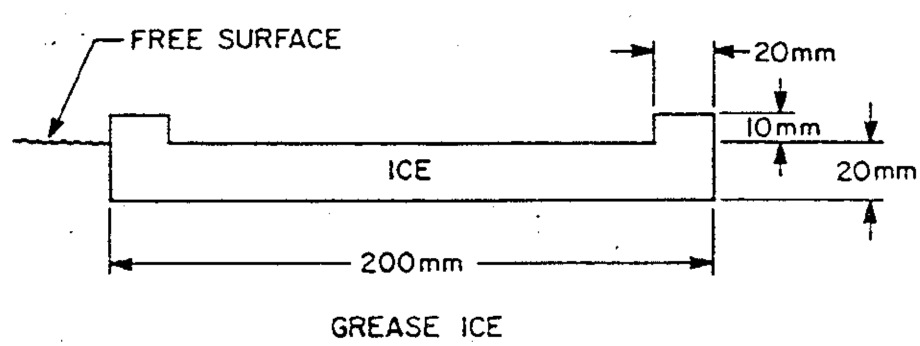


Figure 13. Schematic diagram of a pancake cross-section.

An unmeasured amount of the low freeboard prevented its return to the cracks.

Prudhoe Bay Crude Oil Test

For the experiment, the crude oil although very viscous remained fluid.

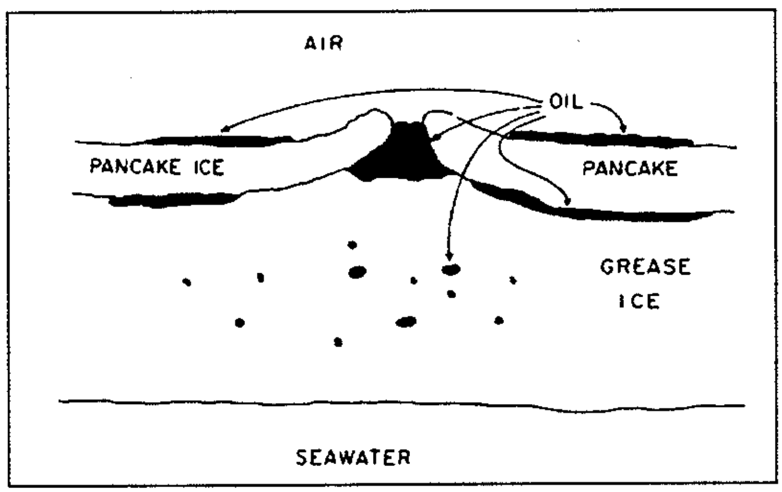
During the discharge, the total ice thickness was 120-130 mm, and the pancakes were 10-30 mm thick. . . . Visually, the oil flowed up out of the discharge tube in viscous slugs resembling poured molasses, rather than in a turbulent jet such as occurred in the diesel spill. After the oil left the discharge tube, we observed the oil to disappear up into the grease ice, which showed no signs of either inhibiting or capturing the released oil.

Five minutes after we began to pour the oil into the funnel, the oil appeared on the grease ice surface in a crack between two pancakes. Within this time, [2 min] the oil spread nearly all the way across the tank within the crack. . . . Because the oil floated on top of the grease ice within the cracks and the low freeboard of the pancake ice, the oil was easily pumped onto the ice surface.

. . . [P]hotographs of the ice surface 30 minute after the discharge, show that a large amount of oil has been pumped up onto the ice by the combination of the oscillating pancake motion and the confinement of the spilled oil by the tank walls. . . . we determined that 290 of the 500 ml [0.29 of 0.5 L] of oil spilled had been pumped onto the ice.

Figure 17 is a sketch of the location of the oil both under and on the ice . . . . Most of the oil appeared either to go on the ice surface or remain in the crack; however, there was a very light skim of oil on parts of the underside of the pancake. Because the flow of oil within the crack was limited by the tank walls, the amount of oil on top of the ice is probably exaggerated in our experiment.

Figure 17 Location of the Spilled Oil in Pancake Ice (from Martin et al., 1981)



Metge, M., and A.S. Telford. 1979. Oil in Moving Pack Ice - Laboratory Study. Proceedings, POAC 79: Fifth International Conference on Port and Ocean Engineering Under Arctic Conditions, Trondheim, Norway, pp 255-264.

This study is also reported in Metge (1978).

Metge and Telford (1979) say the following about their objectives:

> The experiments were conducted to help predict what would happen to crude oil released from a subsea blow out in moving pack ice on Canada's East Coast. . . . It was not possible to model all aspects of the complex oil-ice interaction phenomenon in a small laboratory test. Therefore, the experiments were rather qualitative in nature. They were designed so that the important processes in oil-ice interaction could be observed and identified.

The tests were carried out in a cold room using a small basin 2.7 m by 3.5 m filled to a depth of 3 m with sea water. To simulate the dynamic action of pack ice, a specially designed 2.5 m diameter metal hoop was suspended in the basin. The hoop rotated alternately right and left (approximately 2 cycles per minute), creating a relative motion between the inner and outer floes. At the outside edge of the hoop, the rotation resulted in a velocity of 7.7 cm/s. The hoop also served to confine the oil and the ice.

Three tests were conducted, two used Atkinson Point crude oil and the third test used Prudhoe Bay crude. To begin each test, ice was added to the basin and agitated, resulting in a 5 to 6 tenths concentration with rafting. Then 1 L of oil was injected beneath the ice floes such that a continuous release of 2-3 mm droplets resulted. The oil was observed for 1 to 3 days. After the tests, oil between and on the floes was measured.

Metge and Telford state in their objectives that

> As far as the ice and its motion were concerned, the tests were roughly geometrically similar to Labrador pack ice conditions (ice floes about 10 m in diameter) with a scaling factor of about 1/30. Using Froude scaling, the velocity and time scaling factors would be about 1/5.5.

Separate tests were conducted to compare oil spreading through water and slush in static conditions.

Results

During the tests, the ice was observed to raft and form raised edges similar to East Coast ice. Metge and Telford report that

> After being injected, the oil droplets rose to the surface. With slight agitation, the oil always percolated through any slush present between the floes. Oil droplets that rose under ice floes tended to be trapped there. Some of this oil migrated to the surface of the ice through brine channels, but only after a few hours. Within 10 minutes, the oil spread to cover about half the test basin and it took from 20 to 40 minutes for the oil to cover the whole basin, depending on the oil. Prudhoe Bay crude spread much slower than the less viscous Atkinson oil. If the area between the floes was filled with slush, the slush tended to retain the oil. The oil-slush mixture was much more viscous than either oil or slush alone, forming a thick paste. . . . the movement, rotation, and contacting of floes resulted in oil being transferred from one floe to another and from one area to another, thus increasing the area of oil contamination.
>
> Small waves were generated during part of one test and were found to have no significant effect on the oil-ice interaction processes unless the waves were so high that the ice floes became partially submerged. . . . The [fan-induced] wind tended to move and herd the oil that was present in the areas between the floes.

Figure 3 shows the results of the mixing tests. Figure 4 shows the results of the spreading tests.

Figure 3 Summary of Mixing Test Conditions (from Metge and Telford, 1979)

	Test 1	Test 2	Test 3
Average floe size	35 cm	25 cm	25 cm
Average floe thickness (at beginning of test)	7.5 cm	2 cm	3 cm
Ice Salinity	4	8	11
Air Temperature	-6 to -8C	-8C	-9C
Crude Oil Used	Atkinson	Atkinson	Prudhoe Bay
Time of 25% oil coverage	5 min.	5 min.	5 min.
50%	10 min.	10 min.	10 min.
75%	15 min	15 min.	20 min.
100%	20 min.	-	40 min.
Duration of test	27 hours	42.5 hours	48 hours
Oil on the Ice:			
% water	59%	74%	61%
Volume of oil	351 ml	217 ml	79 ml
Oil between ice floes:			
% water	24%	27%	36%
Volume of oil	212 ml	84 ml	342ml
Oil Loss:			
By evaporation	about 300 ml	about 350 ml	about 300ml
On sides of tank	137 ml	349 ml	279 ml

Figure 4 Results of Spreading Tests (from Metge and Telford, 1979)

		Open Water		Slush (3 cm thick)	
		Slick Size	Slick Thickness	Slick Size	Slick Thickness
(1)	50 ml Atkinson Oil				
	after 1 minute	3702 cm^2	0.13 mm	120 cm^2	4.2 mm
	after 1 hour (final)	16000 cm^2 (limited by tank)	0.04 mm	470 cm^2	1 mm
(2)	50 ml Norman Wells Crude Oil				
	after 1 minute	390 cm^2	1.3 mm	230 cm^2	2.2 mm
	after 1 hour (final)	390 cm^2	1.3 mm	310 cm^2	1.6 mm
(3)	50 ml Prudhoe Bay Crude Oil				
	after 1 minute	390 cm^2	1.3 mm	Prudhoe Bay crude oil did not percolate through 3 cm of slush without some agitation and then it did not spread.	
	after 1 hour (final)	390 cm^2	1.3 mm		

Metge and Telford conclude with the following points:

> Oil mixes with slush to form a thick slush/oil mixture which substantially limits the spreading of oil.
>
> . . . impact mechanisms caused the thick oiled slush to be deposited on the edges of the ice floes and the raised edges prevented the oil from re-entering the water.
>
> Water-in-oil emulsions formed during the oil-ice interaction process and emulsions were found on and between floes. During melting of ice floes, the emulsion appeared as a light brown scum which seemed to be an oil-water-gas mixture.
>
> Oil droplets rising under ice floes were trapped by the roughness of the underside of the ice floes. This oil would eventually migrate to the surface of the floes through brine channels.

Under static conditions, slush ice and floes reduce the spreading of oil relative to an open water situation.

Under moving ice conditions, the rotation and contact of floes transfers oil from one floe to another and one area to another and thus increases the area of oil contamination.

Wilson, D.G. and D. Mackay. 1987. The Behavior of Oil in Freezing Situations. Prepared at the University of Toronto for the Environmental Protection Directorate, Environment Canada, Ottawa. Report No. EE-92.

This study is also reported in Wilson and Mackay (1986).

Wilson and Mackay (1987) wanted to " investigate and quantify the nature of the oil and developing ice field interactions" and more specifically to determine if and how "oil may become incorporated within the developing or "grease" ice, hence removing it from sight and from access by most conventional recovery processes". They also intended to collect data for possible use in a numerical model of oil spill fate and behaviour in a developing ice field.

Oil Incorporation

To study oil incorporation into grease ice fields, oil was introduced into freshwater grease ice in laboratory beakers of 2.5 to 3.5 L volume and the grease ice was agitated. Oil of different densities was created by combining Bayol 35 (a white oil) with measured quantities of tetrachloroethylene (specific gravity of 1.615). Oil thickness, ice particle diameter, and grease ice thickness were also varied. Oil volumes incorporated in the ice, ice to water ratios, and oil droplet sizes were measured. The samples were frozen and then placed in a 21°C room to observe the oil effect on thawing processes.

Oil Slick on Growth of Turbulent Ice Field

To study slick growth and oil weathering in developing ice, a oil mixture of 30%/70% No. 2 oil and No. 6 oil was introduced into a transparent tank measuring 0.35 m each side by 0.35 m deep in a room maintained at -5° C. A metal hoop was cycled up and down 120 times per minute immediately below the fluid surface to create a low energy ripple wave effect. The thickness of the oil was varied and time for ice formation was measured. A test was also performed with a

Bayol/tetrachloroethylene mixture of 0.79 specific gravity.

Emulsions

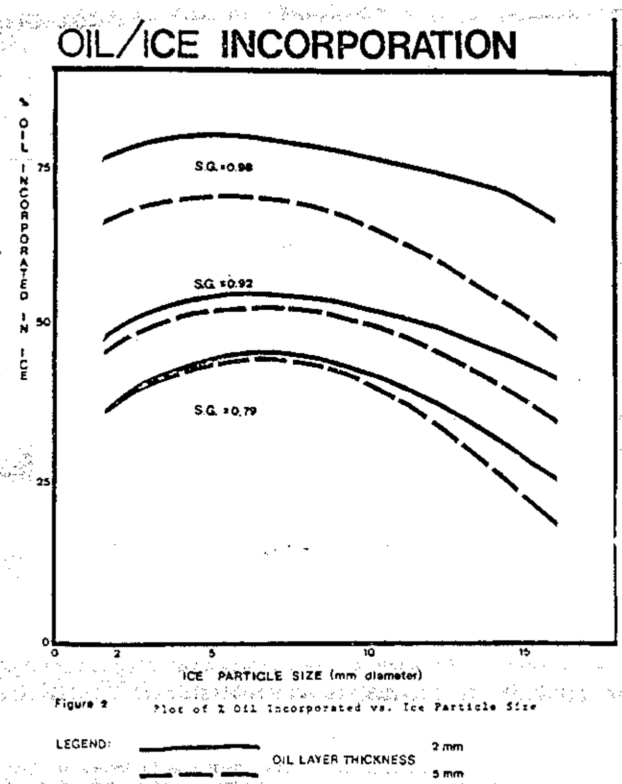
Mixtures of 90% saltwater to 10% oil were shaken for 3-4 hrs to produce oil-water emulsions. A 30%/70% No. 2 and No. 6 fuel oil mixture and an Arabian heavy crude were tested. Observation of emulsion behaviour in grease ice fields and measurement of density and percent water were carried out.

Results

Oil Incorporation

Figure 2 shows the results of the incorporation tests. Wilson and Mackay (1987) report that

Figure 2 Oil/Ice Incorporation (from Wilson and Mackay, 1986)



> The very dense oil tested, with a specific gravity of 0.98 was incorporated into the agitated grease ice field to a maximum level of 78 percent. The oil with a specific gravity of 0.92, similar to that of ice itself, was incorporated to a maximum level of 52% while the least dense oil, with a specific gravity 0.790, was incorporated to a maximum of only 47 percent. The extent of incorporation appears to reach a maximum when the ice particle size is in the range of 5 mm to 8 mm. When the ice particles are very large the extent of incorporation is considerably reduced.

Mackay and Wilson reasoned that oil viscosity, agitation, and low density of grease ice are factors in oil incorporation.

For thawing they found that more time is required to release a denser oil and that "the oil was quite evenly dispersed throughout the first 9 cm of ice".

Using the emulsions described above, it was qualitatively observed that oil incorporation was increased with emulsification. The higher incorporation was attributed to increased viscosity. Oil droplet sizes were larger in more porous ice. (on the order of 10-20 mm versus 5-10 mm). 80-90% of the original quantity of oil was incorporated. During 48 hours of observation neither emulsion mixture was broken down by ice interaction.

Oil-water mixtures that included ice particles were much less successful at producing emulsions, possibly due to damping of the shaking motion.

<u>Oil Slick on Growth of Turbulent Ice Field</u>

Wilson and Mackay describe the oil-ice interaction in the presence of agitation as follows:

> The droplets of oil ranged in diameter from as small as 0.5 mm to as large as 10 mm. The upper layer of the ice-oil mixture was solid but porous in nature with the pores in the ice containing significant quantities of oil. During the early period of the freezing process the oil was wave driven downwards by the hoop and would then resurface due to its positive buoyancy in the water.

> However, as freezing progressed, the ice chunks formed and then broken by the hoop became more numerous and hence formed a thicker mixture in the oil and water. This broken ice increasingly inhibited the ascent of the oil to the surface.

Wilson and Mackay conclude that

> oil incorporation experiments demonstrated that a density somewhat greater than that of ice itself is required for high extent of oil incorporation. The formation of oil emulsions are one method by which the net density of oil may be increased by its combination with denser sea water.
> . . .
> While a grease ice field would dampen waves experimental observations showed that sufficient agitation to force oil particles downward may easily be created. Once the oil particles have been forced downwards in the ice field they may remain there because of the same driving force or because of the natures of the ice field and oil.
> . . .
> The main factors influencing the entrainment are oil density and the level of turbulence within the ice field.

Buist, I., S. Joyce and D.F. Dickins. 1987a. Oil Spills in Leads: Tank Tests and Modelling. Prepared by S.L. Ross Environmental Research Limited and DF Dickins Associates Ltd. for the Environmental Protection Directorate, Environment Canada, Ottawa, Report EE-95.

Two associated papers, Buist et al. (1987b) and Joyce (1987), report on the laboratory phase of the tests.

The objectives of Buist et al. (1987a) were to collect data on

> . . . 1) the spreading rate and wind herding of oil on frazil and grease ice over a range of development stages; 2) weathering rates of oil in freezing situations; and 3) data on the fraction of oil remaining as a surface slick as a function of freezing.

The study consisted of two phases: a laboratory study of oil behaviour in the presence of freezing temperatures, winds, and waves; and outdoor tests in two small-scale leads.

Tests were performed in a wind/wave tank in a test section 7.2 m long and 1.2 m wide. The tank was filled with freshwater to a depth of 0.85 m. Wind speed, oil type and volume, wave action, and ice maturity were varied. Test oils were Mixed Sweet Western crude oil and two mixtures of Bunker C and automotive diesel.

Ice was grown in the tank until it reached the desired maturity, resulting in pancakes about 30 cm in diameter with slightly upturned edges. One L of oil was released about 1 m from the leading edge of the tank. The simulated wind and waves were not started until the oil reached ambient conditions. Observations were taken until the surface of the tank froze over (no waves) or the slick reached an equilibrium (with waves).

Measurements included surface slick dimensions, oil quantity in the ice, and driving variables (i.e., wind speed, air temperatures, water temperatures).

Two 10 m long by 1 m wide leads were cut in ice 29 cm thick. Four squares 1 m by 1 m were cut out of the ice to study effects of oil thickness on fate and behaviour.

> Prior to putting oil in each lead, the accumulated frazil and slush ice was skimmed from the water surface. The oil used for these tests was the Mixed Sweet Western crude used in the wind/wave tank tests. Ten litres of this oil was poured, via a spill plate, onto the surface of both Leads 1 and 2 for a nominal initial thickness of 1 mm. One, two, five and ten litres of oil were poured onto the surface of the four test squares to give nominal initial thicknesses of 1, 2, 5 and 10 mm respectively.

Oil thickness, snow thickness, ice and meltwater thickness, surface air temperatures, and weather were measured.

Results

Laboratory Tests

Buist et al. (1987a) found that immature ice, waves, oil density, and oil viscosity affected oil incorporation:

> An oil's density and viscosity seem to be important for determining the amount of oil frozen in ice; density because it determines the buoyancy of the oil in the water or the water/grease ice mixture, and viscosity because it determines the oil's ability to break up into particles that are small enough to migrate through the porous grease ice and also because it affects the thickness of the slick.
>
> . . .
>
> It was found that the fraction of oil incorporated into ice is increased considerably by wave action. Waves also have a large effect on the spreading of the slick. The oil seems to be able to spread readily in the slush around pancake ice . . . .
>
> In the presence of mechanically generated waves, it was found that the amount of oil in the ice decreased with increasing ice maturity.

Outdoor Tests

The first test commenced on January 27. Buist et al. observed that

> The oil quickly spread to cover the entire lead until the oil reached an area of ice crystals extending approximately 1 m out from the west end of the lead. . . . The oil spreading slowed significantly when it encountered the first loose ice crystals floating on the water surface and stopped completely when it reached the concentrated edge of ice crystals stretching across the lead.
>
> . . .
>
> Ice growth in Zone 1 [unoiled] was rapid, reaching . . . 45 mm in 22 hours. In contrast, the heavily oiled areas took 70 hours to reach an equivalent thickness. First ice formation in the oiled area required a surface disturbance [a slight breeze] to initiate crystal nucleation. . . . Following first crystal formation, the oiled ice in Lead 1 followed a distinct cyclic pattern of diurnal growth and melt as the oil layer warmed during the day (melting the upper surface of ice formed) and cooled at night . . . .
>
> . . .
>
> The snowfall accumulation [on the second day after the release] . . . immediately changed the surface appearance and subsequent physical oil fate in all sites. . . . By February 1, the combination of successive snowfalls and a number of diurnal freeze/thaw cycles led to a situation where new clean snow had accumulated on top of a frozen slush/oil crust overlying several cm of water on top of 3 to 4.5 cm of solid clean ice. Failing a significant rise in air temperatures, the oil was essentially sealed off at this point and isolated from further solar heating.

