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REPORT





Oil in Ice - JIP

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Short state-of-the-art report on oil spills in ice-infested waters. Final

Per Johan Brandvik, Kristin Rist Sørheim, Ivar Singsaas and Mark Reed

SINTEF Materials and Chemistry
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Preface

SINTEF has in cooperation with SL Ross Environmental Research Ltd and DF Dickins Associates LLC on behalf of the oil companies AGIP KCO, Chevron, ConocoPhillips, Shell, Statoil and Total initiated an extensive R&D program; *Joint industry program on oil spill contingency for Arctic and ice covered waters.* This program was a 3-year program initiated in September 2006 and finalized in December 2009.

The objectives of the program were;

- To improve our ability to protect the Arctic environment against oil spills.
- To provide improved basis for oil spill related decision-making:
- To advance the state-of-the-art in Arctic oil spill response.

The program consisted of the following projects:

- P 1: Fate and Behaviour of Oil Spills in Ice
- P 2: In Situ Burning of Oil Spills in Ice
- P 3: Mechanical Recovery of Oil Spills in Ice
- P 4: Use of Dispersants on Oil Spills in Ice
- P 5: Remote Sensing of Oil Spills in Ice
- P 6: Oil Spill Response Guide
- P 7: Program Administration
- P 8: Field Experiments, Large-Scale Field Experiments in the Barents Sea
- P 9: Oil Distribution and Bioavailability

The program has received additional financial support from the Norwegian Research Council related to technology development (ending December 2010) and financial in kind support from a number of cooperating partners that are presented below. This report presents results from one of the activities under this program.

Stein Erik Sørstrøm
Program Coordinator
(stein.e.sorstrom@sintef.no)

Funding Partners

R&D Partners

Cooperating Partners

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SINTEF Materials and Chemistry

Address: NO-7465 Trondheim, NORWAY
Location: Brattørkaia 17B, 4. etg.
Telephone: +47 4000 3730
Fax: +47 930 70730

Enterprise No.: NO 948 007 029 MVA

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Oil behaviour and response options

AUTHOR(S)

Per Johan Brandvik, Kristin Rist Sørheim, Ivar Singsaas and Mark Reed

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Joint Industry Group consisting of Chevron, ConocoPhilips, Shell, Total and Statoil.

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ABSTRACT

The objective of this report is to give a short and "to-the-point" presentation of the status, knowledge gaps and research needs regarding oil spill response in Arctic and primarily in ice-infested waters. This report is a part of the deliverables in a pre-project for an "Oil-in-Ice" Joint Industry project initiated by Chevron, ConocoPhilips, Shell, Total and Statoil.

The conclusions, identified technology gaps and recommendations are to be used to develop a scope of work for an R&D program to support petroleum exploration and production in Arctic areas.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Oil spill	Akutt oljeforurensning
GROUP 2	Ice conditions	Isforhold
SELECTED BY AUTHOR	Contingency plan	Beredskapsplan
	Arctic	Arktis
	Weathering	Forvitring

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1 Introduction

The objective with this report is to give a short and “to-the-point” presentation of the status, knowledge gaps and research needs regarding oil spill response in Arctic and primarily in ice-infested waters. The report is a part of a pre-project for an “Oil-in-Ice” Joint Industry project initiated by Chevron, ConocoPhilips, Shell, Total and Statoil. The pre-project has been organized by SINTEF.

To keep the number of pages to a minimum, previous review reports and papers are referenced and only significant materials relevant to oil-in-ice are included. The sited reports/papers contain further details.

The review reports and papers most frequently used here are:

1. 1992: State-of-the-art review on oil-in-ice recovery, Canadian Petroleum Association (Solsberg & McGrath, 1992)
2. 1996: Summary of the SINTEF Oil-in-the-Northern-Area program (1990-94 - ONA), Vefsnmo et. al
3. 1998: In-Situ Burning of oil spills, NIST-MMS Workshop Proceedings, New Orleans, 1998
4. 1998: Emergency Prevention, Preparedness and Response (EPPR UN-Arctic Council). Field guide for oil Response in Arctic waters, Environment Canada, 1998.
5. 1992/2001: Proceedings from Helsinki Combating Marine Oil Spills in ice/Arctic conditions, seminars 1992 and 2001
6. 2002: The MORICE program (Jensen & Mullin, 2002).
7. 2002: MMS White paper “Potential Components for a R&D program including Full-scale exp. Oil release in the Barents Sea marginal ice Zone (Reed et. al)
8. 2003: Fingas and Hollebone, Fate and behaviour of oil in freezing situations
9. 2004: Interspill review papers (oil-in-ice, *in-situ* burning, mechanical recovery, dispersants)
10. 2004: ARCOP Report by SINTEF: State of the art report on oil weathering and on the effectiveness of response alternatives, 2004
11. 2004: DF Dickins Associates Ltd., 2004 “Advancing Oil Spill Response in Ice infested waters”
12. 2005: ARCOP report by SINTEF: Development of new oil spill response concepts, 2005
13. 2005: Total Norge, State of the art report on oil-in-ice related R&d projects. 2005 Stavanger, Norway

2 Fate and behaviour of oil in ice infested areas

Extensive research has been performed during the last 30 years including field tests, observations, laboratory studies and numerical studies to understand the fate, behaviour and weathering processes that take place when oil is spilled in ice (see figure 2.1). However, the majority of this work is now 10 years or older, as also concluded in a recent review on the behaviour of oil in freezing environments (Fingas and Hollebone, 2003).

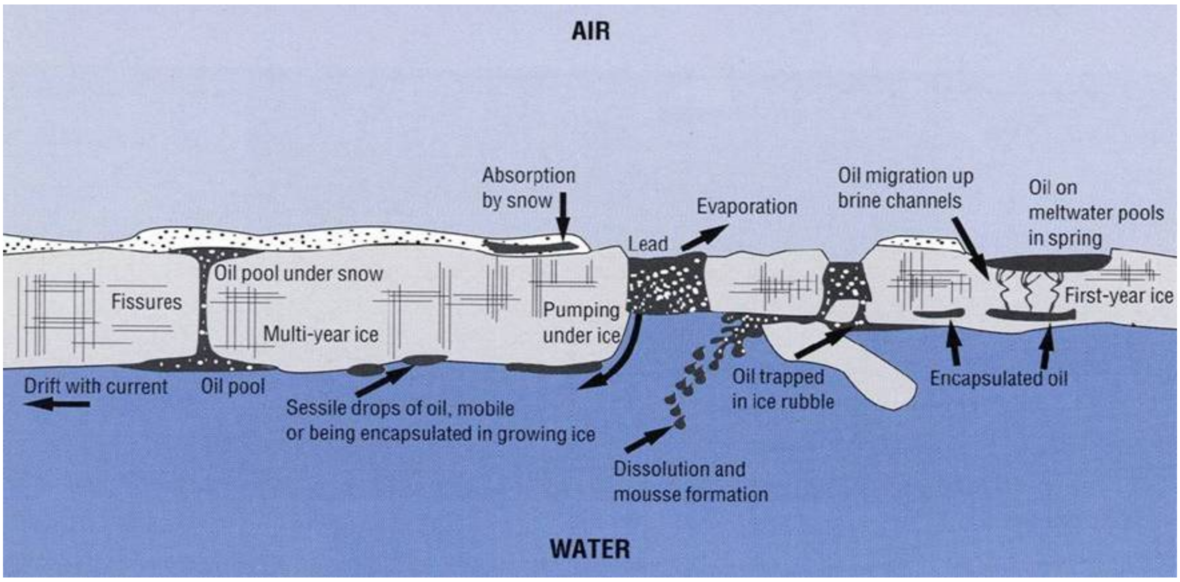


Figure 2.1: Fate and behaviour of oil spilled in ice (Dickins et al, 2004)