The spill in the second lead was followed one-half hour later by snow flurries and 10 m/s winds almost in line with the length of the lead. The oil responded as follows:

> The oil film quickly travelled the length of the lead at rates up to 6 cm/s and accumulated within 2 m of the south end in an arc across the lead, oriented perpendicular to the wind.
>
> While the initial distribution and extent of heavy oiling was entirely wind generated, the oil quickly became embedded in a snow/slush "soup" which effectively prevented any further oil spreading or redistribution. . . . 48 hours after oil release, the oil was incorporated into 3.5 cm of frozen oil slush. Depth of frozen snow/slush at the north end was 5.5 cm indicating . . . that the presence of oil significantly reduces the rate of initial ice growth . . . .

The 1 m by 1 m test plots also showed a relationship between oil thickness and ice growth: "after 116 hours there was a 60% reduction in ice thickness beneath oil of 10 mm as opposed to that beneath oil of 1 mm (27 vs 45 mm)". Figure 15 shows the ice thickness as a function of time and oil. Buist et al. conclude that the effect of oil reduced the "net ice growth rates after several days by approximately 50% (oiled ice/clean ice)". They also found that "the evaporation does not seem to be greatly reduced by the presence of snow in or on the surface oil".

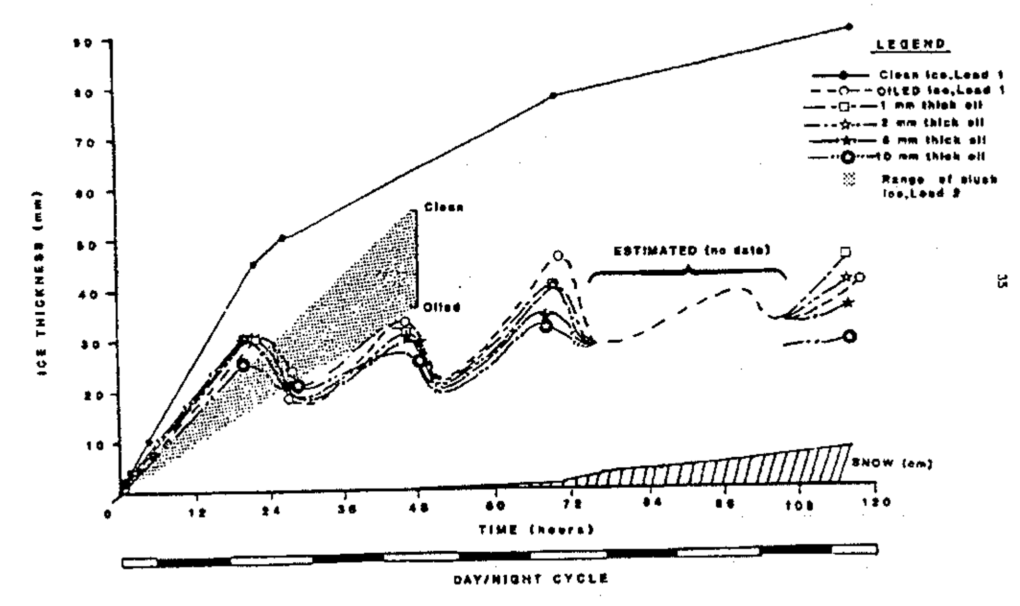


FIGURE 15: CONSOLIDATED ICE GROWTH DATA

Based on the results of the laboratory tests and outdoor tests, several equations were developed for use in a computer model of oil fate and behaviour.

Oil Encapsulated in Grease Ice

During each program iteration a volume of oil becomes trapped in the differential area of new ice growing beneath the slick. The fraction encapsulated is based on the oil properties, and is increased by a density factor:

$$(K_1 + K_2)\rho_o \quad (6)$$

and decreased by a viscosity factor:

$$K_3 + K_4\mu_o \quad (7)$$

The fraction (F) of the oil in that is underlain by new ice growth for that iteration that becomes encapsulated is then given by

$$F = K + K_2\rho_o - K_4\mu_o \quad (9)$$

where
ρ_o = density of oil,
μ_o = viscosity

Substituting from the experimental results and solving for the constants yields values of:

$K = -0.19966$
$K_2 = 0.31053$
$K_4 = 0.0000709$

Effect of Waves

If the calculated wave height in the unfrozen length of the lead exceeds a certain value (that is input by the operator) the fraction of oil incorporated is arbitrarily increased by 0.2, consistent with the results of the wind/wave tank tests.

Snowfall

Based on the results of the outdoor test tank experiments the effect of snowfall is twofold: initially snow is absorbed by the oil until such time as the water content of the oil (or emulsion) reaches a maximum (presumed to be in the range of 75% for the model), after this the snow covers the oil rendering it unavailable for countermeasures.

Payne, J.R., G.D. NcNabb, L.E. Hachmeister, B.E. Kirstein, J.R. Clayton, C.R. Phillips, R.T. Redding, C.L. Clary, G.S. Smith, and G.H. Farmer. 1987. Development of a Predictive Model for the Weathering of Oil in the Presence of Sea Ice. for NOAA/OCSEAP Office, Research Unit No. 664, Anchorage, Alaska.

The objective was to observe the interaction of oil spilled in multi-year ice. The tests were part of a much larger program to develop a computer model for weathering of oil in ice (see Section 4.1 for a discussion of related work).

A pseudo multi-year ice field was created in the laboratory with small-scale ridges, rubble fields, multi-year floes, and refrozen leads. The ice field was grown over 2 1/2 freeze thaw cycles in a flow-through sea water tank, 3.5 m long (including wave paddle), 0.83 m wide and 0.64 m deep. Under ice relief was 8-35 cm and surface ridge relief exceeded 20 cm. For the test, a 0.3 m wide lead was cut across the width of the tank, near the paddle. 0.75 L of Prudhoe Bay crude oil was released, mostly into the lead, but some of the oil was injected under the ice.

Fifty minutes after the oil was released, lead closure pumping was simulated using the wave paddle. After 2 hours the temperature was dropped to simulate a partial refreeze. Three days later a break-up with wave action was started. Throughout the test water samples were taken to measure dissolved hydrocarbons, oil-ice interaction was observed and ice growth was measured. Light winds were generated whenever the refrigeration system was on.

Results

The simulated lead pumping created 3-5 cm waves that washed the oil over the ice. Most of the oil was washed back into the lead with about one third remaining trapped on the surface. Before refreezing began, 90% of the lead was covered by a thin film of oil.

Differences in ice growth under oil were not significantly different than that under ice with the static condition of the test. Oil was found to behave like slush ice and to react to wind herding.

During the break-up, much of the oil stranded on the surface was washed back into the water and 90% of the oil contacted the under ice surface, coating it with 1-55 mm oil droplets. During thawing, the oil droplets migrated up through the ice and would have eventually been released.

5.3 Broken Ice Spreading - Literature Review

Free, A.P., J.C. Cox and L.A. Schultz. 1982. Laboratory Studies of Oil Spill Behaviour in Broken Ice Fields. Proceedings of the Fifth Arctic Marine Oilspill Program Technical Seminar. Edmonton, Alta. - also ARCTEC Inc. Report 570.

The study is also reported in Free et al. (1981).

A series of laboratory tests were carried out to observe small-scale, short term, oil spreading in broken ice. The primary goal was to determine spreading rates.

Two test series were carried out: tests of oil flow through a single, uniform ice gap and tests of oil spreading in a random broken ice field. All tests were carried out in a 14 m long flume tank where one dimensional spreading could be observed. Wind speeds up to 6.3 m/s and currents up to 30 cm/s were attainable. The tests were carried out at full-scale, with the exception of wind, which had a scaling factor of 1.7 from laboratory to field.

Three oils were tested: diesel fuel, SAE 10W and SAE 40W (see Table 3-2 for oil properties). Ice piece size, ice concentration, currents and winds were varied during the tests.

Free et al. (1982) describe the procedures for the single ice gap tests and random broken ice fields as follows:

> Single Ice Gap Tests
> The gap width was varied from the narrowest gap through which oil could flow to a gap so wide that the oil flowed through it as if in open water.
>
> Random Broken Ice Fields
> Tests were performed on two types of random ice fields: ones restrained from

flowing downstream, and ones free to move in one direction. . . .

> . . . For the restrained tests, the ice was prevented from moving downstream by a permeable barrier which did not obstruct oil or water flow but which restricted ice movement.
>
> [For the unrestrained tests] a thick oil reservoir was formed in the back third of a densely packed ice field. Both the ice and the oil were released and permitted to flow downstream. . . . The velocities of the front edge of the ice pack and of the oil slick were measured.

Results - Single Gap Tests

Free et al. found that a minimum gap width was necessary for oil spreading and that the oil spreading velocity could be described empirically:

> This minimum [gap] width is a function of the density and surface tension of the oil, and of the thickness of the oil slick contained behind the gap. For an oil slick approximately 5 cm thick, the minimum gap width was found to be approximately 0.1 cm for diesel fuel, 0.35 cm for SAE 10W oil, 0.45 cm for SAE 40W oil.
>
> The velocity at which oil moves through a gap is a function of the oil density and viscosity, the thickness of the oil reservoir contained behind the gap, the gap width, and the velocity of the driving medium (current or wind). From the data collected during the single gap tests, empirical equations were written for the velocity of a given oil through a single uniform gap. The equations for the three oils tested in this experiment are:
>
> Diesel Oil: $V_o = 0.41\ \delta^{0.81}\ w^{1.19} + 0.015\ V_D$ (1)
>
> SAE 10W Oil: $V_o = 0.22\ \delta^{0.78}\ w^{1.22} + 0.00049\ V_D$ (2)
>
> SAE 40W Oil: $V_o = 0.081\delta^{0.45}\ w^{1.55} + 0.0028\ V_D$ (3)
>
> where V_o = velocity of the oil, in cm/s;
> δ = thickness of the oil slick, in cm;
> w = width of the ice gap, in cm;
> V_D = velocity of the driving medium, in cm/s.
>
> The constants in Equations 1, 2 and 3 are functions of the oil densities and viscosities.

> Note that Equations 1, 2 and 3 do not differentiate between the driving forces due to current or wind. This implies that over the ranges tested in this program neither current nor wind has a significant impact on the velocity of oil flowing through an ice gap. . . .
>
> The maximum gap width which had any effect on the oil spread rate was also found to vary with the type of oil. Diesel fuel spread as if in open water in gaps as small as 7.6 cm. The heavier SAE 10W and SAE 40W oils required gaps as wide as 15 cm for the ice to not affect the oil spread rate.

Results - Random Broken Ice Fields

Restrained Field

Figure 1 presents the results in dimensionless form for the diesel fuel tests in restrained ice fields,

where g = oil seepage rate per unit channel width;
δ = oil slick thickness;
b = characteristic dimension of the ice field.

The characteristic dimension, b, is defined as "the gap width that would exist if the ice pieces had been arranged in a rectangular packing arrangement at the same concentration as the random field". It can be calculated as follows:

$$b = d\left(\frac{1}{\sqrt{c}} - 1\right)$$

where d = ice piece size;
c = surface ice concentration.

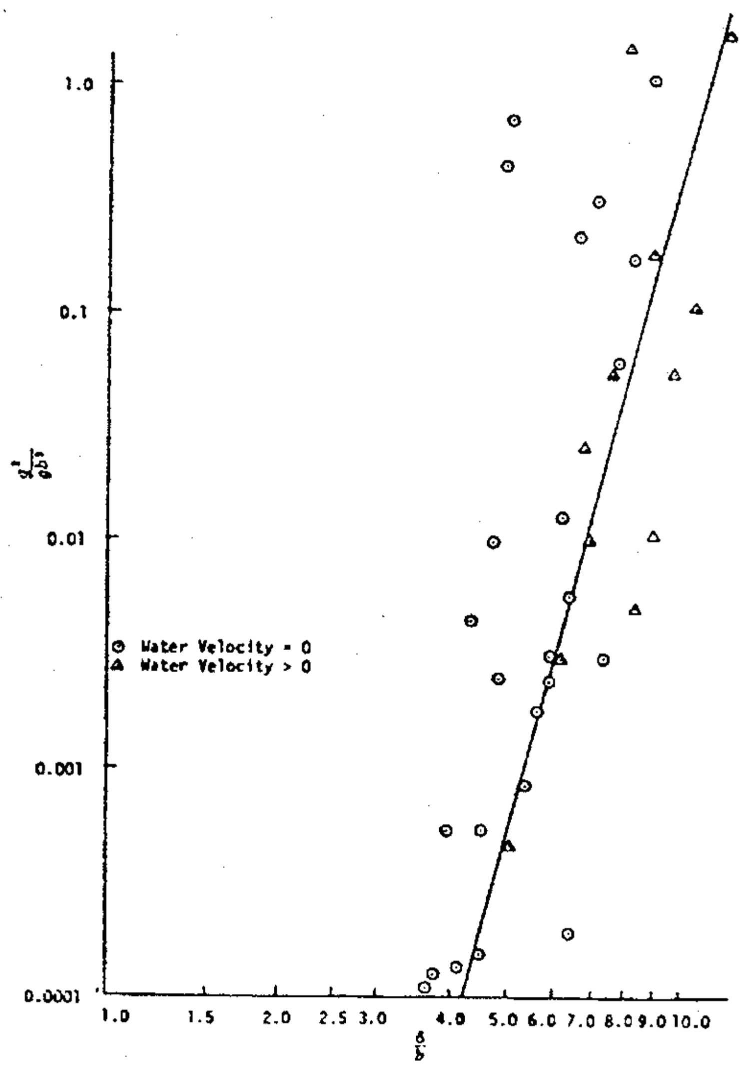
Free et al. also found that

. . . the seepage rate of oil through an ice field is independent of water currents over the range investigated. An oil layer somewhat thinner than the ice block thickness is shielded from the shear stresses due to the current by the large roughness provided by the ice blocks. . . . the oil seepage rate to be expressed in a dimensional form as:

$$q = 2.74 \times 10^{-5} (\delta^{4.37}/b^{2.87}) \quad (6)$$

where q is in cm/s and δ and b are in centimetres. . . .

Figure 1 Oil Seepage Rate Through Broken Ice - Diesel Fuel (from Free et al., 1982)



Free et al. found that the "SAE 10W oil and the SAE 40W oil were both too viscous, and were totally contained by the packed broken ice field".

Unrestrained Field

Free et al. found that in unrestrained ice fields the ice velocity was determined by the oil slick thickness if the thickness ratio squared over the ice thickness and ice field length exceeded a given value:

> . . . for a given current or wind velocity, the velocity of the leading edge of the ice field was directly related to the square of the oil slick thickness, and inversely related to the length and thickness of the ice field. . . . It was noted that when the oil thickness became small, the water or wind velocity rather than the oil pressure dominated, the ice velocity tailed off sharply, and these equations no longer applied.

The equations below and Figures 3 and 4 summarize the findings for ice velocity in diesel oil and SAE 10W with current as a driving force.

$$V_i\,[\text{diesel fuel}] = (106\,\delta^2/(tL) + 0.376)V_w + 433\delta^2/(tL) + 5.44 \quad (8)$$

$$\text{for } \delta^2/(t\,L) \geq 0.00175$$

$$V_i\,[\text{SAE 10W}] = 0.504V_w + 392\,\delta^2/(tL) + 6.04 \quad (10)$$

$$\text{for } \delta^2/(t\,L) \geq 0.004$$

where V_i = ice velocity, in cm/s

t = ice thickness, in cm

L = ice field length, in cm

Using wind as a driving force, Free et al. found that a minimum wind speed of 5.5 m/s (8.45 m/s scaled up for field conditions) was required to affect the oil and ice (see Figure 5). Below this value the ice velocity could be described by an equation

Figure 3 Ice Pack Velocity vs Relative Oil Thickness Driven by Current - Diesel Fuel (from Free et al., 1982)

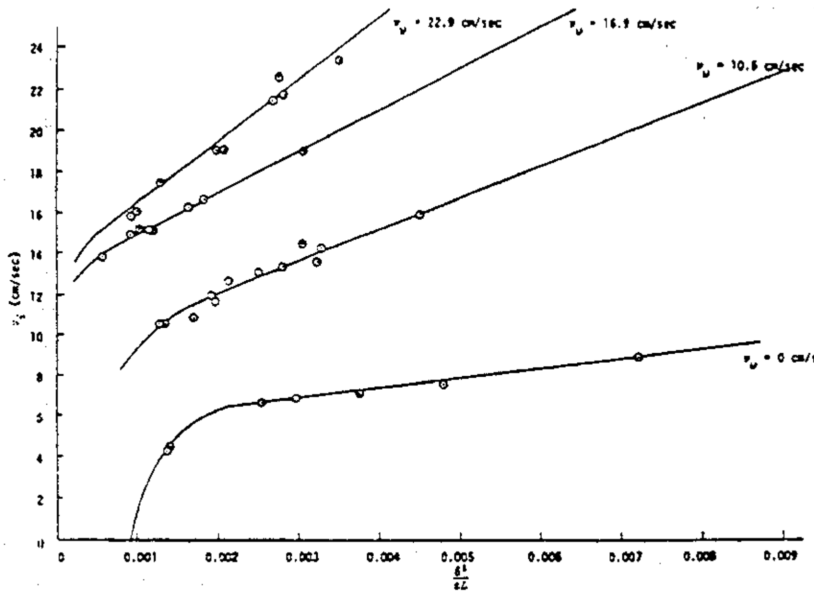
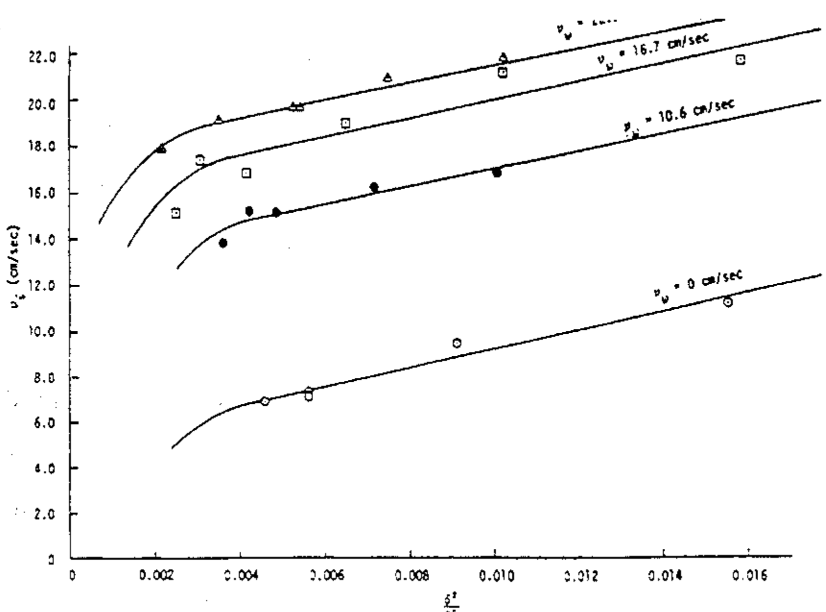


Figure 4 Ice Pack Velocity vs Relative Oil Thickness Driven by Current - 10W Oil (from in Free et al., 1982)



corresponding to the equation derived previously for ice and diesel oil driven by a current:

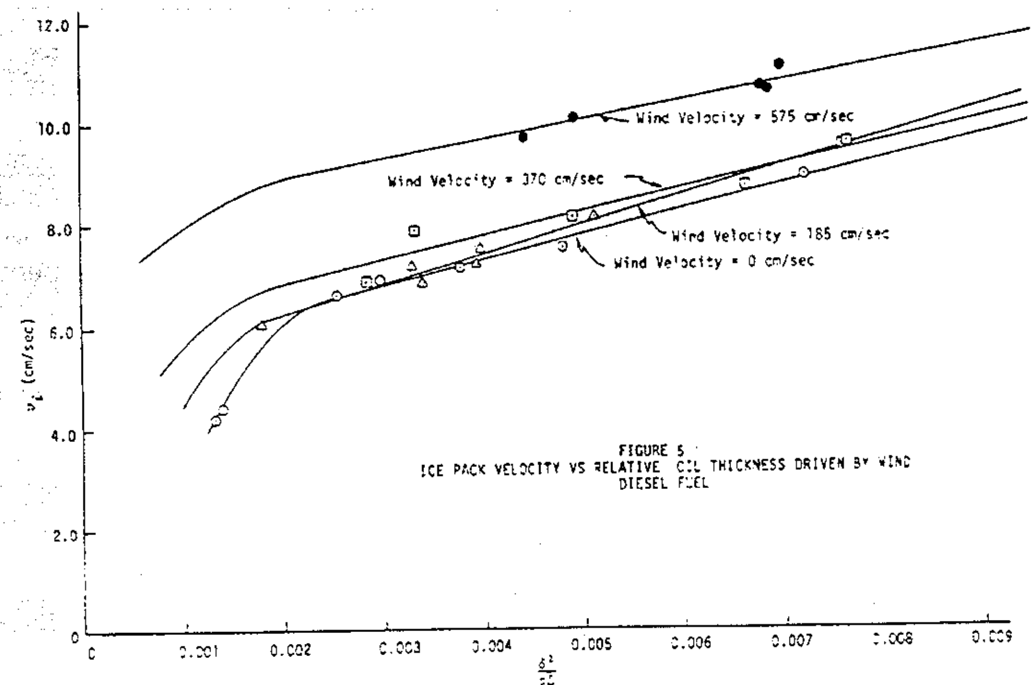
$$V_i \text{ [diesel fuel]} = 533\ \delta^2/(tL) + 5.32 \qquad (12)$$

for wind < 5 m/s (lab scale)

Note that the linear regression analysis yielded coefficients that are slightly different from equation (8).