During the late eighties and early nineties SINTEF performed major laboratory and field studies on fate, behaviour, and weathering of oil under arctic conditions. These studies are summarized in Løset *et al*. (1994) and Singsaas *et al*. (1994). The following state of the art discussions are mainly based on these reports, but supplemented by literature published later.

Operational important weathering processes for oil spill operations like water uptake, emulsion stability and viscosity vary with oil type. Normally they increase relatively fast with increased weathering time in open water. In ice infested water several studies have indicated that this increase with time (e.g. water content) can be drastically changed depending on ice type, ice coverage and energy conditions in the ice. Little knowledge concerning this is available today and only for a limited number of oil types and ice regimes trough lab and field experiments performed in US and Norway.

MMS initiated in 2004 a three year research project focusing on fundamental weathering processes of oil in ice (spreading, evaporation, migration etc.). The main objective for this project is to establish data to develop/refine weathering models to describe oil weathering in ice. Main contractor on this project is MAR incorporated in, in cooperation with S.L. Ross Environmental Research Ltd and DF Dickins Associates, Ltd all in US. This program includes small-scale laboratory testing, basin tests and large-scale experiments in MMS’ Ohmset facility and continues until 2007.

Another ongoing program is performed by the University Centre on Svalbard (UNIS) and SINTEF on Svalbard regarding oil weathering at different ice conditions (Brandvik et al., 2005) and distribution of water soluble components from encapsulated ice (Faksness and Brandvik, 2005), see figure 2.2 and 2.3. This project will supply weathering data for one oil type (Statfjord) and leakage rates for 5 different oil types to be used for calibration of SINTEF Oil Weathering model. This program also includes PhD and MSc students and is funded by the Norwegian Research council and the Norwegian oil companies Statoil and Hydro and will continue until 2007.

Figure 2.2: Meso-scale experiments from Svalbard performed in high and low ice-coverage

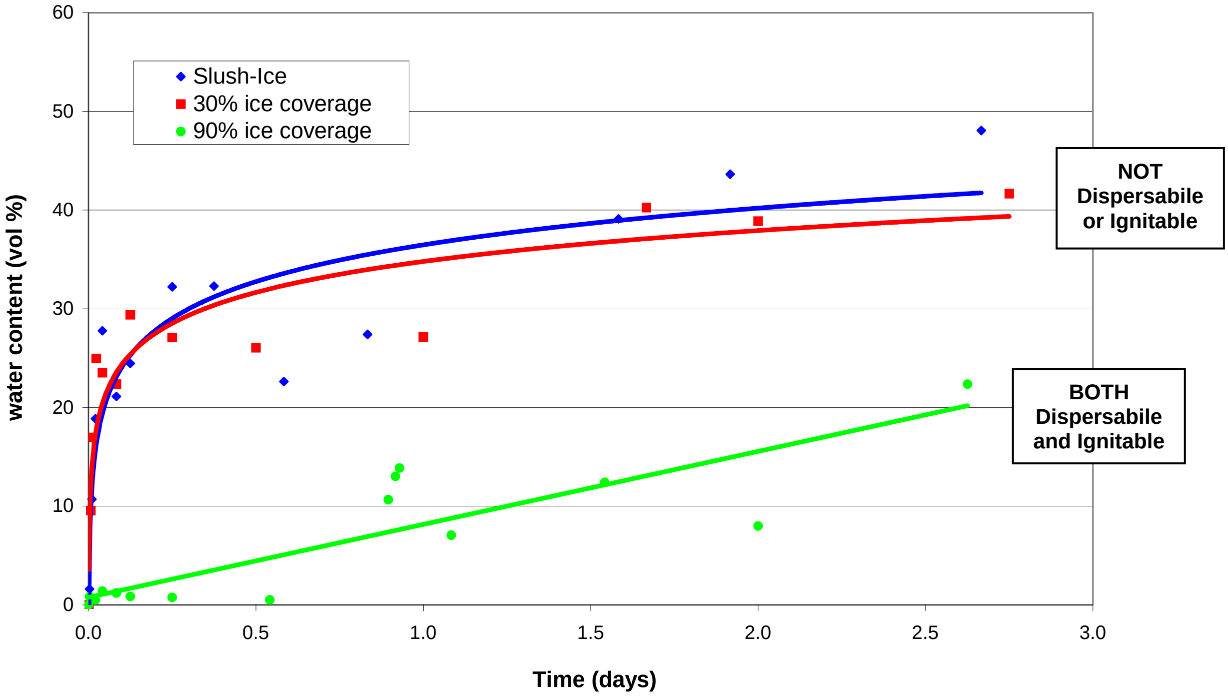


Figure 2.3: Examples of preliminary results from the meso-scale oil-in-ice weathering performed on Svalbard, showing water uptake (%) for the Statfjord crude with three different ice coverage (or energy conditions).

Compared to the in-depth knowledge which exists regarding fate and behavior of oil spills in open water and temperate conditions our knowledge regarding Arctic oil spills are limited. There is a need for international protocols and laboratory and field experiments to collect physical and chemical measurements of oil weathering and use these to validate and enhance oil weathering algorithms for oil weathering models. The objective should be to collect basic research data on evaporation, dispersion, spreading, and other weathering parameters in the marginal ice zone. This data should then be used to improve and modify or develop new algorithms of oil weathering in and on ice.