Relationships for ice velocities above wind speeds of 5 m/s could not be determined due to the limitations of the apparatus.

Figure 5 Ice Pack Velocity vs Relative Oil Thickness Driven by Wind - Diesel Fuel (from Free et al., 1982)



Tebeau, P.A., T.M. Meehan, and S.A. Saepoff. 1984. A Laboratory Study of Oil Spreading Under Arctic Conditions. Unpublished laboratory report available from the U.S. Coast Guard Research and Development Centre, Groton, Connecticut.

Tebeau et al. (1984) write that

> The objective of these experiments was to identify the mechanisms controlling spreading rate, final area, and equilibrium thickness; and to gain some insight into the validity of existing models which predict these spreading parameters.

Specifically they wanted to verify the equations developed by Free et al., 1981 (also presented in Free et al., 1982) and explore their usefulness for field conditions.

The method used is summarized by Tebeau et al.:

> The tests were conducted in a small test tank (120 cm by 120 cm square by 30 cm deep [1.2 m by 1.2 m by 0.3 m]). . . . The open water tests consisted of releasing small volumes (25 or 50 ml) of three types of oil (No. 2 home heating, Prudhoe Bay Crude, or No. 4 fuel oil) . . . . The broken ice tests consisted of releasing the same oils into the tank which was filled with varying numbers of rectangular ice blocks (10 cm x 10 cm x 12 cm). Oil volume, ice concentration, and release rate were varied in the test runs to delineate the physical mechanisms controlling the oil spreading rate, final spill area, and equilibrium thickness. In some tests, actual measurement of the gaps between the ice pieces was attempted.

Two separate sets of tests were conducted: constant flow rate release or instantaneous release. For oil properties see Table 3-2.

Results

Tebeau et al. found that

> In general, the No. 2 heating oil exhibited the non-containment spreading behaviour as defined by Free, Cox, and Schultz (1981), while the heavier oils

(Prudhoe Bay crude and No. 4 fuel oil) exhibited the virtual or total containment behavior [oil slick much thicker than open water equilibrium]. . . .

. . . Prudhoe Bay crude oil continued to spread for several minutes at 71% ice concentration (120 blocks), while spreading was halted within a minute at ice concentrations of 83-85% (200 and 160 blocks). . . . 71% ice concentration case probably corresponds to virtual containment . . . while the behavior at 83-85% ice concentration probably corresponds to total containment. Equilibrium thickness for the Prudhoe Bay crude were measured at 0.34 cm [3.4 mm] for the 71% ice concentration and roughly 1.1 cm [11 mm] for the 83-85% concentration. . . . the spreading behavior of the No. 4 fuel oil at ice concentration down to 73% can best be described as total containment.

. . . for heavier oils and higher ice concentrations, ice concentration becomes important in controlling spill behavior, with the physical properties of the oil being less important.

Figure 12 Plot of Equilibrium Oil Thickness vs. Ice Concentration (from Tebeau et al., 1984)

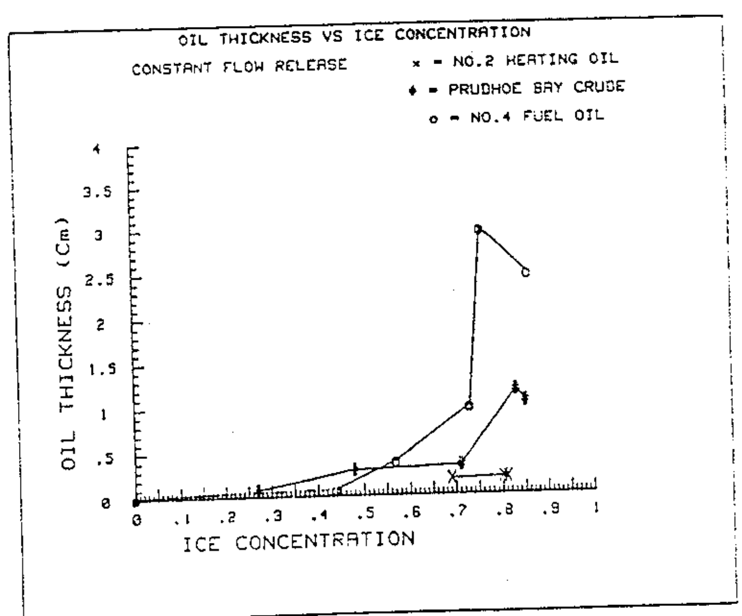


Figure 12 Plot of Equilibrium Oil Thickness vs. Ice Concentration for No.2 Heating Oil, Prudhoe Ba. Crude, and No.4 Fuel Oil.

During the instantaneous releases of oil, Tebeau et al. observed that

> the instantaneous release spill spreads more rapidly than the constant flow rate spill, and produces a somewhat larger spill area. . . . This effect is probably due to the increase in hydrostatic pressure with the instantaneous release in the initial seconds of the spill.

They found again that in high ice concentrations, the oil was totally contained by the ice within a relatively fixed spill area, even when spill volumes were increased.

Tebeau et al. compared their results to the gap width equations developed by Free et al. (1982) and found that the equations overestimated the equilibrium thickness. The predictions of Free et al. (1982) and the results of Tebeau et al. are compared in Figure 18.

Figure 18 Plots of Experimental and Theoretical Values of Oil Spill Thickness vs. Ice Gap Width for Ice Gap Flow, Instantaneous Release (from Tebeau et al., 1984)

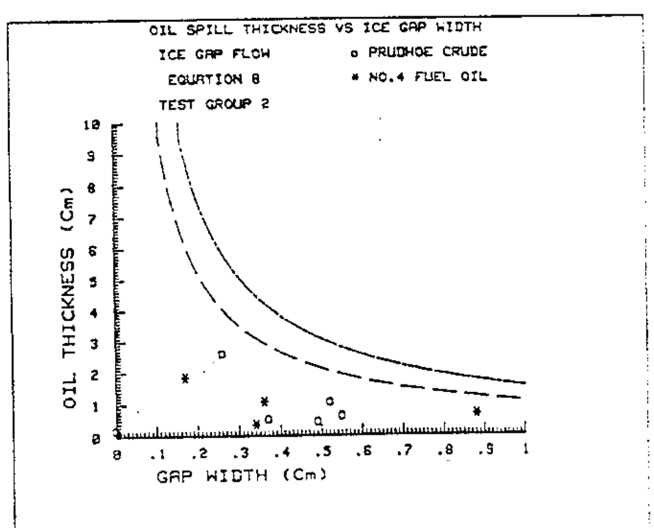


Figure 18 Plots of Experimental and Theoretical Values of Oil Spill Thickness vs. Ice Gap Width for Ice Gap Flow (Equation 8), Test Group II.

To explain the discrepancy between the theory and observations, the modelling of oil flow as Poiseuille flow versus flow in a narrow channel was examined. An equation was developed for equilibrium thickness as a function of hydrostatic force and interfacial tension

$$0.5\rho_o g w(h^2) - 2\,\sigma_{o/w}(1 - \cos\theta) - \sigma_{o/w}(1 - \cos\theta)(w) = 0$$

where ρ_o = oil density
w = gap width
$\sigma_{o/w}$ = oil/water interfacial tension
θ = contact angle assumed to be between 90 and 180°

Tebeau et al. found that an assumed contact angle of 180° gave the best agreement with the experimental data. The equation above is most appropriate for oil thickness less than the gap width.

Tebeau et al. conclude that the "laboratory results will likely apply to a stationary brash ice environment . . . where ice piece sizes are small, and the ice concentration is fairly uniform in space and time". They predict that the usefulness of the laboratory results for predicting the equilibrium thickness in the offshore Arctic will be minimal:

> the gap widths encountered here are generally on the order of several meters, and hence small scale oil/ice phenomenon observed in the laboratory probably do not control oil spreading.

S.L. Ross Environmental Research Limited and DF Dickins Associates Ltd. 1987a. Field Research Spills to Investigate the Physical and Chemical Fate of Oil in Pack Ice. Environmental Studies Revolving Funds, Report No. 062. Ottawa.

Buist, I.A.and D.F. Dickins. 1987. Experimental Spills of Crude Oil in Pack Ice. 1987 Oil Spill Conference, American Petroleum Institute, Washington, D.C., pp 373-381.

This study is also reported in Buist and Bjerkelund (1986).

Three experimental spills of 1 cubic metre each of Alberta sweet mixed blend crude oil, were done in pack ice about 140 km east of Chedabucto Bay, Nova Scotia.

The objective of the study was to evaluate oil spreading in variable pack ice conditions; the fate of oil spilled in pack ice (evaporation, emulsification, dispersion, and incorporation into or on top of the ice) and possible countermeasure techniques.

Ice Conditions

The ice and environmental conditions for each spill are summarized below (from S.L. Ross and DF Dickins, 1987).

Spill No. 1, March 9, 1986.

Ice conditions	4-6/10 small floes and pancakes
Floe size	mean 7 m max 24 m
Floe freeboard	5 cm to 44 cm
Water temperature	-1.4 to -1.6 °C
Oil temperature	-1.0 to -1.5 °C
Ice core temperature	-2.2 °C top to -1.3 °C bottom
Seawater salinity	24 ppt (approximately)
Ice core salinity	0.5 ppt top to 5.0 ppt bottom
Relative floe motion	minimum -7 cm/s

	mean +2.4 cm/s
	max 16 cm/s
	mean convergence -3.4 cm/s
	mean divergence 5.4 cm/s
Ice drift	1.1 km/hr to 140 °T
	1.9 km/hr to 158 °T overnight
Swell	3-4 m
Wind speed	35-45 km/hr

Spills No. 2 and No. 3, March 10, 1986.

	Spill No. 2	Spill No. 3
Ice conditions	7-8/10	4-6/10
with pancakes and heavy slush ice up		to 40 cm thick
between floes		
Floe size	mean 13 m	mean 9 m
max 30 m	max 22 m	
Floe freeboard	5 cm to 52 cm	5 cm to 52 cm
Water/slush temperature	---	-17 °C
Oil temperature	-3.4 °C	-3 °C
Ice core temperature	-2.8 °C top to	
-1.6 °C bottom	---	
Relative floe motion	0.1 cm/s	not measured
Ice drift	0.8 km/hr to	0.7 km/hr to
195 °T	155 °T	
Wind speed	30-35 km/hr	18-22 km/hr

Results

Oil Spreading in Pack Ice

S.L. Ross and DF Dickins (1987) modified Fay's (1969) equations to model the spread of oil spilled in pack ice.

> 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:

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

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

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

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)

A viscosity correction factor $(\mu_o/\mu)^{-0.15}$ was used, where μ_o is the oil viscosity, for the gravity-viscous regime. S.L. Ross and DF Dickins (1987) also stated 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:
>
> $$A\mu I = (\mu_o/\mu)^{-0.15}(1-f_I)A$$

Figure 7 shows the oil spill areas for each spill (corrected to exclude ice) and Fay's spreading curves for the oil at 0°C (corrected for oil viscosity and ice concentration). This simple approach fits the data well for oil spreading in pack ice in the absence of thick brash ice (spill 1).

Figure 8 shows the results of the oil slick thickness data for spill No.1 compared with the model prediction (Buist and Dickins, 1987).

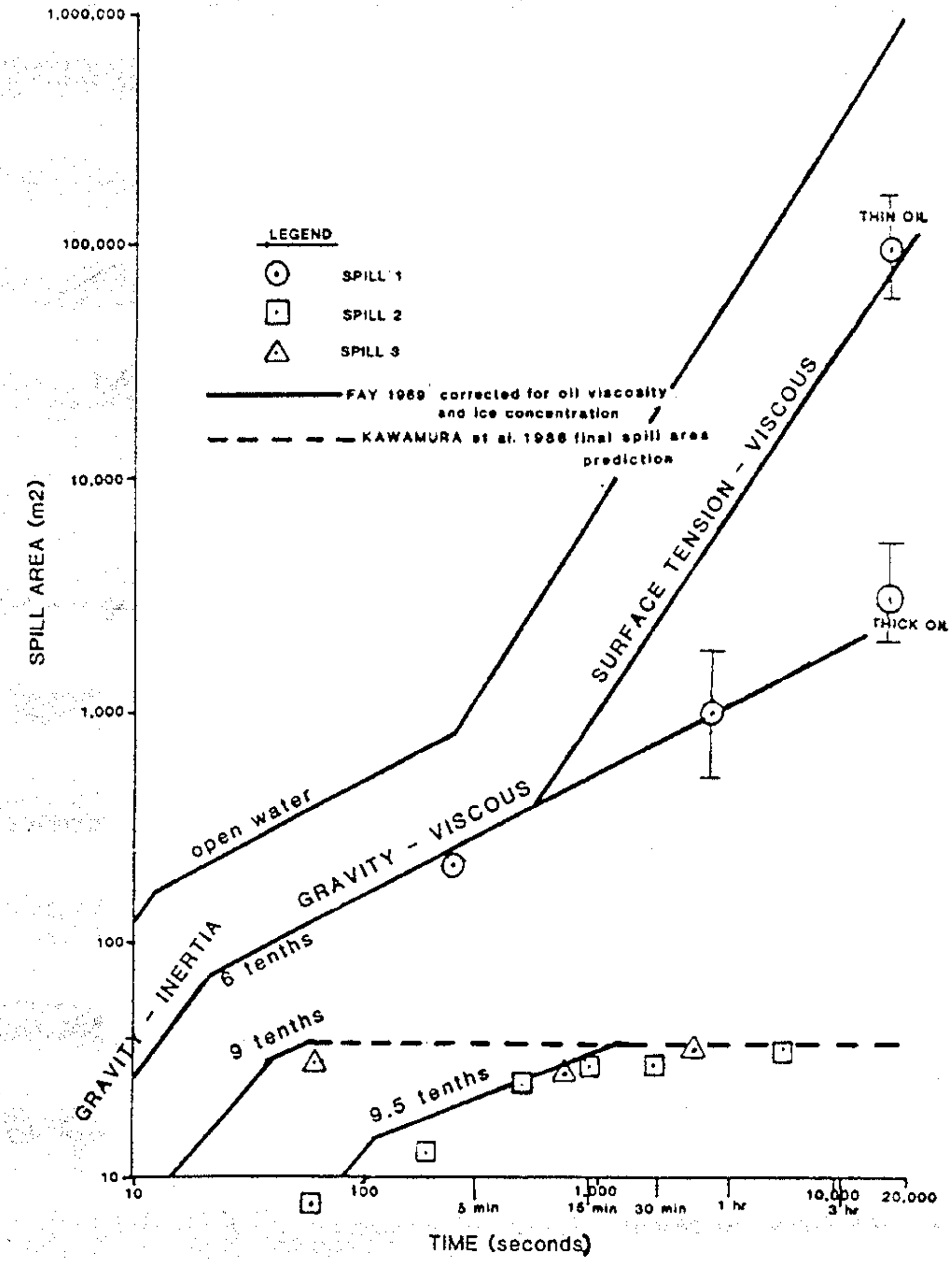


Figure 7. Oil spreading in pack ice

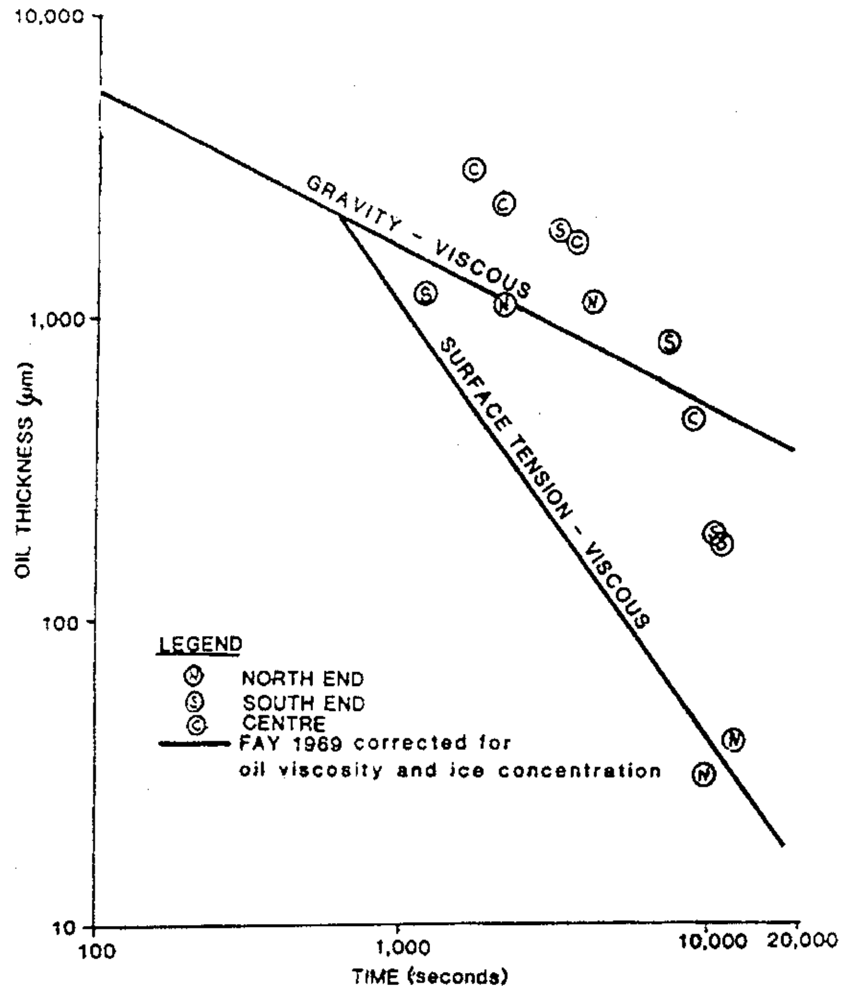


Figure 8. Thickness of spill No.1 vs time

. . . This independent data set confirms the spreading data and model shown on Figure 7. The thicker areas of the slick at the center and downwind south end of spill 1 were spread primarily by the gravity-viscous regime of Fay while the north, upwind portion of the slick was quickly spread by the surface tension-viscous regime. Again, the simple, corrected Fay model predicts the data reasonably well.

Oil Spreading in Brash Ice

S.L. Ross and DF Dickins (1987) found that the high concentrations of brash ice in spills 2 and 3 greatly reduced oil spreading. They concluded 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).

The equation developed by Kawamura et al. (1986) to predict the final area of a spill in snow is (S.L. Ross and DF Dickins, 1987)

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

where:
- d = snow depth (m)
- ϕ = snow crystal factor
- = 1.0 for crystalline snow
- = 0.1 for spherical snow
- ρ_o = oil density (kg/m3)
- ρ_s = snow density (kg/m^3)
- ό = 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 ρ_s = 800 kg/m^3 yields a final spill area of 38 m^2, very close to the final observed areas of 36 and 35 m^2 for Spills 2 and 3, respectively.

Other Observations

Buist and Dickins (1987) observed that

The oil interacted with the ice in three ways: it saturated the brash ice surrounding floes, it splashed onto small pancakes of ice, and droplets were swept beneath the floes by the currents.

The brash ice proved to be an effective barrier to limit the spread of oil [spills 2 and 3]. However, in dynamic conditions the oil eventually mixed with the ice to produce a brown slush which, with the rocking action of the floes, coated the outer rim of small floes and pancakes. . . .

In spill No. 1, oil droplets, about 1 mm to 3 mm in diameter, were observed being swept by currents beneath floes. A core sample from the edge of a floe showed that these droplets were trapped by the underside of the floe and had migrated upward some 25 cm into the brine channels. Analysis of the melted cores showed oil concentrations equivalent to an under-ice oil thickness of approximately 0.15 mm.

Some oil was also found on top of the occasional pancake, though this was rare. Analysis of one such sample scraped from the snow showed that the oil had an effective thickness of 0.25 mm and was extremely weathered.

Conclusions

S.L. Ross and DF Dickins (1987) made the following conclusions:

1. Spreading of oil in pack ice is dramatically reduced, over that in open water, by the presence of ice forms. Simple correction factors to Fay's 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 the 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 . . . 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 ar 10 m, including a 10 degree clockwise Coriolis rotation, and the residual current.

3. . . . .

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 in 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 techniques seemed feasible for brash ice or medium concentration pack ice.

Belaskas, D.P., and P.D. Yapa. 1991. Oil Spreading in Broken Ice. Prepared by the Department of Civil and Environmental Engineering, Clarkson University, Potsdam, New York. Report No. 91-6.

An associated paper by Belaskas and Yapa (1990) describes the preliminary results.

Objectives: To study the relationship of discharge rate and oil volume on the spreading rate in broken ice.

The tests were carried out in a small tank, 1.2 m by 1.2 m by 0.45 m deep, in a cold room. Four ice covers were tested: 1) polyethylene blocks, 20.6 mm by 19.1 mm by 6.4 mm; 2) small plastic cylinders, length 3.25 mm and diameter 3.33 mm; 3) crushed ice from an ice machine, various grain sizes; 4) small ice blocks, 12.7 mm by 12.7 mm by 9.5 mm. Layer thicknesses from 1.55 cm to 7.56 cm were tested with porosities of 0.38 ± 0.02 with the exception of the plastic cylinders which had a porosity of 0.55. No wind or waves were present.

The ice covers was randomly arranged in the tank, levelled to a uniform thickness, and marked to aid in measurement of horizontal spreading. A diffuser in the centre of the tank discharged a set volume of oil at a constant flow rate.

Twenty-one tests were conducted. Oil viscosity was varied from 161.2 to 769 cs, flow rate from 0.0143 to 0.077 L/s and oil volumes from 0.285 to 4.25 L. Slick radius with time was measured, both on the surface and on the bottom of the cover. Tests were completed anywhere between 1.5 min and 1.24 hours. Open water tests were also included.

Belaskas and Yapa found that spreading was related to flow rate and time:

$R = kQ^x t^y$

where R = slick radius in cm

Q = flow rate in cm^3/s

t = time in s

Once the oil penetrated up through the covers, it spread faster on the surface than on the bottom. The plastic cylinders were "relatively impervious to oil", and the results were compared to oil spreading under solid ice. Values found for k, x and t for the various covers are given below.

k, x, and y Values for Polyethylene Block Cover - Constant Discharge

Variable	Top View		Bottom View	
	4.75 cm thick	7.56 cm thick	4.75 m thick	7.56 cm thick
k	0.24	0.80	0.08	0.61
x	0.40	0.05	0.94	0.45
y	0.70	0.70	0.39	0.37

Slopes (y) for Plastic Cylinder Ice Cover

Bottom View	
Constant Discharge	Constant Volume
0.5	0.08-0.19

k, x, and y Values for Crushed Ice and Block Ice Covers - Constant Discharge

Variable	Top View	Bottom View
k	0.12	0.37
x	0.55	0.72
y	0.59	0.47

Figure 4.14 shows the results from the tests in ice block cover.

Overall, spreading was found to be a function of time, discharge rate, and ice cover thickness. Belaskas and Yapa concluded that "The spreading mechanism is dramatically altered by the type of ice cover and permeability of the ice cover, even when porosity has not changed significantly."

Figure 4.14 Oil Spreading in Ice Blocks, Constant Discharge (from Belaskas et al., 1991)

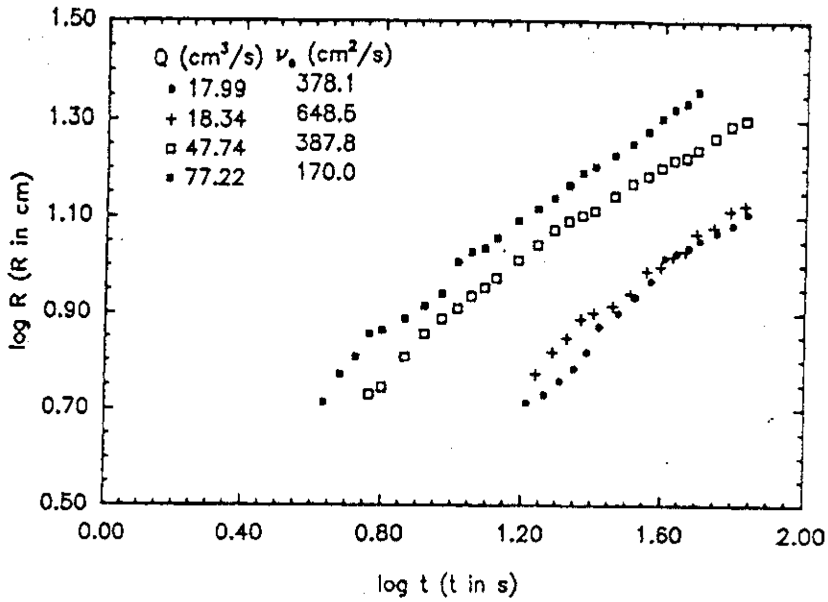


Figure 4.14: Type IV - Top View, constant discharge

5.4 Lead Closure - Literature Review

MacNeill, M.R. and R.H. Goodman. 1985. Motion of Oil in Leads. Eighth Annual Arctic Marine Oilspill Program Technical Seminar, Environment Canada, Ottawa, Ontario, pp 42-52.

This study is also reported in MacNeill and Goodman, 1987. MacNeill and Goodman (1985) investigated the motion and fate of oil during lead closure.

> The experiment was carried out in an outdoor test basin . . . located on the site of the Esso Resources Canada Limited laboratory in Calgary, Alberta. . . . The dimensions of the basin were 15 m x 19 m, with a maximum depth of 2 m. . . . Ordinary salt was added to the basin to bring the salinity of the water up to approximately 28 o/oo, corresponding to the surface salinity that would typically be measured in the southern Beaufort Sea in winter.

Following a preliminary test, the final experimental procedure was

1) The lead was created by cutting the ice across the basin and pulling the two ice sheets apart, so that the sides of the lead match.
2) 5-10 litres of oil was poured on the surface of the lead and allowed to spread to an equilibrium thickness.
3) The lead was closed by pulling one ice sheet straight into the other one using hand winches.
4) Slush was removed from the lead for the initial tests to simplify interpreting the experiment.
5) The oil used in the tests was unweathered "Adgo crude", a heavy Arctic oil. It was chosen both for its availability and low pour point of - 26°C.

Four tests were done on four different leads over a two day period in January 1984. Table 2 presents the test parameters.

Table 2 Test Parameters

Test #	Volume of Oil (L)	Air Temp (°C)	Water Temp (°C)	Ice Thickness (cm)	Freeboard (cm)	Oil Temp (°C)	Salinity (o/oo)	Rate of Closure (cm/sec)
1	10	-3	-0.5	30	0-3	4	24	<5
2	5	-2	-0.5	30	3	7	24	6
3	5	+9	-0.5	30	3	7	24	6
4	5	+2	-0.5	30	3	7	24	12

The main parameter to be varied was the rate of closure. . . . the rate could not be changed with precision but could be measured accurately using the change of the lead width in the pictures from the motor-drive cameras. Three rates were attained: less than 5 cm/sec, 6 cm/sec and 12 cm/s.

Results

Test 1
Ten litres of oil were applied to a lead with some slush in it. The oil spread very little on the surface of the lead, creating a slick 0.5 to 1 cm thick. . . . When the lead closed, there was no observable flow of oil along the lead, but an estimated 3 litres of oil flowed over the ice sheet on the east side of the lead (in regions of negative freeboard) as the sides of the lead pressed together. . . .

Test 2
The amount of oil poured onto the lead was reduced to 5 litres. Probably as a result of less slush in the lead, the oil spread more evenly and thinly than in Test #1, to about 0.2 cm thick. . . . As the lead closed at about 6 cm/sec, oil was squezzed over the ice on both sides of the lead . . . to a maximum of 20 cm from the edge of the lead. An estimated 0.5 to 1 litre of oil covered the ice. Underwater video and photography showed that some oil was squeezed downward between the ice sheets on impact, then rose again. No oil reached the underside of the sheets. Four to 4.5 litres remained between the ice sheets. Again the oil did not move along the lead.

Test 3
. . . dispersant (Corexit 9550) was sprayed on the oil to investigate any effect

on its behavior. Unfortunately, this test was inconclusive because the large amount of slush remaining in the lead prevented complete closure of the lead.

. . .

Test 4
The oil spread over the lead to a similar thickness as in Test 2. However, the lead closed at twice the rate (12 cm/sec), causing the oil to splash over both sides of the ice to a distance of 30-40 cm from the ice edges all along the lead. An estimated 4 litres was on top of the ice. . . . Underwater photography showed that the impact of the ice sheets coming together forced some oil onto the underside of the ice, although the actual amount was negligible, probably less than 0.1 litre. Visually, this oil appeared as globules of oil scattered as far as 75 cm from the closed lead.

Conclusions

The few tests that were performed indicate that the fate of oil in a lead when two ice sheets come together is a function of the rate of closure of the lead: the higher the rate of closure, the more oil that will spill onto the surface of the ice and the less that will be found between the sides of the two sheets. When a 30 cm ice sheet closed at rates up to 12 cm/sec, very little oil found its way under the ice, although the amount appeared to increase with closure rate. The closing motion of the two ice sheets did not pump oil laterally along the straight lead. Where negative freeboard occurred, greater quantities of oil were deposited on the ice.

. . . .

A major concern, when considering the results of the experiment, is how well the rates of closures used correspond to observed field values.

Dickins, D.F., A. Dickinson, and B. Humphrey. 1986. Pack Ice in Canadian Waters: Dimensions and Dynamics of Leads and Floes. Prepared by DF Dickins Associates Ltd. for the Environmental Protection Service, Environment Canada, Ottawa, Ontario, EPS-EE-82.

This report presents statistics on pack ice conditions in the Beaufort Sea, Lancaster Sound, and the Labrador Sea, including a unique data set on lead motion to examine the the phenomenon of "lead pumping". This data will be discussed here. Lead dimension and motion statistics were collected for 255 leads from satellite and side looking air-borne imagery.

In the Beaufort Sea and Lancaster Sound, leads are the dominant pack ice feature:

> Thick first year floes in these areas are only present for 4 to 6 weeks during break-up offshore. Ice concentrations quickly reduce to the point where there are only scattered floes, which will have limited impact on oil spill behavior.
>
> . . . .
>
> The Beaufort Sea and Lancaster Sound are areas of ice efflux, while the Labrador Sea is an area of significant ice influx. Floes are the dominant feature in the Labrador Sea. Leads only occur temporarily when large floes divide.

Results

Figures 3.15 and 3.16 show percent frequency of occurrence of measured rates of change in lead width. Positive rates signify opening and negative rates indicate closing. Both Lancaster Sound and the Beaufort Sea appear as expanding ice environments, that is openings are favoured over closing by a ratio of 5:1. Peak movement rates encountered during opening events tend to be two to five times higher than rates measured during closings. Lancaster Sound experiences lead opening rates as high as 17 km/day, compared to a peak value of less than 10 km/day measured in the Beaufort Sea. The percent occurrence of closure events is similar for the two regions, but closure rates tend to be higher and more evenly distributed in the Beaufort Sea.

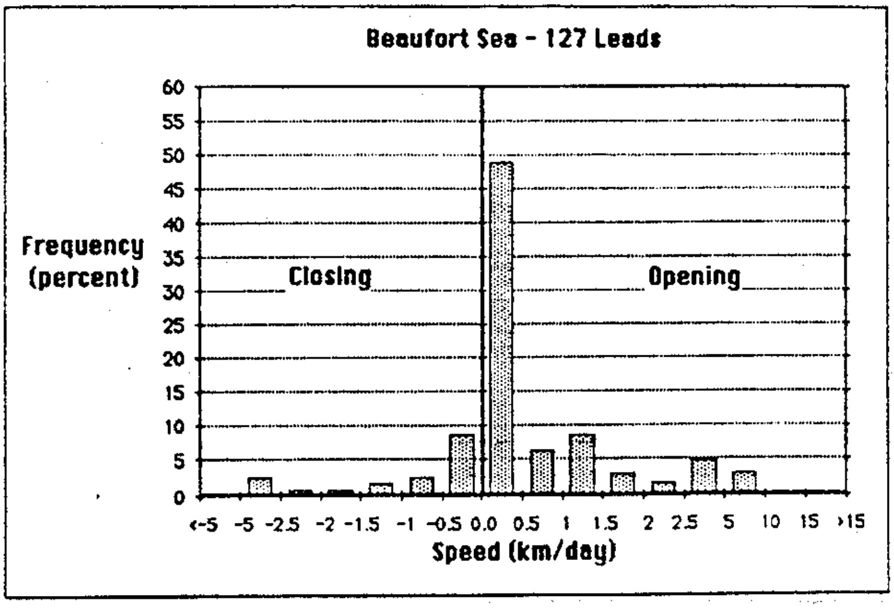


Figure 3.15 **Lead Opening and Closing Rates - Beaufort Sea**

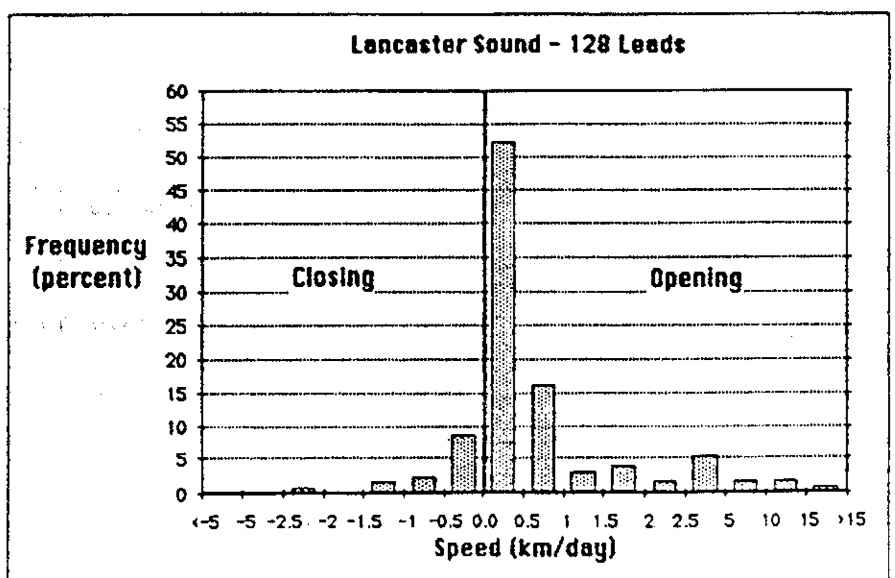


Figure 3.16 **Lead Opening and Closing Rates - Lancaster Sound**

Figures 3.15 and 3.16 clearly show that over 50% of lead motions occur at rates less than 0.5 km/day [0.58 cm/s]. . . . Caution should be exercised in drawing conclusions about instantaneous lead motions from 24 hour displacements. As a first approximation, the average rates of lead openings and closings are less than 20 m/hour [0.55 cm/s].

A unique data set on maximum potential short term lead closure rates is contained in personal observations of ice track closure behind icebreakers. Table 3.3 summarizes findings provided by J.D. Bradford (pers. comm.).

Table 3.3 Icebreaker Track Closure Observations (from J.D. Bradford, pers. comm.)

Location	Date	Ice Thickness (cm)	Closure Rate (m/min)
Barrow Strait	Oct / 73	28	30
Baffin Bay	Apr / 70	121	0.8
N.W. Baffin	May / 70	38	4.6
Lancaster Sound	May / 70	46	15.2
Lancaster Sound	May / 70	152	6.1
Grand Banks	Mar / 71	23	2.1

Lancaster Sound - maximum found in this study 1.73 [2.8 cm/s]
Beaufort Sea - maximum found in this study 2.08 [3.5 cm/s]

Conclusions

The authors make the following conclusions:

Where leads are common, they appear to be expanding more often than contracting. Based on 24 hour ice displacement records, this trend to a diverging ice cover would indicate that lead pumping will not be an important factor affecting oil spill distribution within a pack ice environment in the Beaufort Sea or Lancaster Sound. . . .

Leads closing in a Beaufort Sea pack ice environment invariably lead to the formation of pressure ridges. . . . Any oil which may be pumped up onto the lead edges will be incorporated in the complex block structure of the ridge. Lead pumping effects will then become secondary to the more significant matter of oil incorporation within a deformed ice field.

. . . .

The pulsing ice motions necessary to cause "lead pumping" will more likely be associated with individual floes in an ocean swell, than with leads in an almost continuous ice cover.

5.5 Discussion : Key Processes

The research discussed in the previous sections provides an overview of oil fate and behaviour in broken ice environments. This section provides a summary of the key findings and processes.

5.5.1 Spills of Opportunity

The spills of opportunity demonstrate the behaviour and fate of oil in real situations. The findings from the spills provide a focus for field and laboratory research by identifying processes that are not well understood. They also give researchers an opportunity to verify the results of theoretical and small scale field tests.

It is difficult to directly compare the oil fate and behaviour in the spills of opportunity as oil properties and environmental conditions vary from spill to spill.

In the *Arrow* spill, Bunker C oil was trapped in ice slurries at the edge of the expanding shorefast ice and the oil became incorporated into the crystalline structure of the ice (McLean, 1972). Where the oil was trapped in lagoons the emulsified oil was found to form ice-oil-ice layers.

Wilson and Mackay (1987) concluded that much of the No. 6 oil from the Matane spill was also held in the crystalline structure of the grease ice. Payne (pers. comm.) commented that it was difficult to tell if the JP-5 jet fuel from the *Cepheus* spill became entrained in the grease ice as JP-5 is clear and it evaporated quickly.

Deslauriers and Martin (1978) reported that, in the spill of No. 2 oil in Buzzards Bay, the strong currents transported the oil underneath the ice for large distances. The oil was also dispersed during the opening and closing of leads as the oil flowed under the ice edge as the leads opened or was incorporated into the deformed ice as the leads closed. Oil was also contained in the rafted, ridged, and hummocked ice where, because of its density, the oil rose into the openings in the ice where it was trapped. Winds transported a significant amount of oil from the rafted pools over the ice surface.

The density of the Bunker C oil from the *Kurdistan* spill also resulted in the oil being carried beneath the water surface and under the ice (Reimer, 1980a). The *Kurdistan* spill also showed the importance of brash ice in controlling the fate of oil. In one area, half of the oil was mixed in the brash ice as small particles, and the other half was found on the floe surfaces.

The shorefast ice found in most of the spill situations protected the shorelines from oil contamination, at least until the shorefast ice melted and oiled floes were stranded on the beach.