Status on fate and weathering of oil in arctic conditions are summarised in table 2.1

Table 2.1 Status on fate and weathering of oil in arctic conditions

Parameter	In open water	In ice with increasing ice coverage	Conclusion
Spreading	Spreading due to diffusion, gravity, inertial force, viscosity and interfacial tension. Spreading normally from thick to thin oil films, dependent of oil.	Spreading in ice is dependant on ice types and ice coverage. Increasing oil film thickness with increasing ice coverage. Limited knowledge of oil-ice interactions	Drift, spreading and distribution of oil in sea ice are mainly depending on ice conditions. Limited knowledge of oil-ice interactions.
Drift	Oil drift due to wind and currents	Current assumption is that ice coverage less than 30% the drifting of oil will be independent of the ice. At ice coverage larger than 60-70 % the oil will mainly drift with the ice. Limited knowledge of oil-ice interactions	
Evaporation	Evaporation is rapid and high due to thin oil films. Field and laboratory data available for a wide range of oil types.	Evaporation is a surface phenomenon and increasing oil film thickness due confinement in ice reduces both the rate and degree of evaporation. Reduced evaporation due to a diffusion barrier of precipitated wax (skin) at low temperatures is also observed.	The knowledge of different weathering processes and properties of oil in open water is very good. Field and laboratory data available for a wide range of oil types. Numerical models with good predicting ability available e.g. the SINTEF OWM. To provide reliable predictions of weathering properties of oil-in-ice, more basic knowledge and a deeper understanding of these processes are needed. At present field and laboratory data are only available for a few oil types Reliable predictions (forecasts) are also dependant on the ability to predict the dynamics in sea ice conditions.
Natural dispersion	Natural dispersion dependent of oil type and sea states. Field and laboratory data available for a wide range of oil types.	The rate of natural dispersion will decrease by increasing ice coverage and could be very low due to reduced energy condition in the ice.	
Emulsification	Emulsification will mainly take place in the presence of breaking waves. Field and laboratory data available for a wide range of oil types.	Presence of ice will reduce wave activity and the emulsification will usually decrease by increasing ice coverage. Ice-ice interactions are reported to induce emulsification.	
Water uptake rate	Rapid water uptake, dependent of oil type. Field and laboratory data available for a wide range of oil types.	Water uptake rate will probably decrease with increasing ice coverage due to wave damping effects and will be slow in dense sea ice.	
Leakage of water soluble components (WAF)	Amount and type of components dependent on oil type. Field and laboratory data available for a wide range of oil types.	Only limited laboratory. and field experiments performed by SINTEF and UNIS in 2003-2005	
Stability of emulsion	Stability of emulsion dependent on oil type. Stability increases with increasing weathering degree. Field and laboratory data available for a wide range of oil types.	Stability of emulsion dependent of oil type.	
Viscosity	Increasing viscosity due to increasing water uptake and evaporation. Field and laboratory data available for a wide range of oil types.	The viscosity will increase with increasing water uptake and evaporation as in open sea, but the increase will be slower due to slower evaporation and water uptake.	

3 Circum polar ice conditions

There are number of locations in the circum polar areas that may need the ability to respond to oil spills in ice-covered waters resulting from present and future activities related to exploration, production or transportation of hydrocarbons. These locations includes e.g. the Barents Sea, Pechora Sea, Kara Sea, Baltic Sea (includes Gulf of Finland and Bothnia), Caspian Sea, Bering Sea, Northern Sea of Japan and the Sea of Okhotsk (Owens, 2004). Each Arctic and sub-Arctic region has it own unique combination of environmental characteristics. Ice parameters that may impact oil spill response strategies include the characteristics of landfast, transition, and pack or drift ice regimes, such as ice season duration, decay cycle, ice concentration, ice type, thickness and growth rate, ice drift velocity, currents and physical and mechanical properties (Poplin, 2000). The variability of ice condition precludes the selection of oil a single response technique as the optimum for all oil spill situations.

Offshore oil and gas development in Arctic regions are concerned with severe winter conditions which represent a challenge to oil spill response such as low temperature, sea ice, lack of daylight and the difficultness of detection, monitoring and surveillance of oil spills. Presence of ice can e.g. impose large actions on platforms and may create gouges in the sea floor, which can affect the pipeline integrity. The ice could complicate the access by supply vessels and tankers, and also make difficulties for personnel evacuation. For year -round operations in ice, the platform, pipelines and/or tanker loading system, and oil response equipments need to be designed for ice structure interaction and winterization.

A map showing the Northern Hemisphere Polar region and Arctic oil and gas development areas (present and potential future opportunities) is shown in figure 3.1. In addition, the transportation activities are shown which are for instance related to energy industry, e.g. transportation of oils through the Baltic and Gulf of St. Lawrence. Areas covered with sea ice at the time the map was created are shown in yellow, while the areas with snow are given in white.

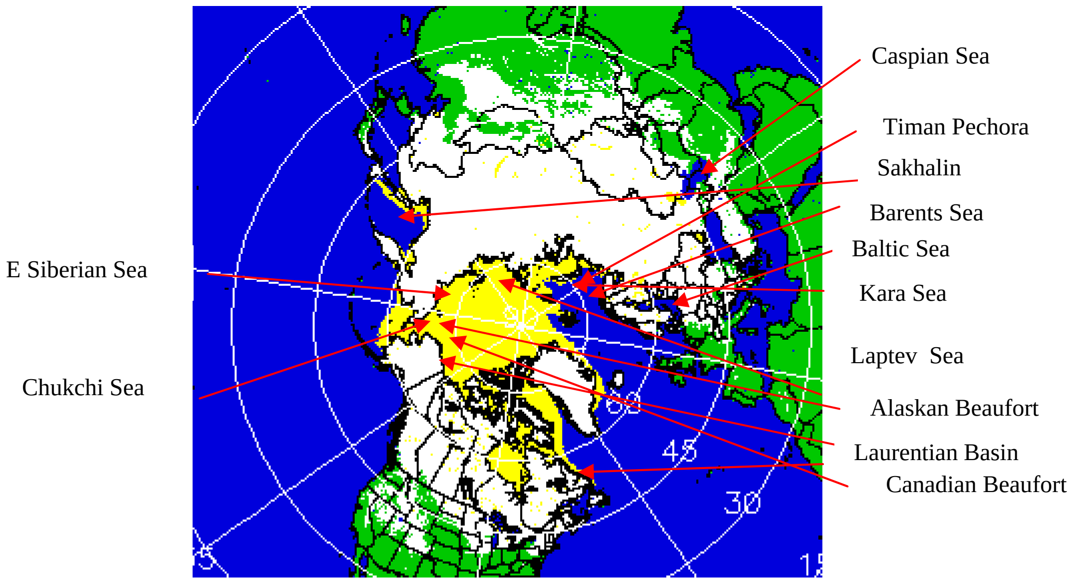


Figure 3.1 Northern Hemisphere Polar region. NOAA Snow and Ice chart 24 Jan, 2006

3.1 Ice monitoring

Sea ice observation and mapping is today mainly based on satellite remote sensing and numerical modelling, supplemented by in situ observation from ships, aircraft and coastal stations. National sea ice monitoring services has been established during the last century in countries where sea ice effects navigation and has other marine activities. In Europe ice services are established in Denmark, Estonia, Finland, Germany, the Netherlands, Norway, Latvia, Lithuania, Poland, Sweden and Russia. Extensive ice services are established in USA and Canada, and Asia China and Japan have also ice services (Sandven et al., 2005). The national ice services produce ice charts according to an international standard defined by World Meteorological Organization (WMO), and at present the ice centres are organized in the international Ice Charting Working Group (IICWG).

Satellite image data have proved to be of major benefit for regional ice surveillance e.g. large scale monitoring of sea ice is routinely performed using Special Sensor Microwave Imager (SSM/I) data which have a coarse spatial resolution of around 50km, but these data are independent of cloud cover and observe the whole Arctic twice daily. The infrared/optical sensor NOAA AVHRR has a higher ground resolution (1 km), but is seriously limited in operability in cloud cover which is common at the ice edge and by darkness, when only thermal infrared imagery can be used. At the present there are no actively operating Russian meteorological satellites and the main sources of satellite information is mainly based on data from the meteorological satellites of NOAA and EOS (Terra, Aqua) series.