5.5.2 Oil Behaviour in Developing Ice

Surfacing of Oil in Grease Ice and Slush

Martin et al. (1976) found that both diesel and Prudhoe Bay crude oil surfaced quite readily and that very little oil was to be found under the ice. Metge and Telford (1979) found that only a slight agitation was necessary to promote percolation of crude oil up through slush. Wilson and Mackay were able to prevent surfacing of the oil and promote incorporation into the grease ice by cycling a metal hoop through the ice surface twice per second and by lowering the density differential between oil and ice by using freshwater ice. Wilson and Mackay also found that surfacing of oil was decreased with emulsification of the oil. Buist et al. (1987a) also found that increased wave action decreased surfacing of the oil.

Observations of oil incorporation into grease ice in field tests and spills of opportunity are almost non-existent, with the exception of the Matane spill.

Horizontal Spreading of Oil in Grease Ice and Slush

Martin et al. (1976) calculated an average slick thicknesses of 1 mm for diesel oil in a mixture of pancake and grease ice.

Several researchers (Metge and Telford, 1978; Buist et al., 1987a) describe mixtures of oil and slush as more viscous that either component and effectively containing the oil. Oil spreading freely in a lead was observed by Buist et al. (1987a) to stop when the oil encountered a concentrated edge of ice crystals. Buist et al. (1987a) found that the oil spread rapidly in slush under wave action.

Oil Behaviour in Pancake Ice with Waves

Martin et al. (1976) and Metge and Telford (1979) found that the combination of wave action and raised rims of pancake ice were able to trap significant quantities of oil onto the ice. In one test, Martin et al. found that oil on the ice exceeded 50% of the total, although the artificial containment of the oil by the test tank exaggerated the oil behaviour. Metge and Telford (1979) observed that the pumping action of the floes, and transferring of oil from floe to floe, increased the oiled area.

In the field, oil was only observed on occasional floes by S.L. Ross and DF Dickins (1987) in a experimental spill in pack ice, whereas in the *Kurdistan* spill, half the oil was on the ice in some areas.

Oil Incorporation of Snow

Snowfalls occurred during two of the outdoor tests. Scott (1973) noted that the snow passed through the oil and formed ice underneath it. Buist et al. (1987a) found the the snow and the oil mixed to form a slush.

5.5.3 Broken Ice

In the Arctic broken ice environments (5-8/10 concentration) are typically found as pack ice is converging or diverging under the influence of winds and currents. Broken ice environments usually last at most several weeks to a month in the Arctic, although they may survive longer in other areas.

Few studies have addressed the problem of oil in broken ice. Free et al. (1982), in laboratory tests, found that the ice concentration, when large enough, could confine oil and result in a slick thickness much higher than the open water equilibrium thickness. Free et al. (1982) developed several equations for ice velocity under the effect of oil and current (wind < 5 m/s).

Tebeau et al. (1984) attempted to verify the results of Free et al. They noticed the same trend in confinement of the oil in high concentrations (about 7/10 ice concentration for Prudhoe Bay crude oil). However, they concluded that equations for oil spreading based on their results or those of Free et al. (1982) would likely have little applicability to the Arctic environment. Both laboratory tests used small ice pieces sizes and correspondingly small gap widths (on the order of 1 cm or less) between ice pieces, whereas large ice pieces with large gap widths would be found in the Arctic.

The most suitable equations for oil spreading in broken ice are given by S.L. Ross and DF Dickins (1987). They present a modified Fay equation that models the containment provided by the ice. Their results are based on a small spill in pack ice.

S.L. Ross and DF Dickins also provide the best equations to date for oil spreading in brash ice: a combination of the modified Fay equation (for broken ice) and Kawamura's predictions for oil spreading in snow. As in the *Kurdistan* spill, brash ice was found to be very effective at confining the oil. More field studies or observations from spills of opportunity are required to verify their results.

5.5.4 Lead Closure

The idea of "lead pumping" has often been proposed in the literature as a mechanism for dispersing oil onto ice surfaces. MacNeill and Goodman (1985) conducted large-scale laboratory tests to determine the rates of lead closure necessary to cause oiling of the lead edges. They found that as closure rates increased from 6 cm/s to 12 cm/s the amount of oil spilled onto the surface of the ice increased.

Dickins et al. (1986) examined satellite and air-borne imagery to determine 24 hour lead closure rates. In the Beaufort Sea and Lancaster Sound, where leads are the dominant pack ice feature, the leads seem to be opening more often than closing. They found that 50% of lead motions occurred at rates less than 0.5 km/day (0.6 cm/s) and the maximum lead closure rate was about 3 km/day (3.5 cm/s). Although higher instantaneous lead closure rates have been observed in ship track closures, Dickins et al. (1986) concluded that "lead pumping" is unlikely to be an important mechanism in dispersing oil in these environments. Rather, any oil that may be spilled on the ice surface will be incorporated into the deformed ice as ridges are formed.

In the Buzzards Bay spill, Deslauriers and Martin (1978) reported that oil in the leads was either carried under the ice edge by the strong currents when the leads opened or incorporated into the deformed ice as the leads closed. Oil was transported over the ice surface by wind action from pools of oil found in rafted ice.

6.0 OIL BEHAVIOUR ON SNOW AND ICE

The bulk of field and laboratory studies investigating the fate and behaviour of oil and ice have focused largely on scenarios that exclude significant oil/snow interactions. There have been, however, a number of studies which consider surface oil spill processes on, through and under snow with ice as a substrate. These studies include field test programs, theoretical derivations of driving and resistance forces and spills of opportunity.

The first studies examining the fate and behaviour of oil interactions with snow, began in the early 1970's. McMinn, 1972 developed a comprehensive set of process equations fashioned after Fay's (1969) theory of oil spreading over water. Mackay et al. (1975) investigated both hot and isothermal spills on snow providing data on oil penetration processes. The accidental spill of diesel fuel at Nome, Alaska provided qualitative information on the ability of snow to contain oil (Allen,1978). Izmaylov (1980) investigated the effect of oil spills on the albedo of snow covered ice and observed the influence of oil on snow melt. Kawamura et al.(1986) developed a general spreading model based on a series of small-scale chemical spills on both ice and snow. Further field testing and theoretical development were conducted by Belore and Buist (1988) resulting in a definitive work on the modelling of oil spills in snow. Bech and Sveum (1991) conducted five experimental spills and identified a primary and secondary spread area based on split oil distribution.

The key papers that address the topic of oil on snow/ice surfaces are reviewed in the following sections. These papers were divided into three subtopics. These subtopics are as follows: (1) Theoretical Studies Involving Field Test Verification, (2) Field Studies, and (3) Spills Of Opportunity. This chapter closes with a separate section summarizing limitations of the studies to date and suitability of the process equations presented.

6.1 Theoretical Studies Involving Field Test Verification - Literature Review

McMinn, LTJG T.J. 1972. Crude Oil Behavior on Arctic Winter Ice: Final Report. Environmental and Transportation Technology Division, Office of Research and Development, United States Coast Guard, Project 734108, Washington, D.C., NTIS Publication No. AD-754, 261 p.

This paper describes a series of field experiments designed to investigate the spreading of oil on snow and ice surfaces. Other papers include McMinn and Golden (1973) and Chen (1972). The most comprehensive of the three papers is McMinn (1972). A large portion of this paper is devoted to the development of a simplified theory to explain the mechanics of oil spreading under Arctic conditions. The theory section from McMinn's paper contains a thorough treatment of process equations developed from first principles and is therefore presented almost entirely intact.

McMinn writes

> The purpose of this experiment is to examine theories developed for oil spreading over ice and snow and to compare these theories with spreading data taken in the field. In this regard the experiment attempted to prove that oil spreading on snow/ice can be accurately predicted and that spreading rate and ultimate pool size are independent of oil properties and ambient air temperature. . . .
>
> . . . A total of four spills were made for the purpose of analyzing oil spreading. Three of the spills were made on the snow surface (sea ice surface covered by a snow thickness of approximately 20 cm). . . . The fourth spill was made on the lake ice surface . . . In each case the oil used was North Slope produced crude oil at a temperature of 58°F.

Theory

> According to Fay, oil spreading on water is controlled by four physical phenomena; gravity, surface tension, inertia, viscosity. Initially, the oil driving

force is due primarily to gravity generated pressure. Since pressure acts in all directions from a single point, forces due to this gravity pressure tend to force the oil outward from the center in all directions. Hence the force due to gravity (Fg) equals:

Gravity Equations

$$F_g = \int_0^h P\,dA$$

where $P = \rho g h$ and $A = 2\pi rh$

$dA = 2\pi r dh$

therefore

$$F_g = 2\pi\rho g r \int_0^h h\,dh$$

$$F_g = r\pi g h^2 \qquad (1)$$

(Note: Definition of symbols at end of this review)

Surface Tension Equation

The point at which surface tension forces begin to control spreading is the point where the force due to gravity equals the force due to surface tension. The spreading force due to surface tension (F_s) equals:

$$F_s = \sigma_r (2\pi r)$$

where σ_r the resultant surface tension vector when oil interfaces an ice surface and $2\pi r$ is the circumference of the oil pool. Equating the surface tension force and the gravity forces: $F_s = F_g$, we get:

$$\sigma r(2\pi r) = \pi r \rho g h^2 \qquad \textbf{(1.1)}$$

We now solve equation 1.1 for the thickness (h) of the oil at the instant $F_s = F_g$. We shall call this thickness the critical thickness (h_c). The critical thickness (h_c) where surface tension forces begin to dominate spreading is therefore: **(2)**

$$h_c = \sqrt{\frac{2\sigma_r}{\rho g}}$$

Hence in summarizing the positive oil spreading forces we find the following sequence:

(1) Gravity forces dominate spreading until $h = h_c$;
(2) At h_c, $F_s > F_g$ and surface tension forces dominate.

A similar situation is found when investigating the forces responsible for retarding the spreading of oil. The primary oil spread retarding forces are due to an inertial deceleration force and a viscous drag force.

Inertial Force Equations

Let us first consider the inertial forces. Inertia (F_i) is a retarding force that by definition equals mass x deceleration. For our purpose:

$$F_i = m\,dv/dt \quad \text{where} \quad m = \pi r^2 h \rho \quad \text{and} \quad v = r/t$$

$$\text{hence } F_i = \frac{\pi r^2 h \rho r}{t^2} \tag{3}$$

$$F_i = \frac{\pi \rho r^3 h}{t^2}$$

Viscous Force Equations

The viscosity forces (F_u) are essentially friction forces due to the deformation of horizontal layers of the oil. The dynamic viscosity of the oil (**u**) is by definition the ratio of the shear intensity to the rate of deformation (**dv/dh**). We represent this by:

$$u = \frac{\tau}{dv/dh} \quad \text{where} \quad \tau = F_u/\pi r^2$$

$$\text{and} \quad dv/dh = v/h$$

for our purposes: $v = r/t$

$$\text{so} \quad v/h = r/ht$$

Our definition of viscosity now becomes: (4)

$$u = \frac{F_u h t}{\pi r^2}$$

Solving for viscous drag, we obtain:

$$F_u = \frac{\pi u l^3}{th}$$

If we examine the inertia to viscous force ratio, $\rho h^2/ut$ we see that this ratio, for a particular oil, increases as h^2/t increases. It is evident from the 1/t relationship that initially, or when time is small, inertial forces dominate the retarding forces and as time increases and the inertial/viscous ratio becomes smaller, viscous forces dominate retarding forces.

Application of Theory to Field Experiments

In the field tests conducted for this study, the oil was slowly released from an insulted oil storage tank. This release condition was selected in order "to simulate a broken pipeline or a slowly leaking surface vessel (ship, barge, etc.)".

Therefore it is convenient and accurate for us to represent the total volume of oil spilled by:

$$\text{total volume} = V_t = \bar{Q}\,(t) \qquad (5)$$

Where $\bar{Q}$ represents the average flow rate and t the total time of oil discharge. The total volume (V_t) also equals:

$$V_t = \pi r^2 h \qquad (6)$$

Equating the two volumes and solving for (r) we obtain: (7)

$$r = \sqrt{\frac{\bar{Q}t}{\pi h}}$$

A term, one we shall call "effective roughness height" or z_o is now introduced. z_o is a quantification of effective snow/ice roughness height that it affected by: 1) surface roughness; 2) ice permeability and porosity; and 3) viscosity of the fluid (oil). . . .

Noting equation (7) and considering the definition of z_o, we draw the conclusion that spreading will cease when h (oil thickness) $\approx z_o$ (effective roughness height). Substituting z_o for h and renaming r to r_{max}, equation (7) becomes:

$$r_{max} \approx \sqrt{\frac{Qt}{\pi z_o}} \tag{8}$$

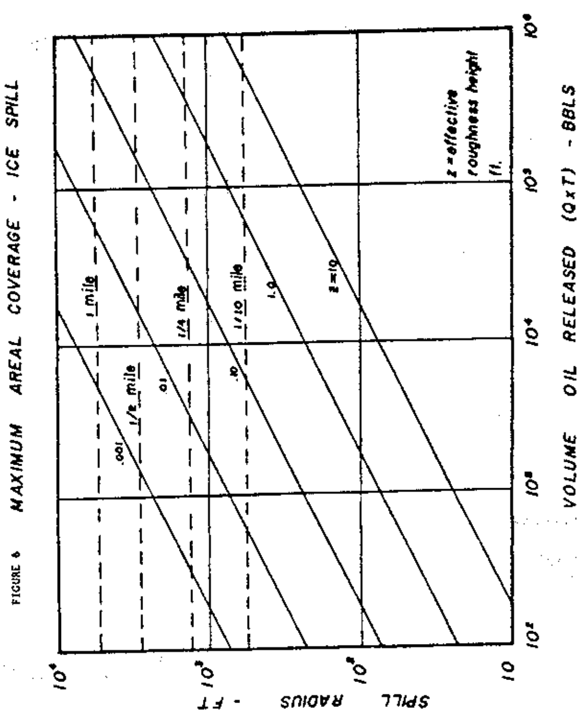
This equation is plotted in Figure (6) over a range of roughness heights. From this figure a reasonable prediction of terminal pool radius for a given flow rate, time, and z_o can be made. . . .

. . .our determination that the lower limit of z_o is approximately 0.1 ft allows us, at this time, to predict the maximum area a spill of a given volume would ultimately cover.

. . . Examining equation (2) we see that the transition point from gravity to surface tension spreading occurs when the oil diminished to a critical thickness (h_c) of:

$$h_c = \sqrt{\frac{2\sigma_r}{\rho g}}$$

Figure 6



(Note: the surface tension σ_r is the resultant surface tension vector when oil is spreading on an ice surface)

We will now attempt to solve for h_c using representative values of ρ (density) and σ_r (surface tension) obtained for the Prudhoe Bay test crude. A density of 0.890 gm/cc will be substituted for ρ. The resultant surface tension σ_r is calculated as being:

$$\sigma_r = \sigma_r(1 + \cos\theta) \tag{9}$$

where θ equals the oil contact angle. For a contact angle of 45° and an oil surface tension of 30 dynes/cm (measured value of Prudhoe Bay Crude):

$$= 30\ (1 + \cos 45^\circ) = 30\ (1.702) = 51 \text{ dynes/cm}$$

Using the above mentioned values of ρ and σ_r and 980 gm/sec^2 as the acceleration due to gravity (g):

$$h_c = \sqrt{\frac{2x51}{.89x980}} = .342cm$$

From this calculation we can predict that gravity spreading forces will dominate positive spreading forces until an oil thickness of approximately one-third cm is reached. However, as we previously stated in our analysis of terminal spreading limits, oil spreading will cease when $h = z_o$, which has been determined to range down to an oil thickness of approximately 3.04 cm. . . .

It can easily be seen that h will never reach the critical thickness necessary for the transition from gravity to surface tension spreading forces. It can safely be predicted then, that gravity forces are the only significant contributors to positive oil spreading over ice forces and that spreading terminates prior to entering the surface tension spreading regime.

Since the final thickness of an oil spill on ice is quite large when compared to an oil spill on water, and as previously discussed the ratio of inertia to viscous retarding forces vary as h^2, we can also make the assumption that viscous retarding forces are negligible contributors to the resultant retarding force. Neglecting, then, the surface tension spreading forces and the viscous retarding forces, our discussion leaves us with only gravity spreading forces (eq.1) and inertial retarding forces (eq.3) affecting the spreading of oil on ice. Equating the gravity spreading and inertial retarding forces we obtain:

(10)

$$\pi r \rho g h^2 = \frac{\pi \rho r^3 h}{t^2}$$

Again depicting the volume (V) of spilled oil as:

$$V = \bar{Q}t = \pi r^2 h$$

and solving for thickness (h) to obtain: (11)

$$h = \frac{\bar{Q}t}{\pi r^2}$$

allows us to represent the oil thickness (h) in terms of average flow rate ($\bar{Q}$), time (t), and spill radius (r).

Substituting **h** (eq. 11) in equation (10):

$$\pi r \rho g(\bar{Q}t/\pi r^2)^2 = \frac{\pi \rho r^3(\bar{Q}t/\pi r^2)}{t^2}$$

and solving for radius (r) we obtain: (12)

$$r = .756(g\bar{Q})^{1/4} t^{3/4}$$

We conclude therefore, that oil spreading over ice will progress as a function of time and flow rate as described in equation (12) until oil thickness reaches effective roughness height where spreading stops.

Experimental Results and Conclusions

Spreading rates obtained from field data were non-dimensionalized and plotted against theoretical values in Figure 7.

> As can be seen from Figure [7], the slope of the experimental data is less than that predicted by the simplified theory. . . . The equation of the field data Figure [7] can be duplicated by the following equation:
>
> $$r = 1.3\ (Q^3 g)^{-1}\ T^{1/2}$$

Figure 7   Spreading Rate - Winter Ice

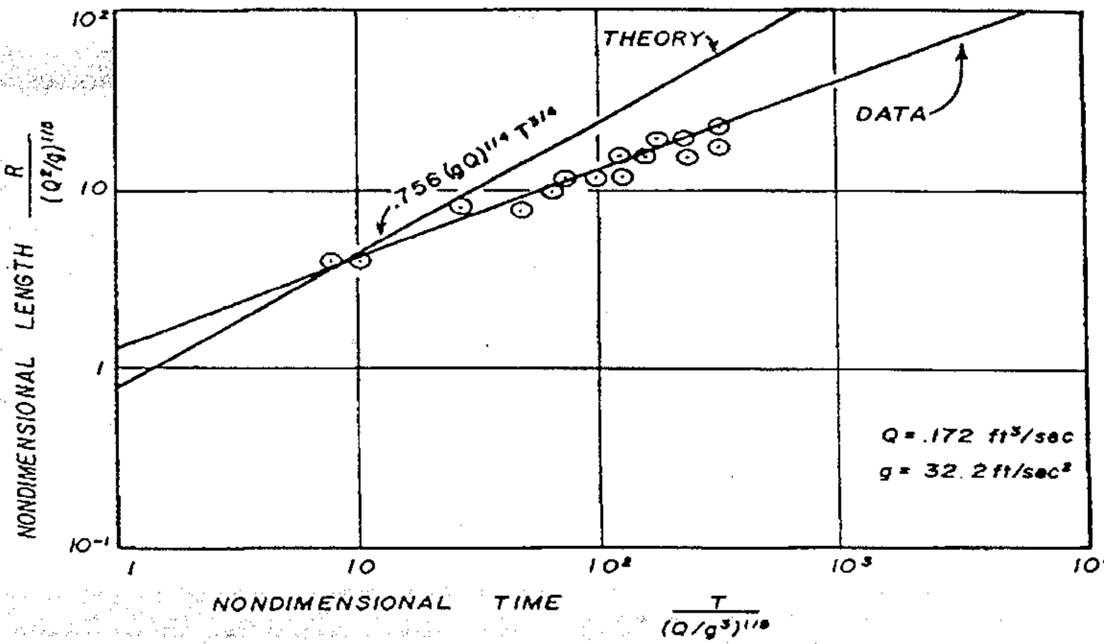


Figure 6: Spreading Rate – Winter Ice.

. . . To some extent the discrepancy between theory and experiment is within the range of experimental error, of greater significance is the fact that the experimental results validate the theoretical assumption that only gravity and inertia forces must be considered when predicting spread rate. . . .