Today, it exists an available ice information system for support of Arctic navigation and offshore activities which is based on a complex approach to the methods and means for collecting information on ice conditions. The Arctic and Antarctic Research Institute (AARI) has developed modern hardware and special software system which has a module for analysing and forecasting ice and hydrometeorological conditions. Ice information support is a component of hydrometeorological services of sea operations and ice mapping is performed using the information on ice regime, historical database and ice models. Stochastic and hydrodynamic models for prediction of ice cover distribution from 1-7 days up to 3-6 month has been developed and are currently in use. Russian weekly ice charts of the arctic region, including the Northern Sea Route (NSR) are published of AARI on regular basis and contain information on ice conditions in the Arctic Seas. An available Russian ice information system could be considered as a base for the future NSR optimal ice information system design (Smirnov, 2005).

Finnish Ice Service is responsible to provide in formations on sea ice conditions e.g. to coordinate winter navigation. The ice information service consists of three operative systems; i.e. ice observation input network, ice analysis, and forecast and ice information output communicating system.

Statistical information about ice conditions, in particular total ice concentration, e.g. in the Barents Sea and Pechora Sea is provided for example by the Ice Services of the Arctic and Antarctic Research Institute (AARI), St. Petersburg, Russia and the National Ice Center (NIC), Washington D.C., USA. Figure 3.2a to 3.2d (ice charts) visualize examples of ice analysis showing different ice conditions from satellite images for the years 2002 to 2005. (Ref: Ice Center Arctic and Antarctic Research Institute (AARI), St. Petersburg, Russia).

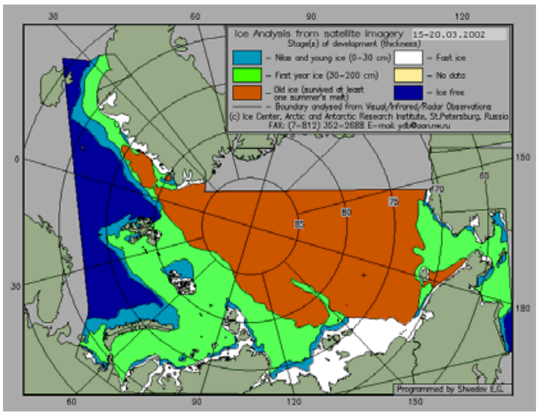


Fig. 3.2a Stage(s) of development in March 2002

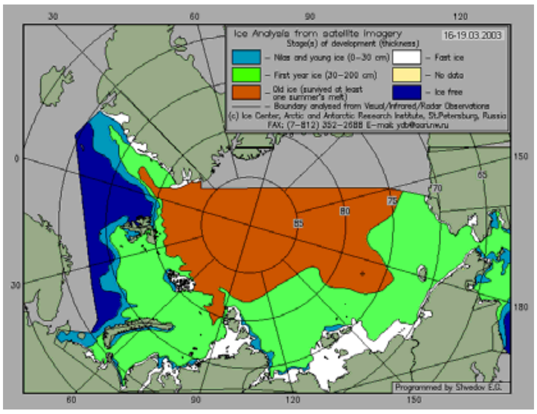


Fig.3.2b Stage(s) of development in March 2003

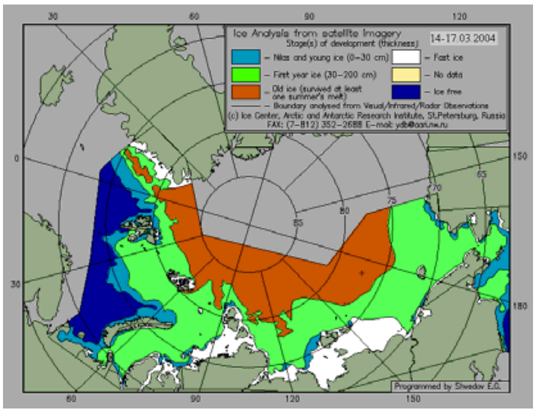


Fig. 3.2c Stage(s) of development in March 2004

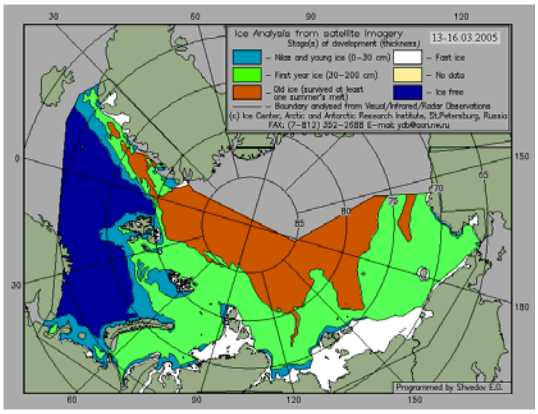


Fig. 3.2 d Stage(s) of development in March 2005

3.2 Ice concentration

The effect of ice concentration on oil movement has been observed in field studies, laboratory and tank tests and actual arctic spill experiences. Differences in natural containment as a function of ice concentration directly affect the selection of oil spill strategies (Dickins and Buist, 1999). Table 3.2 shows the variation in average ice coverage throughout the ice season for various circum polar locations. The data were extracted from the National Ice Center (NIC) sea ice maps for 1972-1994 (National Ice Center, 1996) using ICE 98 (a program developed by CANTEC Consultants Ldt) (Owens, 2004). Table 3.2 also shows the coordinators of a location within each sea for which data were collected, since some of the seas have significant gradient of ice concentration from North to South or extending out from shore, especially at the beginning and end of the ice season. The nomenclature for sea ice is used to describe the ice concentration established by the World Meteorological Organization (WMO) in 1970, where 1-6/10 is defined as open drift ice with many leads and polynyas (region of open water surrounded by ice) where the floes are generally not in contact with one another, 7-8/10 is defined as close pack ice where the floes are mostly in contact. The concentration of 6-7/10 represents a transition period between these two states of pack ice. 9-10/10 is the ice concentration from very close pack ice to consolidated ice or compact ice.

Table 3.2 Variation in weekly average ice- cover by region (Owens, 2004). The table shows the average number of weeks per year with a given ice concentration. Ice concentration (ice coverage): 0/10 Ice free, < 1/10 Open water, 1/10-3/10 Very open drift, 04/10-6/10 Open drift, 7/10 -8/10 Close pack ice/drift, 9/10-10/10 Very close pack ice/compact ice

Location	Weeks Open water	Weeks <5/10	Weeks >5/10	Weeks >8/10
Chukchi Sea 68°N, 170°W)	14	6	32	28
Beaufort Sea:				
-Alaskan Sector: North of Prudhoe Bay (70°30'N, 148°W)	0	12	40	38
-Canadian Sector: North of Mackenzie Bay (79°30'N, 137°W)	0	14	38	32
Gulf of St.Lawrence (48°30'N, 62°W)	34	8	10	4
Baltic Sea:				
-Bothnian Bay (63°30'N, 21°E)	26	16	10	0
-Gulf of Finland (60°30N, 26°E)	30	12	10	0
Barents Sea:				
-East of Svalbard (77°N, 30°E)	8	10	34	24
-South of Svalbard (75°N, 20°E)	18	20	14	0
Kara Sea	0	10	42	36
Laptev Sea	0	0	52	42
Sea of Okhotsk:				
-NE Sakhalin (53°N, 144°E)	24	8	20	14
-Aniva Bay (46°30'N, 143° E)	32	16	4	0

3.3 Norwegian water

3.3.1 Barents Sea

Marginal Ice Zone (MIZ) is the transition region between the ice-covered and ice-free sectors of the ocean. The marginal ice zone (MIZ) in the Barents Sea is normally composed of distinct ice floes, which increase in size with increasing distance from the ice edge. For instance, Løset et al.(1997) reported from the 1988 IDAP (Ice Data Acquisition Program) survey in the western Barents Sea that the MIZ consisted of a relatively narrow edge zone (< 5 km wide) with floes typically 5-10 m across. Brash ice occupied most of the surface area between the floes in the edge zone. For the transition zone, 5-65 km from the edge, the mean floe size in general increased with distance from the ice edge

In general the eastern Barents Sea is ice free, where as in the southern part of Pechora Sea (see 3.4.1) young ice and nilas up to 30 cm thickness is predominant. The most common type of ice in the Barents Sea is first-year ice. The ice thickness can be up to 2 m for undeformed first-year ice and 3-5 m for multi-year ice. In general, multi-year ice floes are observed on several occasions but rather seldom south of Hopen Island.

3.4 Russian waters

3.4.1 Pechora Sea

The ice period lasts from the end of October/mid November until the end of July/early August (Mironov et al., 1994). The ice conditions in the eastern part of the Pechora Sea are more severe than in the western part. In particular, the average duration of the ice season in the western part is 185 days, while in the east it is 240 days (maximum 300 days). The most extensive ice cover is observed in March-April, when 10/10 of the sea surface is covered with ice (Spichkin and Egorov, 1995). There is a great scatter in the times of ice freeze and melt/retreat. The ice free period can vary from 0 to 130 days. For instance, the ice free period for the Prirazlomnoye Field is about 110 days (Mironov et al., 1996). Four periods of long and four periods of short duration of ice cover were observed during the last 54 years. Three significantly different ice zones form in the Pechora Sea: landfast, floating (drift ice) and intermediate (shear zone), where drift ice interacts with fast ice. The landfast ice zone in the Pechora Sea may extend 10-15 km offshore, reaching depths of 12-15 m. The maximum average thickness of the sea ice in the eastern part of the Pechora Sea is 1.1 m, but the absolute maximum is 1.6 m. The frequency of ice ridges increases from the shore to the external fast ice boundary and from the west to the east.

3.4.2 Kara Sea

Fast ice formation in the Kara Sea usually starts to form as young coastal ice near coastal areas and islands after the beginning of stable ice formation, which especially happens during the October month. Drifting ice thickness varies between 1.4 and 1.6 m, although ice thickness may reach 2.0 m. The thickness of stratified ice may reach 3 m.

3.4.3 Chukchi Sea

The Chukchi Sea is bounded to the south by the Bering Straits. It is bounded on one side by Wrangel Island on the west and the Beaufort Sea to the east. The sea is largely ice-covered (between 50 and 100%) between mid-November and mid-June, but is generally ice-free, at least in the southern regions, during the month of August and September (Sanderson, 1988).

3.4.4 White Sea

The White Sea lies in the northern part of Russia, between 32 and 44 East and 63 47` and 68 4` North. Its total area is about 95000 square km, the shoreline - about 3000 km, the average depth - 60 meters, the deepest place - 330 meters.The White Sea is a shallow, semi enclosed sea with tide up to 2 meters and has ice cover from December to May. The water masses in the White Sea basin are formed mainly with mixing the river run-off and water inflow from the Barents Sea through the Gorla Strait (Kaitala et al., 2004).

3.4.5 Caspian Sea

The northern part of the sea freezes in the winter and the ice formation usually starts during November. The whole northern part of the sea is covered with ice in severe winters. In soft winters, the ice is formed in shoals within the 2-3 meter isobaths. The occurrence of ice in the middle and southern parts of Caspian Sea starts in December - January. Ice has its origin at the east coast, at the west coast it frequently is taken to by the currents from northern part of the sea. The fast ice in the northern part of the Caspian Sea is usually 0.1-0.3 m thick.

Ice conditions in Caspian Sea are summarized in Dickins (2003):

- The North Caspian Sea is characterized by relative thin ice lasting for a small proportion of the year, typically 40 -50 cm maximum for three month of the year
- Ice cover varies significantly from winter to winter and the southern ice boundary is extreme variable
- In an average year, the region north of a line from Tuleny islands to the Kulali islands has a greater than eight-tenth ice coverage

3.5 Japan Sea

At present time, there is no oil and gas production on the shelf of the Japan Sea, but it is an intensive oil products transportation route. The reference according to the ice condition in the Japan Sea and Bering Sea is mainly based on the Oceanographic Atlas, Russia (Rostov et al.)

3.5.1 The Japan/East Sea

The Japan/East Sea is located in the North-Western Pacific between the continental coast of Asia, the Japanese Islands and Sakhalin Island. According to the ice conditions, the Japan/East Sea can be divided into three areas: the Tartar Strait, the area along the coast of Primorye from Povorotny Cape to Belkin Cape and Peter-the-Great Bay. In winter, the ice is constantly observed just in the Tartar Strait and Peter-the-Great Bay, in the rest water area, excluding the closed bays and inlets in the north-western sea area, the ice is formed from time to time. In the Sea of Japan the ice cover reaches its maximal development in the middle of February. In average, the ice covers 52% of the Tartar Strait area and 56% of the Peter-the-Great Bay.

3.5.2 The Okhotsk Sea

The Okhotsk Sea is located in the North-Western Pacific near the Asian coast; it is separated from the ocean by a chain of the Kuril Islands and Kamchatka Peninsula. In the south and west it is bounded by the coast of Hokkaido Island, eastern coast of Sakhalin Island and the coast of the Asian continent. A long winter leads to the strong cooling of the sea surface accompanied by the intensive ice-formation almost in all sea areas. Here, both the fast ice and the drifting ice occur. As a whole, by the severity of the ice conditions the Sea of Okhotsk is comparable to the Arctic Seas. Average ice period in the north-western area of the sea makes 260 days, in the northern areas and near the coast of Sakhalin Island - 190-200 m, in the south - 110-120 days a year. During the most severe winters the ice cover occupies up to 99% of the total sea water area, and in warm winters - 65%. Northeast Sakhalin: The annual pack-ice regime is highly dynamic and variable; freeze-up usually begins in late November or early December. Tidal current superimpose circular ice movements and the average ice speed is expected to be 0.5 m/s, but speeds over 0.8 m/s can be reached 10% of the time.