. . . Had surface tension or viscous forces contributed significantly to spreading, the data plot would be expected to be composed of two straight lines of different slopes.

Oil Interaction

When oil is first subjected to or "spilled" over the ice/snow surface there is very little migration of the oil down the ice column. . . .

. . . From a cursory examination one would expect the warm (60°F) oil to move, by gravity and capillary forces, down through ice/snow pore channels. However, penetration of oil into the surface did not occur to any substantial degree.

. . . The reasons for the lack of penetration into the surface by the oil is theorized as follows.

. . . Immediately after the 60°F oil hits the surface a temperature differential of ~70°F is created. The warm oil immediately causes an increase in temperature and subsequent melting of a thin surface layer of snow/ice. The melted snow/ice (water) moves, by gravity and capillary forces, down the snow/ice column a distance on the order of 2 mm where the water refreezes thereby blocking downward movement of oil.

Effects of Blowing Snow

Fresh snow blowing across the oil tends to stick and migrate downward into the oil. . . . By taking samples and separating the two phases, the mixture was determined to contain up to 80% (by volume) snow. . . .
The mixture was quite dry in appearance as long as the temperature remained below the pour point (+15°F)of the oil; however, as the temperature increased above the pour point, the oil within the mixture became more fluid and would physically flow out of or drip from the snow/oil mixture.

Effects of Heavy Falling Snow

. . . it appeared that a heavy snow did not affect the oil as greatly as did the blowing snow. A heavy snow fall resulted in a rapid accumulation of snow upon the surface of the oil which was believed to become compacted at the upper snow/oil interface. It is theorized that this compaction reduced the volume of snow infiltrating the oil.

LIST OF SYMBOLS

A_t	-	total area
d	-	diameter of oil slick
F_i	-	force due to inertia
F_g	-	force due to gravity
F_s	-	force due to surface tension
F_u	-	force due to viscosity
h	-	thickness
h_c	-	critical thickness
g	-	acceleration due to gravity
Q	-	oil flow rate
$\bar{Q}$	-	average oil flow rate
ρ	-	density
r	-	radius of oil slick
r_m	-	maximum radius of oil slick
σ	-	surface tension

σ_r	-	resultant surface tension
θ	-	contact angle
t	-	time
t_m	-	maximum time
V	-	volume
z_o	-	effective roughness height
$f(t)$	-	is a function of time
$f(z_o)$	-	is a function of z_o

Chen, E.C., J.C.K. Overall and C.R. Phillips. 1974. Spreading of Crude Oil on an Ice Surface. Canadian Journal of Chemical Engineering, Vol 52, pp 71-74.

Chen et al. conducted a series of experiments using five crude oil types split on three different surfaces. The primary objective of this study was to develop a process equation capable of accurately estimating the spreading rate of oil and the extent of oil spreading on an ice surface.

Using the same initial equations mentioned by Fay (1969), and implemented by McMinn (1972), Chen et al. developed a complete equation for gravity-viscous spreading for oil spreading on an ice surface. The equation considers viscosity change over time due to the aging of oil. This equation is as follows:

$$\frac{R}{V^{1/3}} = K(t\rho g V^{1/3}/\mu)^{1/5} + C$$

Where:

R = Radius of the oil slick (cm)

V = Volume of oil (cm^3)

K = Constant, dimensionless

t = time (sec)

ρ = density of oil (g/cm^3)

g = acceleration of gravity (980 cm/sec^2)

μ = viscosity of oil (poise)

C = Constant, dimensionless

Three artificially prepared ice surfaces were created each with a different surface roughness (i.e., p = 0,0.15,0.34). Five crude oil types were poured onto these surfaces and the spreading processes of the oil/ice interactions were observed.

Results and Conclusions

Bases on the results obtained, the following conclusions may be drawn for the gravity-viscous spreading of crude oil on ice:

(1) The radius of the oil slick, **R**, increases linearly with $(t/\mu)^{1/3}$, the slope being $K(\rho g V^2)^{1/3}$. In dimensionless form, $(R/V^{1/3})$ is proportional to the non-dimensionalized group, $(t\rho g V^{1/3}/\mu)^{1/3}$, with constant **K** equal to 0.24.

(2) The effect of surface roughness on the gravity-viscous spreading may be considered to be insignificant.

(3) A change in oil volume does not affect the correlation of spreading.

(4) In the temperature range studied, i.e. from -3 to -14 C, the effect of temperature on spreading can be accounted for by changes in viscosity, μ.

Siu, S.K., C.R. Phillips, and E.C. Chen. 1977. The Continuous Spilling of Hot Oil on Ice. Journal of Canadian Petroleum Technology, January-March, 1977, Montreal, pp 31-34.

A number of small-scale laboratory spills were conducted using heated crude oil. This work considers the scenario of a hot oil pipeline rupture resulting in a continuous non-isothermal spill on an ice surface. This study investigates hot oil spreading on an ice surface considering oil temperature, ice temperature and spill rate as key parameters controlling the oil/ice spreading processes.

Slick area is expressed as a function of elapsed time as follows:

$$A = \left(\frac{k\rho g\pi^{1/2}Q^2t^3}{\mu}\right)^{2/5} = K\nu^{-0.4}Q^{0.8}t^{1.2}... \qquad (5)$$

Where: $K = (kg\pi^{1/2})^{2/5}$

A = slick area, cm^2

g = gravity, 980 cm/sec^2

k = dimensionless constant

Q = spilling rate, ml/sec

t = elapsed time, sec

μ = viscosity of oil, poises

υ = kinematic viscosity of oil, stokes

ρ = density of oil, g/cm^3

Norman Wells crude oil was heated to an approximate temperature of 60° C and spilt at a constant rate onto artificially prepared ice. Careful measurements of oil temperature after release, oil viscosity and density, and oil spill radius were made during the course of the spills.

Results and Conclusions

Based on the results obtained, the following conclusions may be drawn:

(1) for continuous spilling of hot oil on ice under the conditions of the experiments, the oil slick area is proportional to elapsed time to the power 0.8;

(2) oil slick area increases with both oil and ice temperature;

(3) if the geometric mean of the oil and ice temperature is chosen as the representative temperature T_g, the oil slick area under the conditions of the experiments is proportional to $\exp(-0.2B/T_g)$;

(4) in the experiments, the increase of the oil slick area, A, with the spilling rate, Q, is not linear - A is proportional to $Q^{0.7}$.

Kawamura, P., Mackay, D. and M. Goral. 1986. Spreading of Chemicals on Ice and Snow. Environment Canada, EETD, Report No. EE-79, Ottawa, Ontario.

The objective of this study was to quantitatively determine the spreading behaviour of various chemicals spilt on snow and ice surfaces. Although the study does not consider crude oil or diesel fuel, its contribution to knowledge with respect to oil on/in/under snow is the theoretical development of process equations resulting in a general spill model.

Background Theory

> It has been established by several workers, such as Fay (1969) that the spreading process can be divided into three distinct stages. In each of these stages, one spreading force is balanced by one retarding force. The three stages are: gravity-inertia, gravity-viscous, and surface tension-viscous. . . . The third stage of spreading is the most complicated and least understood. In this stage, the spreading rate is determined by the combination of chemical-air, chemical-solid, and solid-air interfacial tensions, as well as the chemical viscosity, the nature of the solid surface (eg. the type of solid and its roughness), the rate of evaporation of the chemical and wind speed.
>
> These three interfacial tensions combined with the viscous force producing a net spreading force of:
>
> $$\Delta\sigma = \sigma_i-(\sigma_{ic}+\sigma \cos \theta)$$
>
> where $\Delta\sigma$ is the net spreading force, σ_i is the air-solid interfacial tension, or the solid surface tension; σ_{ic} is the liquid-solid interfacial tension, and a is the liquid-air interfacial tension, or the liquid surface tension; and θ is the contact angle. The contact angle is the angle at which the chemical contacts the ice surface. The magnitude of this angle depends on the relative values of the three interfacial tensions.

Development of General Spill Model

> In this model, a basic area-time relationship is proposed of the form:
>
> $$A = A_f\ (1-\exp(-(t/\gamma)x))$$
>
> where A is the area, A_f is the final area at infinite time (t) and γ and x are

constants. Regardless of the value of **x**, the area is 63% of the final area when t equals γ. γ is thus a "spreading time constant". Increasing **x** slows down the initial spreading and accelerates the later spreading. It controls the slope of the A-t graph when **t** equals γ, a large value of **x** giving a large slope.

The final area, A_f, is estimated from the initial spill volume (V), the volume change (until spreading stops) due to evaporation, absorption, etc. (ΔV), and a final equilibrium spill depth on the surface (h_f), such that

$$V - \Delta V = A\, h_f$$

ΔV is estimated as the algebraic sum of three terms:

Loss due to evaporation $= h_e\, A_f$
Loss due to absorption in soil $= h_a\, A_f$
Gain due to dissolution of snow $= h_s\, A_f$

Therefore, $\Delta V = A_f\, (h_e + h_a - h_s)$

In all cases the **h** terms represent mean values which apply at the time of cessation of spreading.

. . .

The final equation is:

$$A = \frac{V(1-\exp(-(t/\gamma)^x))}{h_f + [C_e K_e (P_v/RT) + C_a K_a]\gamma - \Phi H_s}$$

The advantage of this equation is that it is simple and contains terms for absorption, evaporation, and snow or ice dissolution. The constants which must be determined by experiment are as follows:

- γ spreading time constant, which is expected to be primarily a function of viscosity
- x slope term
- C_a absorption constant
- C_e evaporation constant
- h_f final spill thickness which is expected to depend on the surface, viscosity and interfacial tension.

The terms K_a, P, V, T, K_e, ϕ, and H_s can be estimated directly from spill conditions and chemical properties, and are not adjustable.

The spreading time, t_f is:

$$t_f = (4.605)^{1/X}\,\gamma$$

Spill Experiments and Results

A variety of small-scale spills were conducted using various chemicals. Results from these experiments provided the constants needed to complete the final practical equations.

Results from the chemical spills on an ice sheet yield the following final equations used to predict final spill area:

$$\frac{\gamma V^{1/6}}{g^{.5}} = 2.5E\text{-}05\,\frac{V^{7/6}\mu^{.5}\rho_c^{1.625}g^{1.875}}{\sigma^{2.125}}$$

and the spreading time constant:

$$\frac{A_f}{V^{2/3}} = 6.0\,\frac{V^{.18}\rho_c^{.33}g^{.21}}{\mu^{.24}\sigma^{.09}}$$

Results from the chemical spills on snow-covered ice surface yield the following final equation used to predict final spill area:

$$\frac{A_f}{V^{2/3}} = 0.45\,\frac{V^{.2}d^{.2}\rho_c^{.8675}g^{.4125}\mu^{.05}}{(\varphi\rho_s)^{.48}\sigma^{.4375}}$$

and the spreading time constant:

$$\frac{\gamma V^{1/6}}{g^{.5}}=0.18\frac{V^{.62}d^{.6}\rho_s^{1.1}\mu^{.78}g^{1.425}}{\rho_c^{.065}\sigma^{1.815}}$$

where:	g	gravitational constant
	μ	chemical viscosity
	ρ_c	density of chemical
	σ	liquid surface tension
	φ	snow density parameter
	ρ	density of snow

> . . . The extent and the rate of subsurface spreading in snow media is significantly smaller and slower than for a corresponding spill on an ice surface. . . . The final spreading time can be approximated to be 8 times the time constant. The key variables required for these correlations are: chemical viscosity, spill volume, snow depth, density and crystal type.

Belore, R.C. and I.A. Buist. 1988. Modelling of Oil Spills in Snow. Proceedings of the Eleventh Arctic and Marine Oilspill Program Technical Seminar, pp 9-29.

The project is also reported in S.L. Ross and DF Dickins (1988). These two papers (essentially identical) describe "the development of process equations to predict the fate and behaviour of oil spills on land or ice in or under snow." Small and mid-scale testing of the fate and behaviour of oil in snow were conducted including:

(1) Small-scale evaporation studies

(2) Mid-scale spreading and evaporation studies

Small-Scale Evaporation Studies

> Pyrex baking trays containing 1 cm of oil initially filled to various depths with snow were placed in an exposed location near Woodlawn, Ontario for two weeks in February. . . .
> Evaporative loss was determined periodically by recovering small (20 ml) samples of oiled snow from the bottom of each tray, carefully melting and decanting the water phase. . . .

Mid-Scale Spreading and Evaporation Studies

> Two test spills of about 200 L each of MSW [Mixed Sweet Western] crude were conducted from catwalks above the snow. The oil was released into the snowpack (spill #1 virgin snow, spill #2 densified snow) at the centre of each test area and its spreading along four radii monitored by timing the appearance of oil in the bottom of bore holes spaced 30 cm apart. . . . Oil samples were collected and analyzed as described above to determine evaporation rates. . . .

Theory of Spreading of Oil on Snow

> The theoretical spreading model is based on a balance of forces per unit volume of oil, as used by Fay (1969) in analyzing oil spreading on water, modified to reflect the physical situations of oil on snow or ice. The three forces involved in the spreading are gravity, viscous and inertia, the first being a driving force and the latter two resistances. Surface tension forces are neglected since oil on ice or snow inevitably ceases spreading at thicknesses (on the order of 5 mm) much greater than those at which surface tension

forces become dominant. The forces can be defined as:

	Continuous Source	Instantaneous Spill
Gravity	$= \rho g\, Qt/r^3$	$= \rho\, gV/r^3$
Viscous	$= \rho\, \nu^{1/2}\, \pi\, r^3/Qt^{5/2}$	$= \rho\, \nu^{1/2}\, \pi\, r^3/Vt^{3/2}$
Inertia	$= \rho\, r/t^2$	$= \rho\, r/t^2$

where ρ = oil density (kg/m^3)
g = gravitational acceleration (m/s^2)
Q = oil flowrate (m^3/s)
V = oil volume (m^3)
t = time (s)
r = spill radius (m)
ν = kinematic viscosity of oil (m^2/s)

Equating the driving force to each of the resistances yields the equations that define the two spreading regimes for oil on snow or ice:

	Continuous Source	Instantaneous Spill
Gravity-Inertia	$r = (gQ)^{1/4}\, t^{3/4}$	$r = 1.5\, (gV)^{1/4}\, t^{1/2}$
Gravity-Viscous	$r = (gQ^2/\pi\nu^{1/2})^{1/6}\, t^{1/2}$	$r = (gV^2/\pi\nu^{1/2})^{1/6}\, t^{1/4}$

Belore and Buist, 1988, compared continuous source data of McMinn and Golden (1972) and Glaeser and Vance (1971) for the two spreading regimes.

> Although the data fit is not perfect, the trend certainly indicates that spreading of continuous oil releases on snow or ice occurs primarily in the gravity-viscous regime. . . .
>
> . . . In summary, the spreading of oil on snow or ice for a continuous source or instantaneous spill can be adequately modelled by the equations given for gravity-viscous spreading.

Theory of Infiltration of Oil into Snow

The flow of liquids through a permeable media is governed by the D'Arcy equation which can be written as:

$$Q = KA\Delta P/\mu L$$

where K = specific permeability of snow (m^2)

A = flow area (m^2)

L = flow path length (m)

ΔP = pressure driving force along flow path (Pa)

μ = dynamic viscosity of fluid (Pas)

Following the derivation of Mackay et al. (1974) for flow into snow beneath a surface spill:

for $\Delta P = \rho g\ (x+L)$ where x = thickness of oil on snow (m)

$$Q = KA\rho g\ (1+x/L)\mu$$

and the linear rate of penetration of oil into snow is:

$$dL/dt = (K\rho g/E\mu)\ (1+x/L)$$

where E = void fraction of snow

= porosity

= $1-\rho_s/\rho_i$

ρ = snow density (kg/m^3)

ρ = ice density

= 917 kg/m^3

The major unknown in these equations is **K**, the specific permeability of snow which is a function of snow density, crystal size and age. A simple equation for specific permeability is presented in the next section.

Theory of Horizontal Flow of Oil in Snow

The horizontal flow of oil in snow at an impermeable layer was modelled as follows, beginning with the D'Arcy equation rewritten as:

$$L = KA\Delta P/\mu Q$$

substituting A $= 2\pi Lh$,

V $= Qt$,

h $= V/E\pi L^2$,

and ΔP $= \rho gh = \rho gV/E\pi L^2$

where h = height of oil layer in snow (m)

yields $L = (2K\rho gV / \pi E^2\mu)^{1/4}\, t^{1/2}$ for an instantaneous spill, or
similarly $L = (2K\rho gQ / \pi E^2\mu)^{1/4}\, t^{1/2}$ for a continuous release.

Specific Permeability of Snow

Shimizu (1969) has shown that the specific permeability of snow may be adequately determined from:

$$K = 7.7 \times 10^{-2}\, d_o^2 \exp(-7.8\, \rho_s/\rho_i)$$

where d_o = mean grain size of snow (m)

For situations where snow properties are unknown, the permeability can be estimated to within a factor of 2 by using d_o = 0.5 mm and ρ_s = 400 kg/m to yield:

$$K = 6 \times 10^{-10}\ m^2$$

This is a reasonable approximation since K appears to the power 1/4 in the equation for horizontal flow in snow, and thus a margin of error in **K** of 200% translates to an error of less than 20% in **L**.

Mackay et al. (1974) experimentally determined K for snow with a variety of oils. Their results ranged from 1.5 to 7.8×10^{-10} m^2.

Experimental Results

Results from the mid-scale experiments were compared to the theoretical models.

Although there is considerable scatter, the theory for spreading of an instantaneous release (i.e., equation with V) fits the data, after a time of 150s (the oil release time), reasonably well. The theory for spreading of a continuous source, although it approximates the data in the time period up to 150s, does not appear to have the correct slope. This may be due to the fact that the oil was warm (8°C) when poured and could have melted the snow as it spread until it cooled to below 0°C.

Experimental data along with spill data from Mackay et al.(1974) were compared to the instantaneous release model in a non-dimensional format.

> With the exception of the data collected during the discharge (up to a non-dimensional time of about 5000) the model fits the data reasonably well. . . .

Experimental results from the small-scale evaporation of oil in snow indicated that the unpacked oil/snow mixture had the highest evaporative loss.

> At first glance the results from the mid-scale tests seem anomalous; however, it must be kept in mind that the temperature during the mid-scale tests (-3°C) was much higher than during the small-scale tests (-17°C), thus the mid-scale tests could be expected to experience more rapid evaporation.

At the time of writing, the oil transport by blowing snow experiment had not been completed.

Determination of the Snow Mass Transfer Coefficient

Using the evaporative exposure approach of Stiver and Mackay (1982) where:

$$F_v = (T/10.3\ T_G)\ln(1 + (10.3\ T_G/T)\ \theta\ \exp\ (6.3 - 10.3\ T_O/T)$$

and $\theta = kAt/V = kt/x$

where

F_v	= volume fraction evaporated
T	= environmental temperature (°K)
T_G	= slope of modified ASTM distillation curve (°K)
	= 539 °K for MSW crude
T_o	= intercept of modified ASTM distillation curve (°K)
	= 385 °K for MSW crude
θ	= evaporative exposure coefficient
k	= mass transfer coefficient (m/s)
A	= spill area (m^2)
V	= spill volume (m^3)
x	= slick thickness (m)
t	= time (s)

setting $A = (T/10.3\ T_G)$

and $B = (10.3\ T_G/T)\ \exp\ (6.3 - 10.3\ T_O/T)$

gives $F_V = A \ln (1 + B\theta)$

rearranging yields

$$\theta = (\exp (F_v/A) - 1)/B$$

or substituting for θ

$$x (\exp(F_v/A) - 1)/B = kt$$

thus a plot of $x(\exp (F_v/A) - 1)/B$ vs t will have a slope of k, the overall mass transfer coefficient. Using the resistance-in-series approach to mass transfer:

$$1/k = 1/k_w + H/k_o + L/D_s$$

where k_w = air-side mass transfer coefficient (m/s)
= $0.002U^{0.78}$ (Mackay and Matsugu 1973)
k_o = oil internal mass transfer coefficient (m/s)
H = Henry's law constant for the oil
D_s = diffusivity of oil vapours in snow (m^2/s)
L = depth of oil below snow surface (m)

thus a plot of $1/k$ against snow depth (L) should have a slope of $1/D_s$ and intercept of $1/k_w + H/k_o$. . . . The least squares fit to the small-scale data from the trays with uncompacted snow gives a slope of 5.5×10^4 s/m^2 or $D_s = 1.8 \times 10^{-5}$ m^2/s. This is close to reported values of water vapour diffusivities in snow of 6 x 10 m^2/s (de Quervain 1972).