3.6 North American waters

3.6.1 The Bering Sea

The Bering Sea is located in the Northern Pacific between the Asian and North American continents in the west and east, and the Aleutian and Komandorskie Island Arc in the south. The Bering Sea is the northernmost of the Far Eastern Seas and the most severe by its climate characteristics and ice conditions. The Bering Sea is known to have complicated ice conditions, especially in the northern part. Ice formation and distribution in the sea are mainly conditioned by the atmospheric circulation, intended coastline and large shallow water areas in the north-western and especially in the north-eastern parts. In winter and spring about half of its water area the pack and drifting ice. Almost all ice mass is formed and melts immediately in the sea basin. As a whole, the duration of the ice period with regard to the winter being severe or not makes 80-252 days for warm winters, 120-294 - for moderate ones, and 170-365 days for severe winters.

3.6.2 Beaufort Sea (USA and Canada)

The Beaufort Sea is nearly entirely covered with ice during 9 and more month per year. Ice formation begins in late September –early October. Generally, during the middle of winter the Beaufort Sea is 10/10 ice covered and from November to May the ice coverage usually exceeds 5/10 coverage (Sanderson, 1988). The average thickness of the ice are 1.5-1.8 m. Ice cover may be conditionally divided into fast ice, which include interaction of the fast ice edge and drift ice, and the zone of multi-year drift ice.

3.7 Baltic water

The Baltic Sea is a seasonal ice covered sea. The season normally takes place from October-November to May-June. The annual maximum ice extent occurs between January and March, normally in late February – early March. The ice covers on average about 200 000 km², which is almost a half of the total area of the Baltic Sea. During extremely mild seasons the maximum extent is well below 100 000 km². The minimum extent was reached in 1989 with only 52 000 km². The Baltic Sea ice occurs as fast ice in coastal areas and skerries and as drift ice further out. The ice dynamics problem offers n own regime of scales somewhere between large polar sea with permanent ice circulation system and small basins where the mobility of the ice is very limited. The size of the Baltic Basin is 100-300 km, the thickness of undeformed ice is up to 1 m, and ice ridges are typically 5-15 m thick (Leppäranta, 2001).

4 Modelling of drift and weathering of oil-in-ice

The behavior of oil in ice is complex, and difficulties in modeling the physics of ice movement and formation on scales of meters are magnified when the uncertainties of oil behavior are added. A very significant literature exists for describing oil-ice interaction studies over the past 30 years. Dickins and Fleet (1992) give extensive overviews of the subject up to the beginning of the 1990's.

Work since has focused mainly on spreading of oil in and under ice (Yapa and Weerasuriya, 1997; Yapa and Belaskas, 1993; El-Tahan and Venkatesh, 1994), but calibrations rely largely on small scale, short term laboratory studies. After the first hour or so, spreading in the field will be governed by ice lead dynamics, which tend not to be included in these solutions. A further summary is included in the more general manuscript on the state-of-.the-art in oil spill modeling by Reed et al (1999), with the most recent published review probably being that of Fingas and Hollebone (2003). This latter work refers primarily to older literature from the 1970's and 1980's, so is of marginal value.

The most realistic field data on the weathering of oil in the presence of sea ice is that reported by Singsaas et al. (1994). These data shows that the processes of evaporation, dispersion, and emulsification are all significantly retarded in ice leads, contrary to the conclusions drawn by Payne et al. (1987) from mesoscale laboratory experiments. Wave-damping, the limitations on spreading dictated by the presence of sea ice, and temperature appear to be the primary factors governing the observed weathering rates.

A key problem in achieving any improvement in modeling these processes lies in our very limited ability to model the behavior of the ice itself at the necessary spatial scales, which are on the order of meters. The real time forecasting attempt reported by Reed and Aamo (1994), and the model development and hindcasting work by Johansen and Skognes (1995) exemplify the problems encountered when oil-ice interaction models are put into active use in the field. The present limited ability to model ice behavior at the 1-10 m scale also seriously limits the extent to which use can be made of the advances in modeling of oil spreading cited above. Ice coverage is a dynamic variable, and can change from 50% to 99% overnight, with extreme consequences for oil weathering due to changes in thickness.

The most recent published work to our knowledge in oil-ice interaction modeling is that carried out by Gjøsteen (2004). Some Russian researchers are also active in this area, but do not tend to publish in the English language journals, and only occasionally appear in conference proceedings (e.g Ovsienko et al., 1999). Both Gjøsteen and Ovsienko have developed spreading models that allow spreading of oil between ice floes. One key challenge in the advancement of the state –of-the- art will be to parameterize ice cover and oil spreading models in a coordinated fashion that can take advantage of these mathematical procedures.

Modeling of oil weathering in the presence of sea ice remains at an *ad hoc* level, limited largely by the state-of-the-art in modeling (or parameterization) sea ice physics at the appropriate scale. Advances have been made in our understanding of oil weathering processes in the presence of sea ice. This new understanding has come primarily through field work, the results of which have corrected misconceptions introduced through prior laboratory weathering studies. Significant advances in oil-ice interaction modeling will require that oil behavior and fates, ice cover, and hydrodynamic models be coordinated to take advantage of new knowledge in both ice cover and oil-ice interaction modeling.

5 Present oil spill response options for ice infested areas

The following oil spill response alternatives are summarised in this chapter.

- Mechanical recovery
- In situ burning
- Dispersants

5.1 Mechanical oil recovery

Most ice-infested areas have ice-free seasons when technology developed for oil spill combating for open waters can be used. For such open waters and with non-icing conditions, use of existing mechanical equipment will be feasible. In ice-covered waters and under icing conditions, existing equipment has not been proven to be effective for oil recovery. The main problems are associated with accessibility of the oil, ice processing and manoeuvrability of a working platform. The opportunity to test and adapt techniques under real field conditions often has been lacking during development of recovery equipment.

Oil recovery operations in ice infested waters will be confronted with totally different problems than in open waters (e.g. Johannessen et al., 1996 and Evers et al., 2004).

1. Limited flow of oil to the recovery device
2. Limited access to the oil
3. Deflection of oil together with ice
4. Separation of oil from ice
5. Contamination of ice /cleaning of ice
6. Increased oil viscosity
7. Icing /freezing of equipment
8. Strength considerations
9. Detection of oil in various ice conditions

5.1.1 Early R&D on oil-in-ice recovery (1970-80)

Motivated mainly by the potential to develop large hydrocarbon resources in arctic and sub arctic regions, mechanical recovery of oil in ice was studied extensively in USA and Canada in the 1970s. In Canada, following the government decision to allow drilling in the Canadian Beaufort Sea, the government-funded Arctic Marine Oil spill Program (AMOP) was initiated in 1977, with the aim to develop oil spill countermeasures for ice-infested waters. Several other oil-in-ice research programs were initiated by government or industry. R&D projects had also been organized in Norway, Sweden, Finland, Germany, Japan and UK, but no large programs were organized such as in North America.

Work conducted on mechanical oil recovery methods in the 1970s and 1980s mainly centered around further development of commercially available equipment for open water conditions, with modifications usually focused on ice processing. AMOP research focused on winterization of three Canadian skimmers, the Morris Industries disc skimmer, the Bennet/Versatile oleophilic belt skimmer and Oil Mop Pollution Control’s belt skimmer. In the US, the Marco belt skimmers, the ARCAT mop skimmer and the Lockheed disc/drum were given special attention due to their potential to function under winter conditions.

In 1992, a state-of-the-art review on oil-in-ice recovery was published by the Canadian Petroleum Association (Solsberg & McGrath, 1992). In all, 47 primary technologies were presented along with a summary of less feasible concepts. The latter either was considered to hold little promise for future R&D or had already been considered in prototype development and testing. The 1992 study summarized the status of oil-in-ice research and identified the most promising approaches in terms of seven oil removal principles:

1. Disc/Drum skimmers (low development potential)
2. Rope skimmers (high development potential)
3. Sorbent belt skimmers (low potential)
4. Submerging plane skimmers (low development potential)
5. Vacuum skimmers (low development potential)
6. Weir skimmers (low development potential)
7. Combination skimmers (high development potential)

The main disadvantages with the skimmer principles which were evaluated to have a low potential were the problem with separating oil and ice causing jamming, low recovery and possible damage. Two principles were regarded as promising: the rope skimmer and combination skimmers. The combination skimmers were expected to be able to separate oil and ice to enhance oil recovery.

Rope mop systems are adhesion skimmers and have been reviewed extensively for application to oil-in-ice. The oleophilic rope principle has demonstrated its effectiveness in removing medium viscosity oils in low wave conditions, at relative velocities of up to several knots, and in debris (including ice). Vertically-oriented rope mops driven by a driver/wringer unit suspended from a crane, e.g. the Foxtail skimmer (Figure 5.1) represents an appealing technology for removing oil-in-ice since selective positioning is possible and since there is no need to actively process ice encountered by the recovery unit.

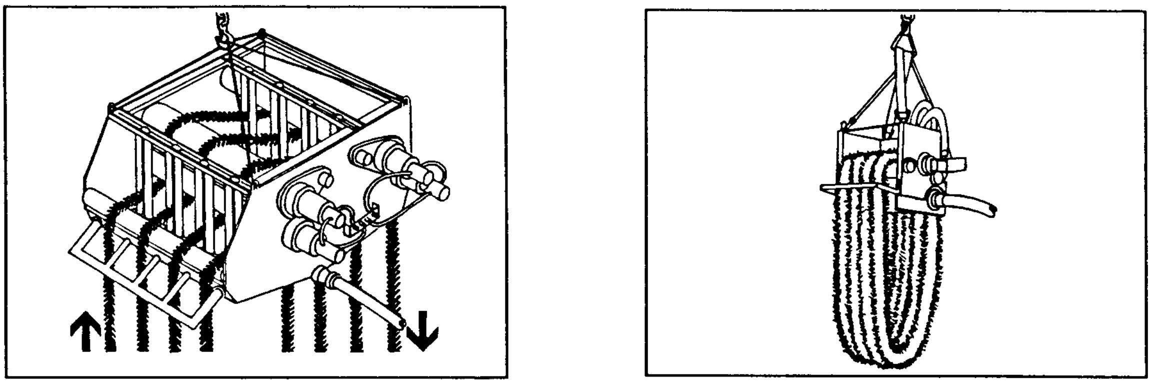


Figure 5.1 Vertical rope mop skimmers

A diverse number of other skimmers were considered and tested for recovering oil in ice. The Lori Brush Skimmer (Finland, Figure 5.2) had potential for recovering viscous oil in broken ice. Implemented in the Lori Ice Cleaner, a two stage brush system using brushes and water jets to process or clean ice and recover viscous oil. This principle has potential recovery of viscous oils from small ice forms, i.e. ice pieces that can underflow the skimmer. An outrigger type of ice deflector called Arcticskim developed in Alaska was also evaluated as potential, with limitations due to damage by ice floes, oil deflection, and the concentration and jamming of smaller ice forms which might prevent oil from reaching the skimming mechanism (Figure 5.2).

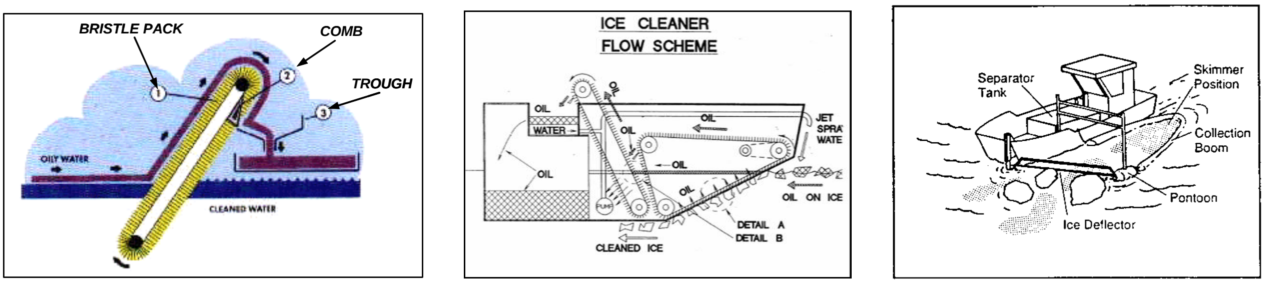


Figure 5.2 Other concepts. LORI brushpack (left), LORI Ice Cleaner (middle), Arcticskim (right).

5.1.2 Later R&D and present status in North America

The North Slope of Alaska contains the largest oil field discovered in North America, the Prudhoe Bay, together with many satellite fields. Onshore production began in 1977, while offshore production began in 1987 (Endicott/Duck Island) and was expanded with North Star in 2000.

As a part of an effort to enhance oil-in-ice handling capability Ross & Dickins (1998) evaluated the cleanup capabilities for a large blow-out in the Alaskan Beaufort Sea. The mechanical equipment included in the evaluation was traditional boom and skimmer systems stockpiled by Alaska Clean Seas. The recovery capability of a spill from a surface blow-out in broken ice during freeze-up was evaluated to be very low.

In 1999 Alaska Clean Seas expanded its marine oil spill response capability in Prudhoe Bay and established a barge-centred system for oil spill containment, recovery and intermediate storage. The barge is operated by an conventional icebreaker. The main components of the equipment are a LORI Brush skimmers, Archimedean screw pumps (Desmi), and heavy offshore Ro-booms for containment. This was considered the best available technology (BAT) for maximizing oil encounter rates under these conditions. This system was tested in different ice conditions during 2000 and the test results are summarised by Bronson et al. (2002). Spilled oil was not part of the tests and therefore oil encounter rate, oil recovery rate and oil throughput rate were not estimated. According to Bronson et al. (2002), the tests demonstrated that the response operating limit of the specific barge-based system deployed in July and October 2000 was less than 1/10 ice coverage. Prior to testing, the operating limit was expected to be about 3/10 ice coverage.