Conclusions

1. Oil spreading on snow or ice can be modelled using the equations for the gravity-viscous spreading regime:

For a continuous source: $r = (g\, Q^2 / \pi\, \nu^{1/2})^{1/6}\, t^{1/2}$

and for an instantaneous spill: $r = (gV^2 / \pi\, \nu^{1/2})^{1/6}\, t^{1/4}$

2. Oil infiltration into a snowpack can be modelled using the D'Arcy equation:

$$Q = KA\ \rho g(1 + x/L)/\mu$$

and

$$dL/dt = (K\rho g\ /E\mu)(1 + x/L)$$

3. The horizontal spreading of oil on an impermeable surface beneath a snowpack can be modelled by:

For a continuous source: $L = (2Kg\rho Q/\pi E^2\mu)^{1/4}\ t^{1/2}$

and for an instantaneous release: $L = (2Kg\rho V/\pi E^2\mu)^{1/4}\ t^{1/4}$

in which: $K = 7.7 \times 10^{-2} d_o^2 \exp\ (-7.8\rho_s/\rho_i)$

4. The evaporation of oil beneath a snowpack can be modelled by the evaporative exposure approach using:

$$1/k = 1/k_w + H/k_o + L/D_s$$

where the diffusivity in snow was found to be:

$$D_s = 1.3 \times 10^{-8}\ (\rho_s/\ \rho_i)^{-3.9}$$

6.2 Field Studies - Literature Review

Mackay, D., P.J. Leinonen, J.C.K. Overall, and B.R. Wood. 1975. The Behaviour of Crude Oil Spill on Snow. in Arctic, Vol. 28, No. 1, pp 9-20.

Mackay et al. (1975) carried out a number field and laboratory studies of oil spills on snow. Although in all cases the substrate beneath the snow was not ice, the general behaviour of the oil travelling through the snow would likely be the same for snow on any solid substrate.

> The following studies are described here.
>
> (1) Field, isothermal oil spills at the Beare Road landfill site, Scarborough, Ontario.
> (2) Field, isothermal spills at Norman Wells, Northwest Territories.
> (3) Field, hot oil spills on University of Toronto land at Dorset, Ontario.
> (4) Laboratory studies of oil permeation of snow. . . .

Results

<u>Isothermal Spills at Beare Road</u>

Oil volume:	180 litres
Oil type:	Alberta mixed sour blend crude
Oil temperature:	0°C
Oil application:	poured from drums
Snow thickness:	20 cm

> . . . it was found that in winter the snow acted as an excellent absorbent and there was little penetration of oil into the soil. . . .
>
> . . . An oil spill on snow thus initially contaminates an area only about one eighth the area affected by a summer spill; however, after thawing has

occurred, the area contaminated may exceed the summer spill area by a factor of two. Clearly it is desirable to clean up a winter spill before the thaw.

Isothermal Spills at Norman Wells, N. W. T.

Oil volume:	630 litres
Oil type:	Norman Wells crude
Oil temperature:	0°C
Oil application:	applied evenly over an area
Snow thickness:	50-60 cm

> Immediately after the spill it was observed that the oil had penetrated the surface snow to a depth of 2-3 cm. After 30 hours it was observed that it had penetrated in places to the ground. This penetration had not occurred over the entire surface, but small vertical rivulets of oil had formed with a random distribution.

Hot Oil Spills at Dorset

Oil volume:	360 litres
Oil type:	Alberta crude
Oil temperature:	60°C
Oil application:	2 drums poured on snow surface
Snow thickness:	61 cm

> The hot oil immediately melted holes in the snow, reached groundlevel after 2 minutes and then continued to flow away under the snow. . . . The oil cooled rapidly, reaching ambient temperature within 5 minutes. Four hours after spillage the oil flow had apparently stopped and the entire site was excavated to determine the final dimensions of the oil-contaminated area. The data are presented in Table 1. . . .
>
> . . . During the first two minutes of the spill the vertical flow of oil into the snow was controlled by the rate of melting. Approximately two volumes of crude oil at 60°C are required to melt one volume of snow. Apparently, as the

TABLE 1: Dimensions of Hot Oil Spill at Dorset

Time (min.)	Total ground flow distance (m)	Total ground area contaminated (m^2)	Total snow volume contaminated (m^3)	Total snow volume contaminated by ground flow (m^3)
2	0	0.2	0.34	0
14	4	5.1	0.52	0.18
20	4.5	6.5	0.66	0.32
30	4.9	—	—	—
40	5.2	7.3	0.74	0.40
240	5.8	8.8	0.90	0.56

hot oil melts the snow, the oil-water mixture rapidly penetrates into fresh snow due to both gravity and the impact pressure of the oil being discharged. The melt hole deepens and simultaneously the oil-water mixture permeates the snow horizontally. . . .

Laboratory Studies of Oil Permeation in Snow

. . . A series of exploratory semi-quantitative experiments were carried out to study aspects of the behaviour of oil-snow systems.

These experiments examined a number of small scale effects of oil migration through snow. They included:

(1) Oil-ice-air surface effects

(2) Flow of oil in snow between glass plates

(3) Steady-state flow of oil in snow

(4) Hot-oil spills

The results of field and laboratory experiments suggest that there are at least three regimes of isothermal oil flow in snow.

(a) Steady-state flow of oil through oil-saturated snow.
(b) Unsteady-state penetration of oil into fresh snow.
(c) Unsteady-state oil drainage from oil-saturated snow.

Such flows are commonly quantified by the Darcy equation for flow of fluids through porous media (Darcy 1856; Perry 1963):

$$Q = K A \Delta P / (\mu L)$$

> where Q is the oil-flow rate (cm^3/sec.), K is the permeability constant dependent on the structure of the porous medium (cm^2), A is the cross-sectional area of the flow (cm^2), ΔP is the pressure driving force (dynes/cm^2), μ is the viscosity (poise) and L the depth of penetration (cm). The flow rate of oil into snow could be characterized by this equation in steady- or unsteady-state form, including the effects of interfacial tension as a term in ΔP. The permeability K can presumably be related to the snow structure, this having been done for other media by Bear (1972).

The mean permeability value for the steady-state flow experiment performed in the laboratory was 3.3×10^{-6} cm^2. This value "enables a rough estimate to be made of rates of oil penetration into snow."

> In these calculations (Darcy's equation) the pressure-drop term ΔP is equated to $\rho g(H + L)$ where H is the head of oil above the snow, L the depth of the snow bed, and ρ and g are as already indicated. . . .
>
> . . . It should thus be possible to predict the properties of isothermal flow of oil into snow, provided that information is available on the snow and oil properties. Viscosity is likely to be the most important single variable, particularly if the temperature is close to the oil pour point.
>
> The interaction of hot oil with snow is presently only poorly understood, and more quantitative estimation of behaviour must await a better understanding of the effects of heat and phase change, the flow of oil-water mixtures in snow and the subsequent freezing of such mixtures.

Izmaylov, V.V. 1980. Effect of Petroleum Products on the Snow-Ice Covers of the Arctic. in Polar Geography and Geology, Vol. 5, No. 4, Oct-Dec 1981, pp 235-241.

Izmaylov (1980) examined the effects of oil contamination on the melting of snow-ice covers as observed from a series of field experiments.

> To solve, some problems concerning the effect of chemical pollutants on polar water and ice, we performed 12 field experiments in April-October 1978. . . . The purpose of one of the experiments was to study the effect of various types of petroleum products on the temperature and melting of the snow-ice cover. The observations were made in four study areas with ice of varying thickness and age, artificially covered with crude oil, diesel fuel (DF), and gasoline (B-70).

Spill Test Sites

Site No.1

Study area No. 1 was located on an ice berg about 30 m thick. One of the plots in the first study area was covered with crude oil, forming a 1-to 2-mm thick spot measuring 1.5 X 1.5 m and covering 90% of the snow surface. The snow in another observation plot was left clean.

Site No.2

Study area No. 2 was located on old fast ice 5 m thick. . . . diesel fuel and gasoline spots 1-2 mm thick and measuring 2 X 2 m were made in plots. . . . A third plot was left clean.

Site No.3

Study area No. 3 was located on autumn fast ice approximately 2 m thick. Three plots were marked out. Diesel-fuel was applied to the first plot and gasoline to the second. The spills covered 90% of the snow surface for the respective plots (approximately 2 X 2 m spots each). A third plot was left clean.

Site No.4

Study area No. 4 was located on young spring ice 20 cm thick. The plots sizes and petroleum product spills were the same as for site No. 3.

Results

Crude oil, diesel-fuel, and gasoline spots produced an increase in the temperature of the snow-ice cover to a depth of 5-25 cm (no observations were made below this depth) in the spring-summer period (from May 26 to June 28, 1978). The temperature of the snow and ice was almost always higher under the spots than in clean plots during the observation period. According to 144 thermistor observations, the snow and ice temperature under the spots averaged 1.6°C higher than in clean plots. Small variations in the difference between snow and ice temperatures at the same depths in clean and polluted plots were produced mainly by direct and diffuse solar radiation and the corresponding temperature gradients in the air-petroleum-snow-ice system.

Approximately 7-10 days after the petroleum products were spilled over the experimental plots, their effect on the temperature of the snow-ice cover weakened markedly. This is probably attributable to the evaporation and disintegration of the light and partly medium fractions of the petroleum products in the first 10 days after they were spilled. Although the temperature of the snow and ice was still higher in the polluted than in the clean plots 7-10 days after contamination, the difference did not reach 1°C.

Observations of the melting of snow in clean and contaminated plots clearly showed the effect of each of the petroleum products used (Fig 7a-d). Crude oil had the strongest effect on the melting rate of the snow-ice cover (study area No. 1, Fig 7a). For example, 24 cm of snow melted within 5 days, from June 5 to 10, in the plot covered with crude oil when solar radiation was the strongest over the observation period, while only 2 cm melted in the clean plot. A total of 29 cm of snow and 10 cm of ice melted within 34 days of observation in the plot contaminated with crude oil in study area No. 1, while only 19 cm of snow melted in the neighbouring clean plot. The snow and ice in study areas No. 2 and No. 3 melted 2.2 times faster, on the average, under diesel-fuel spots and 1.7 times faster under gasoline spots than in clean plots. In study area No. 4 on young ice, 11 cm of snow and 9 cm of ice melted under the diesel-fuel spot, 11 cm of snow and 6 cm of ice under the gasoline spot, and only 9 cm of snow in the clean plot over the same period. The same factors that determine the effect of petroleum products on snow and ice temperatures determine their effect on the melting of the snow-ice cover.

Conclusion

Izmaylov (1980) made the following conclusions based on the 1978 experiments. The snow in the plot covered with crude oil (iceberg) melted on June 10, that on pack ice

Figure 7

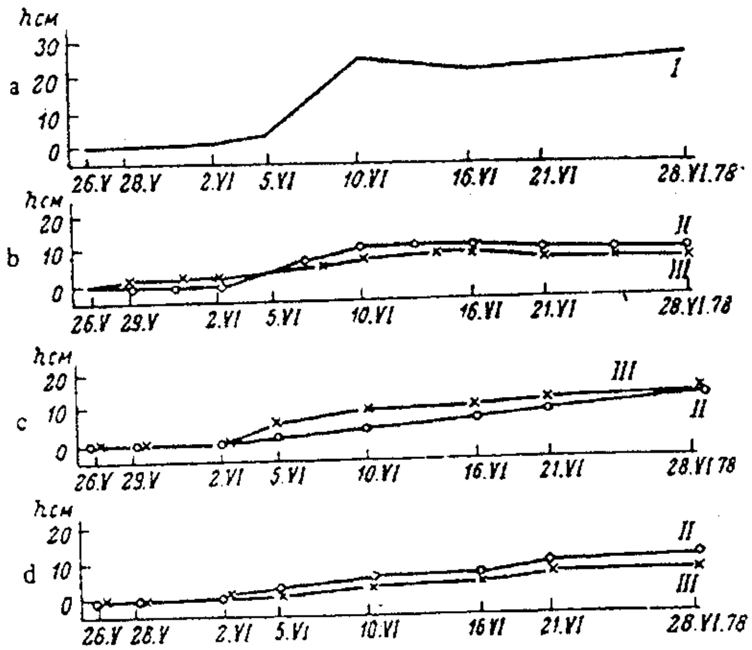


Fig. Difference between the melting of snow and ice in plots covered with diesel fuel and clean plots (II) and plots covered with gasoline and clean plots (III).
Data were obtained: a—on an iceberg b—on pack ice
c—on autumn ice d—on young ice.

covered with diesel fuel on June 16, and that on winter ice and young ice on June 11.

Petroleum products at the surface of snow and ice disturbed their natural thermal state, raising the temperature of the snow to 5.3°C in spring.

The melting of the snow-ice cover was much more rapid in contaminated than clean areas. It was accelerated most by crude oil and least by gasoline. The rate of snow melting under the crude oil spot was 10 times higher at the beginning of the experiment than in the clean plot and this difference decreased to a ratio of 2:1 with time.

The magnitude of the effect of petroleum products on snow and ice melting depends on their physicochemical properties and rate of evaporation into the atmosphere, and on the thickness of the snow and ice.

The change in the temperature and thickness of the snow-ice cover polluted with petroleum products depends on the thickness of the spot or film of these products, their relative area on the snow and ice surface, their specific gravity, viscosity, heat capacity, thermal diffusivity, color, and capacity to evaporate (freeze out), on the magnitude of net radiation, the volumetric heat capacity and thermal diffusivity of snow and ice, the thickness, structure, and density of the snow-ice cover, and on the temperature gradient in the air-oil-snow-ice-water system.

Nelson, W.G. and A.A. Allen. 1982. The Physical Interaction and Cleanup of Crude Oil with Slush and Solid First Year Ice. Proceedings of the Fifth Arctic Marine Oil Spill Program Technical Seminar, 1982, pp 37-59.

This paper is part of a series of field experiments that were conducted by the Alaskan Beaufort Sea Oilspill Response Body (ABSORB). The paper concentrates on crude oil and diesel fuel injection under ice, and, surface oil applications. This second area of concentration provides relevance data to the behaviour of oil on/in/under snow.

Method and Results

> Crude oil was sprayed into the air to examine the physical interaction of the oil with snow under cold ambient air temperatures and under warmer conditions.

The first spray was conducted at an ambient air temperature of -23°C. The snow was approximately 0.3 metres thick with a measured specific gravity of 0.4.

> A volume of approximately 1 m^3 of Prudhoe Bay crude oil (at 48°C) was sprayed onto the snow surface at a rate of 19 litres/min. A total surface area of 465 M^2 was covered, resulting in an average application density of approximately 2.2 L/m^2. Oil penetration into the hard snow surface did not exceed 5 cm. A typical penetration of about 1 cm occurred over most of the area. The limited penetration was due to the rapid cooling of the sprayed oil droplets by the cold air and dense structure of the snow.

The second spill was conducted 2 weeks later at a much warmer temperature of +4°C. The snow conditions had deteriorated significantly from the last test as was evident from the nearly saturated snow-slush structure.

> One cubic metre of Prudhoe Bay crude oil was applied again at the same rate and over the same surface area as the first spray. The oil was applied at the same temperature (48°C) but, unlike the first test, the oil immediately saturated the snow to a much greater extent. The oiled surface from the April 16, 1981 (first spray), spray was left for two weeks so that burn tests could be

conducted on a weathered surface spill and on a fresh spill for comparison. During this time, a subsidence of 5 cm was noted on the oiled surface. This subsidence relative to the surrounding unoiled snow was due to the albedo reduction occurring on the oiled snow. By April 30 (second spray), the snow under the weathered (2-week old) oil was soft; however, the oil did not saturate the snow as did the oil during the second warmer spray period.

The oil that had been on the snow surface for two weeks had concentrated, partially due to the surface ablation, and had a much more viscous appearance than the newly sprayed oil.

Oil samples obtained from the oiled snow layers resulted in water contents of 75 to 90% and were typical of both the weathered and nonweathered layers. These water fractions were typical of what one would encounter during the mechanical removal of an oiled snow layer.

Bech, C. and P. Sveum. 1991. Spreading of Oil in Snow. Proceedings of the Fourteenth Arctic and Marine Oilspill Program Technical Seminar, pp 57-71.

This field experiment was designed to study the natural spreading of Oseberg crude oil and Marine diesel in snow. A total of five experimental spills were conducted using both crude oil and diesel fuel. Each spill consisted of 1000 litres of oil released in one of two ways:

(1) Surface release on top of the snow layer
(2) Surface release under the snow layer on the ice.

Test Oil

Oseberg crude and diesel oil were selected as model oils in the experiment. The physical - chemical properties of Oseberg crude and diesel oil are given in Table 1.

As this was an isothermal spread study the temperature of the oil varied with the air temperature, between -4.5 and -18°C throughout the experimental period. The porosity of the snow varied between 0.4 and 0.5.

Table 1: Physical-Chemical Properties

Properties	Diesel	Oseberg
Density (g/ml)	0.847	0.85
Surface Tension (nM/m)		
air/oil	29	29
oil/seawater	20	21
Pour point (°C)	-27	-24
Flash point (°C)	55	46.1
Viscosity (-5°C,cp)	6.2	54

Method

A total of eight experiments were done. The spill rate varied between 0.7 and 2 litres/sec. approximately. Table 2 gives a summary of the spread experiments. . . .

The design of these studies was similar to that used by Belore and Buist (1988). By pumping oil from a reservoir, 1000 litres was released from the centre of the experimental area which was 10 x 10 metre. The spread was monitored from catwalks along the four axes. The experiments were conducted with virgin snow which had a thickness of 60 cm (approx.). . .

Table 2: Summary of the Experiment with the spread of oil in snow

Exp. #	Oil type	Release rate (1/sec)	Spill conditions	Plane
C1	Oseberg crude	0.72	Under snow	Horizontal
C2	Oseberg crude	0.74	On snow	Horizontal
C3	Oseberg crude	0.72	On snow	Sloping
C4	Oseberg crude	1.38	Under snow	Horizontal
C5	Oseberg crude	2.08	On snow	Horizontal
D1	Diesel	0.72	Under snow	Horizontal
D2	Diesel	0.72	On snow	Horizontal
D3	Diesel	0.72	On snow	Sloping
D4	Diesel	2.15	Under snow	Horizontal
D5	Diesel	1.85	On snow	Horizontal

Results

Horizontal Spread of Oil Under Snow

Table 3 lists the results from the spread studies. As can be seen, the oil is distributed in two areas: a primary and a secondary spread area. In the primary spread area, the thickness of the contaminated snow is nearly the same as snow thickness. The extent of this area is defined by the surface spread. At the edges it decreases to the level of the secondary spread area. Oil concentrations in this area depend on the capacity of the snow to absorb the oil. The secondary spread area is defined by the spill volume, oil and snow properties and the permeability of the ground. The thickness of the oil layer on the ground varied in this area from 2 cm to 10 cm. The difference between what we have called the primary and secondary spread areas is

Table 3: Results From the Spread Studies

	Exp. #	Temp (°C)	Visc. (cp)	Spill rate (l/sec)	Perm. m^2	Area* m^2	Area ** m^2	Prim. area *** m^2
Release under snow	C1	-4.5	35	0.72	$1.6x10^{-7}$	12	28	3.5
	C4	-9.4	250	1.38	$1.6x10^{-7}$	4	33	4
	D1	-17.7	10	0.72	$2.2x10^{-6}$	16	72	0.6
	D4	-9.4	7	2.15	$1.6x10^{-6}$	19	64	3.2
Release on snow surface	C2	-4.5	35	0.74		3	23	5
	C5	-9.4	250	2.80		27	14	3.8
	D2	-13	7.5	0.72		1.5	60	1.5
	D5	-9.4	7	1.85		19	118	19

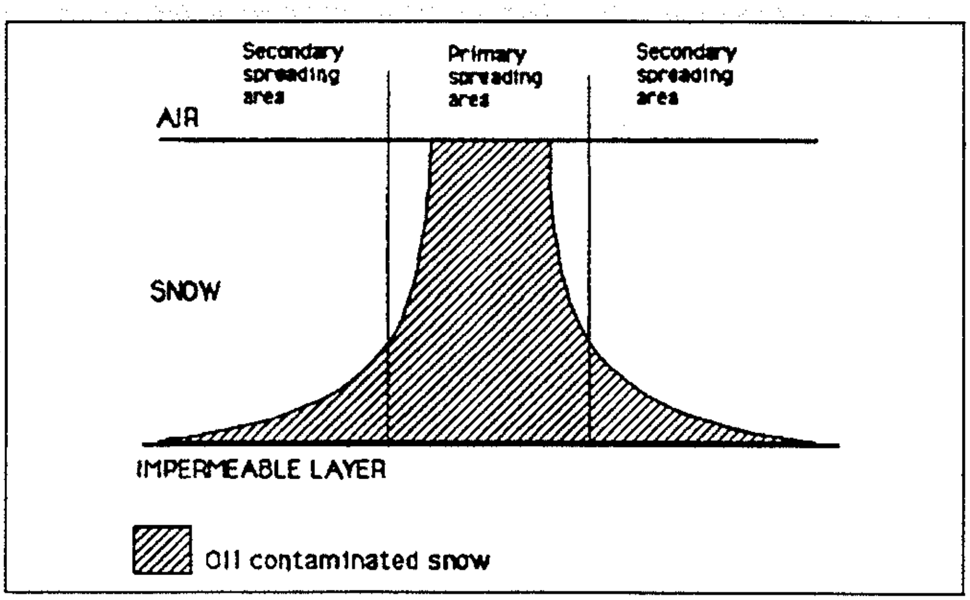
* Contaminated area just after release

** Contaminated area some days after release, when spreading has stabilized

illustrated in Figure 3.

Diesel oil spreads faster than crude oil due to lower viscosity. . . . In these experiments the most pronounced difference between spreading of crude and diesel oil was the total contaminated area under the snow when oil had stabilized. As can be seen from Table 3, diesel oil contaminates approximately twice the area of crude oil. The great difference between contaminated area

Figure 3: Primary and Secondary Spreading Area



immediately after release and a few days later indicate the very slow spread of oil. . . .

Spreading of Oil with Release on Snow Surface

Experiments C2, C3, C5, D2, D3 and D5 studied the spread after surface release of oil. The spread of oil on snow is strongly dependent on the snow surface properties and the spill rate. . . . Just after release oil spreads quickly but once penetration has started, further surface spreading was limited. In oil-saturated snow the penetration rate increases relative to unpolluted snow, where surface tension reduces the flow (Mackay et al., 1974). . . .

In experiments D2 and D5 diesel oil was released on the snow surface. . . . The final spread of oil under snow in these experiments was 60 and 118 m^2 respectively.

The spread on the surface depends on the spill rate. As in the studies with the spread of oil under snow, the final total contaminated area depends on oil properties in addition to the snow properties.

6.3 Spills of Opportunity - Literature Review

Allen, A. 1978. Case Study: Oil Recovery Beneath Ice. Proceedings, Tenth Annual Offshore Technology Conference, Dallas, Texas, Vol. 1, pp 261-266.

This spill of opportunity case study focused largely on the recovery operations associated with a 6,000 gallon diesel oil spill. The spill occurred on land in subzero temperatures with oil migrating through the snow and soil to an adjacent river. Qualitative estimations of the ability of snow to contain oil are briefly mentioned.

> On March 22, 1977, 6,000 gal of No. 2 diesel oil were spilled in Nome, Alaska, when a 25,000-gal storage tank was filled beyond its capacity. The storage tank, is located adjacent to the Snake River just about a mile and a half from its mouth on the northern coast of Norton Sound . . .
>
> Since the spill was not detected until the following day, the nearly 6,000 gal of diesel oil were allowed to move freely out over the snow-covered terrain, up and over a modest bank along the river, and down into an open melt zone created by a hot water discharge from the nearby power plant. . .
>
> The oil had sufficient time to saturate the snow and soil between the storage tank and the river, and to move into and beneath the ice layers surrounding the exposed melt zone. . .

<u>Environmental and Snow Conditions</u>

> The air temperatures before and during the spill and the subsequent cleanup activities were consistently at or below 0°F (-18°C). Temperatures frequently dropped to -20 to -30°F (-29 to -35°C) and remained there for days at a time. . . .
>
> One to 2 ft of snow covered most of the ground near the storage tanks, while lesser amounts were typical over open areas where drifting was less pronounced. Snow at the spill site and over the ice-covered river was loose and dry in consistency, granular in structure, and yet sufficiently compactible to form effective barriers (or berms) for the temporary containment of oil.

<u>Oil Storage in Snow</u>

> During the initial response activities, certain steps proved to be effective in minimizing any further spread of the oil at or near the source of the spill. It is estimated that several hundred gallons of oil were removed (by heavy equipment). . .

. . . During a recent CES Cold Weather Training School in Anchorage, similar snow conditions were found to yield diesel/snow mixtures where as much as 35 percent of the oil/water mixture (after melt-down) was diesel. After 1 week of exposure, the same diesel/snow mixture was sampled again, yielding a 20-percent concentration of oil. . . .

Once any obvious surface contamination was cleared, thin layers of clean snow then could be cast over the exposed ground so that portions of any remaining concentrations of oil could be drawn up out of the soil and into the new snow.

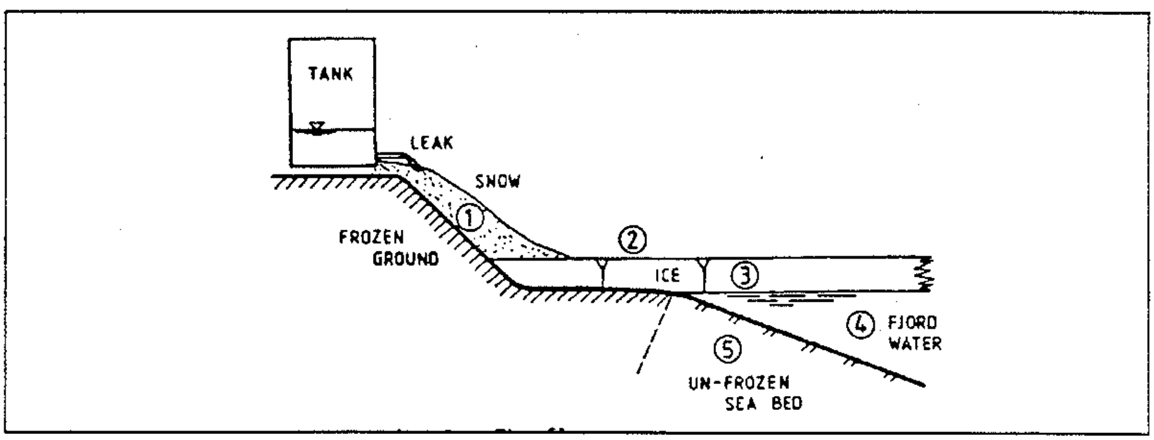
Carstens, T., and E. Sendstad. 1979. Oil Spill on the Shore of an Ice-Covered Fjord in Spitsbergen. Proceedings, POAC 79: Fifth International Conference on Port and Ocean Engineering Under Arctic Conditions, Trondheim, Norway, pp 1227-1242.

Carstens and Sendstad (1979) studied the various transportation routes of a diesel fuel leak from an above ground oil container. Part of the study involved some field observations of oil percolation through snow.

<u>Method</u>

> After a tank truck was filled at the storage tanks in Svea on 20 April 1978, the normal routine of unloading the plate at the end by closing two valves was not followed. As a result some 130 m^3 of diesel fuel seeped out of the tanks during the 26 days before the leak was disclosed on 16 May. . . .
>
> . . . The spread of the oil from the tank occurred through several media in which the flow was governed by different mechanisms. Fig.1 illustrates the various zones.

Figure 1



> The flow zones from the pipe end the oil percolated through a snowdrift (1) down to the ice. The oil then spread on the ice (2) to places where it could flow through the ice (3) into the water masses of the fjord (4). Some oil migrated into the seabed (5).

Observations

Observations on the Ice

On 16 May the air temperature rose above freezing,tripping off rather early the annual snowmelt. With the first appearance of water on the ice, due to simultaneous local melting and to runoff from land, the first oil also appeared. Melting oil-containing snow released oil along some 200 m of the toe of the snowdrift near the tanks. The oil floated on top of the melt-water as a thin light-diffracting film, as drops or as a continuous yellow layer about 1 mm thick.

Oil in the Snow and on the Ice

Samples of naturally drained, warm snow were taken 9 June in the drift through which the oil had percolated. The residual interstitial oil content varied between 0.6 and 2.8 volume percent.

Surface sample of the ice taken the same day contained from 1.9 to 7.9 volume percent of oil. Four days later the oil concentration in the ice had increased and showed values from 4.4 to 21.7 %. These results agree with those of Barber (1971) although he used crude oil from Prudhoe Bay.

Discussion of Oil Transportation through the Snow

The density of old, cold snowdrifts may be assumed to 0.2 - 0.3 g/cm with corresponding porosities $p = 0.78$ and 0.67 and void ratios $e = 3.55$ and 2.03. For a coarse estimate of the permeability k we apply formulas from soil mechanics (Taylor, 1948) of the type $k \approx e$ or $k \approx e/1+e$. The result is a k-value of order 100 m/day, which is low compared with values from the snow literature (Bader, 1939; Kuriowa, 1968).

With a slope S of order 1:10 from the leak to the flat ice, Darcy's law $v = kS$ gives a travel time of about 1 week for the oil to surface on the ice. Since no oil appeared, it must have been intercepted by cracks in the ice.

6.4 Discussion

6.4.1 Theoretical Studies

McMinn's paper (1972) serves as a good primer considering the basic force relationships of oil spreading on snow. The experimental results favour his theoretical assumption that only gravity and inertial forces need be considered for oil spreading rate. The more recent paper written by Belore and Buist (1988) suggest that modelling of oil/snow interactions is more adequately predicted by using gravity-viscous regime equations. Belore and Buist (1988) used data from McMinn and Golden (1972) and Vance (1971) to verify their gravity-viscous process equations. It is recommended that process equations from Belore and Buist (1988) be used for both continuous source and instantaneous spills.

The general spill model developed by Kawamura et al. (1986) considers evaporation, absorption of chemicals by substrate and dissolution of snow by chemical processes. This spill model is applicable to petroleum products that are generally more volatile then crude oil however if the oil product properties are known, this general model could be used as an alternative method for predicting final spill area.

More research is required to verify process equations for predicting oil spill behaviour.

6.4.2 Field Studies

Experimental data obtained from these field programs have provided important information on oil/snow interactions. There are, however, many areas which have not, as yet, been investigated. One issue that has not been quantified is the ability of snow to contain oil. Qualitative observations have suggested capacity estimates of contained oil volumes within a given volume of snow but little work has been done to develop an understanding of the effect of snow properties on oil volume storage. This issue is of importance not only in terms of clean-up operations but also in terms of oil/snow infiltration.

6.4.3 Spills of Opportunity

Numerous spills of opportunity have occurred involving oil spilt on/within/under snow, however, very few have reported any significant findings with respect to quantifying oil/snow interactions. As is the case with most spills of opportunity, the spill site is commonly not in an accessible location. Often there is little time to gather equipment and develop a scientific research program specific to the nature of the spill. Despite the lack of quantitative information obtained from spills of opportunity, field observations inspire research. The two spills of opportunity reviewed here are significant if only to identify the need for further research. The first paper very briefly mentions the capacity of snow to store oil and the second identifies snow properties influencing oil migration through snow. Both are areas that require further investigation.

7.0 LINKAGES BETWEEN OIL/ICE INTERACTION AND WEATHERING

While the primary objective of most oil/ice interactions studies has been to determine the location of oil in ice, as a secondary concern various researchers have presented data on the weathering of oil in the presence of ice. Several researchers such as Pane et al., (1984, 1987, 1989 and 1991) have devoted considerable effort to studying oil-in-ice emulsification, dissolution and other processes. However, given the enormous body of data and knowledge that has been developed for open water weathering, the literature concerning oil/ice weathering is limited by comparison. As a result, conclusions on the effect of ice are best approached through the topics of evaporation, emulsification, etc., rather than from the perspective of oil-ice interaction.

A summary of the overall effect of ice on oil weathering is presented below, to give the reader an appreciation for the parameters of concern. For detailed descriptions of chemical behaviour, the reader is urged to turn to the other BOSS topics.

Pane, J.R., G.D. McNabb, JR., and J.R. Clayton, JR. 1991. Oil-Weathering Behavior In Arctic Environments. Proceedings from the Pro Mare Symposium on Polar Marine Ecology, Trondheim, May 12-16, 1990. Polar Research 10, pp 631-662.

Excerpted from Pane et al., 1991:

When crude oil or refined petroleum products are released to ice-free marine environments, oil weathering processes occur. These processes include spreading, evaporation, dissolution, dispersion of whole-oil droplets into the water column, photochemical oxidation, water-in-oil emulsification, microbial degradation, adsorption onto suspended particulate material, ingestion by organisms, sinking, and sedimentation. . . .

When oil is released into ice-covered waters, many of the same weathering processes are in effect; however, the various forms of sea ice impart drastic, if not controlling, changes to the rates and relative importance of these processes. Oil released into a growing slush ice field during late fall or early winter may be subject to stranding on upper ice pan surfaces and rapid water-in-oil emulsification, followed by partial density-mediated submersion and incorporation into the ice canopy. For the oil on the upper-ice surface of pans and smaller floes (if present), diffusion-controlled evaporation weathering predominates; however, for that portion of the oil that remains in the ice/water matrix, the emulsification processes may be rapid enough to occur before significant evaporation and dissolution weathering can reduce the oil toxicity and affect the overall mass balance of the slick. Likewise, oil from a subsurface release under an existing ice canopy is subject to encapsulation before evaporation weathering, although dissolution of aromatics has been demonstrated (and the potential exists for aromatic hydrocarbon transport to the benthos with rejected brine generated during ice growth).

Once encapsulated in the ice, the oil is not subject to further weathering until the spring thaw and ice breakup. The presence of brine channels, which have their origin in the initial freezing process, then becomes especially important during warming periods. As the ice begins to warm, pools maintained as 'salt flowers' on the ice surface over winter, as well as brine trapped between the ice crystals, begins to drain through the ice. Oil, initially trapped under or in the ice, then may appear on the upper ice surface due to density-mediated migration up through the open brine channel pathways. If the oil is emulsified prior to encapsulation, this migration process is retarded significantly, and the presence of temperature gradients within the ice also inhibits such flow. Thus, migration rates for oil in brine channels during the spring thaw may vary as a function of oil chemistry and viscosity (as controlled by water content due to previous emulsification and temperature gradients within the ice), as well as depth in the ice canopy. . . .

Implications for oil released in multiyear ice also were considered. . . . rotting multiyear ice appeared to have a much lower tendency to produce a slush ice matrix during melting, and the formation of stable water-in-oil emulsions occurred over a relatively longer period of time.

. . .

Finally, specific mechanisms for brine-induced transport of dissolved aromatic hydrocarbons to benthic ecosystems in actively freezing Arctic waters were recognised during these studies. If oil is released into water under freezing conditions of active ice growth, lower molecular weight aromatic components can be advected with the sinking brine generated during frazil ice formation to the stable bottom boundary layer where, as conservative dissolved compounds, they can persist without evaporation for periods of up to several months.

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- very brief, no behaviour.

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- report focuses mainly on countermeasures; however, some relevant material is presented.

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- general drift model, no oil-in-ice behaviour.

Tide crack: Crack at the line of junction between an immovable ice foot or ice wall and fast ice, the latter subject to rise and fall of the tide.

Weathered ridge: Ridge with peaks slightly rounded and slope of sides usually 30° to 40°. Individual fragments are not discernible.

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

Appendix B

Author List

AUTHOR	Remarks
Allen, A.A.	Consent received.
ARCTEC Canada Ltd.	Company's name changed to Fleet Technology Ltd. Consent received from G. Comfort, Manager, Cold Regions Technology Centre, Fleet Technology Ltd.
Barnes, P.W.	Consent received.
Bech, C.	Whereabouts unknown. Consent received from second author, P. Sveum.
Belaskas, D.P	Attempted to contact through P. Yapa, correspondence not returned.
Belore, R.C.	Consent received.
Buist, I.A.	Consent received.
C-CORE	Consent received from J. Whittick of C-Core.
Carstens, T.	Unable to contact, wherebouts unknown.
Chen, E.C.	Consent received.
Comfort, G.	Consent received.
Cox, J.C.	Consent received.
Deslauriers, P	Attempted to contact through E. Gundlach and S. Martin, whereabouts unknown.
Dickins, D.F.	Consent received.
Free, A.P.	Attempted to contact through J. Cox and a former employer, Dewberry and Davis, whereabouts unknown.
Glaeser, LTJG	Attempted to contact through Cdr P. Tebeau, U.S.C.G. Research and Development. U.S.C.G. onsent received from Cdr. P. Tebeau, whereabouts unknown.
Goodman, R.	Consent received.

Greene, G.D.	Whereabouts unknown. Consent received by third author, D. Mackay.
Hirvi, J-P.	Unable to contact, whereabouts unknown.
Hoult, D.P.	Attempted to contact through Cdr P. Tebeau, U.S.C.G. Research and Development. U.S.C.G. consent received from Cdr. P. Tebeau, whereabouts unknown.
Kawamura, P	Whereabouts unknown. Consent received by second author, D. Mackay.
Keevil, B.E.	Attempted to contact through second author, R. Ramseier, whereabouts unknown.
Kisil, C.A.	Whereabouts unknown. Consent received from thesis advisor, D. Mackay.
Kovacs, A.	Consent received.
Mackay, D.	Consent received.
MacNeill, M.	Attempted to contact via R. Goodman, whereabouts unknown.
Malcolm, J.D	Whereabouts unknown. Consent received from second author, A.B. Cammaert.
Martin, S.	Consent received.
McMinn, LTJ	Attempted to contact through Cdr P. Tebeau, U.S.C.G. Research and Development. U.S.C.G. consent received from Cdr. P. Tebeau.
Metge, M.	Consent received.
Nelson, W.G	Consent received.
NORCOR Engineering	Corporate author unavailable. Consent received from client (Brian Smiley, Institute of Ocean Sciences, Department of Fisheries and Oceans).
Payne, J.R.	Consent received.

Purves, F.	Attempted to contact via Allan & Unwin, publishers, correspondence not returned.
Puskas, J. E.	Attempted to contact via S. Sykes, whereabouts unknown.
Quam, H.A.	Attempted to contact through R. Goodman and Imperial Oil, Edmonton. Whereabouts unknown.
Ramseier, R.	Consent received.
Reimer, E.M.	Consent received.
Rosenegger, L.W.	Attempted to contact through R. Goodman, whereabouts unknown.
S.L. Ross Environmental Research Ltd.	Consent received.
Scott, B.F.	Attempted to contact via Inland Waters Directorate, whereabouts unknown.
Tebeau, P.	Consent received.
Topham, D.R.	Consent received.
Venkatesh, S.	Consent received from author and from E. Truhlar, Director, CMOS publications for paper in *Atmosphere-Ocean*.
Weiskopf, F.B.	Attempted to contact through J. Cox, whereabouts unknown.
Welsh, J.P.	Attempted to contact through Cdr P. Tebeau, U.S.C.G. Research and Development. U.S.C.G. consent received from Cdr. P. Tebeau, whereabouts unknown.
Wilson, D.G.	Whereabouts unknown. Consent received by second author, D. Mackay.
Wolfe, L.S.	Attempted to contact through Cdr P. Tebeau, U.S.C.G. Research and Development. U.S.C.G. consent received from Cdr. P. Tebeau, whereabouts unknown.
Yapa, P.D.	Correspondence not returned.

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