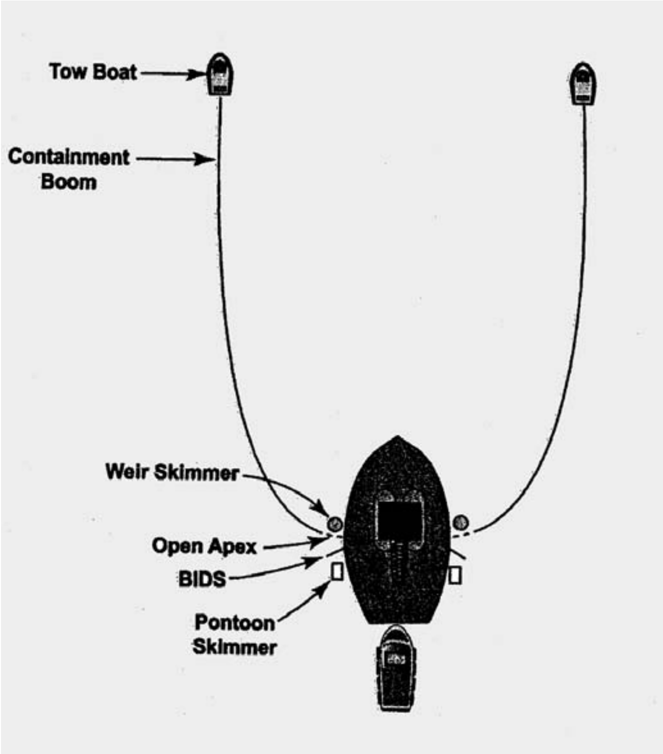


Figure 5.3 Prudhoe Bay barge-based containment and recovery system showing booms and alternative skimmers (left), on its way out from West Dock during freeze-up (right).

ACS has established contingency plans for various ice-conditions like onshore, in creeks and rivers, shoreline, offshore during open water season, broken ice and winter with continuous ice, see ACS Technical Manual, vol. 1 (available at www.alaskacleanseas.com). Freeze-up in the Alaskan Beaufort, until the ice reaches some 30 cm in thickness, is typically a three to four weeks period in October. ACS considers the freeze-up to offer the most difficult conditions for spill response offshore, together with the spring break-up. Winter conditions, where the ice is thick enough to support heavy machinery, is considered easier, partly because of the ice acting as the working platform, partly because the ice is landfast, and oil deposited under ice will be stationary until spring break up.

5.1.3 Later R&D and present status in Norway

The ONA program

In Norway an R&D program on oil combating in northern and Arctic waters (ONA, started 1989) was dealing mainly with fate and behavior of oil in cold water/ice and later different contingency methods. This program was motivated by exploratory drilling for hydrocarbons in the Barents Sea, and was funded by the Norwegian Clean Seas Association (NOFO). The program culminated in 1993 with experimental spills of crude oil (26 m^3) in the Barents Sea ice to study spreading, weathering and fate of the oil. Due to lack of discoveries from the exploratory drilling in the Barents Sea, this R&D program came to a halt just as the focus was planned to be shifted towards improvement of combating techniques for oil in ice. The ONA program was divided into several different tasks:

1. Biodegradation of oil spills
2. In-situ burning of oil
3. The Arctic physical environment
4. Use of dispersants and demulsifiers
5. Mechanical oil recovery
6. Oil properties
7. Operational aspects (including logistics for the full-scale field experiment)

Most of the technical reports from this program were unfortunately written in Norwegian. However, many publications from this program, and also a review report (Vefsnmo et. al, 1996), are available in English. The publications available in English are referenced below.

1. Biodegradation of oil spills
The measured biodegradation rates were very low and evaluated not to be of interests for treating acute oil spills in ice (Sveum, P and Faksness, L-G (1993) and Sveum, P and Bech, P (1993)).

2. In-situ burning of oil and emulsions
Experiments were performed in the SINTEF burning laboratory in Trondheim and at field facilities on Svalbard. During the 1991-94 activities included; burning of water free and emulsified oils, importance of wind and waves, characterization and toxicity of burn residues and testing/development of igniters (Bech et al, 1993, Guenette C. and Sveum P., 1995 and Guenette C, 1997). Several of these activities were performed in close cooperation with related R&D institutions in US (e.g. SL Ross)

3. The Arctic physical environment
Studies were performed on the meteorological and oceanographic conditions relevant for oil spill countermeasure operations. MetOcean data for the northern part of the Barents Sea was collected and are available in a comprehensive report written in Norwegian. Parts of this are available in the English summary (Vefsnmo et. al, 1996).

4. Use of dispersants and demulsifiers
Dispersants and demulsifier testing were performed under Arctic conditions (low temperature and varying salinity), Brandvik et al. (1993). Also preliminary testing of dispersant in ice was performed in the laboratory and meso-scale facilities. The main challenges pointed out were the lack of suitable products and equipment for dispersants application with oil-in-ice.

5. Mechanical oil recovery
A literature review regarding mechanical recovery of oil in ice was worked out and some concepts were tested with oil in SINTEFs large scale climate laboratories (basins). The concepts of ice deflecting by using booms were also tested in basins and evaluated theoretically (Carstens et al., 1992, Løset, S. and Timeo, G., 1992).

6. Oil properties
Several oil types were weathered in a very early version of SINTEFs meso-scale flume for oil weathering with ice present. It was not possible to freeze salt water ice in the flume at that time so fresh water ice blocks were added. Weathering properties like evaporative loss, emulsification, natural dispersion etc. were monitored. Preliminary viscosity measurements and estimates of pumping rates at low temperature was performed for relevant skimmers and pumps. Singsaas,.et al. (1993).

7. Operational aspects
This activity contained the operational aspects concerning the full-scale oil release in the marginal ice zone in 1993. The field operations are described in Johannessen, B.O. and Jensen, H. (1993).

At present the interest in Norway for oil spill countermeasures in the northern areas is again increasing, partly due to new interest from the oil companies regarding exploratory drilling and, partly due to the increasing tanker traffic outside the Norwegian coast from Russia to Europe and USA. To improve the preparedness against oil spills, Norway and Russia in 2003 have widened the scope of an existing bilateral agreement to cooperate in this area, and the first training course within this agreement took place in Murmansk in October 2003.

For oil-in-ice recovery, the experience in Norway related to real spills is at a low level. Oil spills in ice have been very few, and only of small scale in sheltered coastal waters or inland waterways. To our knowledge the only skimmer that has been thoroughly tested in Norway in cold climate and with ice present, is the Foxtail rope mop skimmer. This is one of the most common skimmers in the Norwegian national contingency plans, and Solsberg & McGrath (1992) considered it to have a good development potential for oil-in-ice recovery. Based on tank tests in ice and in temperatures down to -18^{o}C, SINTEF has recommended a series of modifications for the Foxtail in cold conditions (Johannessen et al., 1996).

On behalf of the oil industry, NOFO has based their oil spill contingency mainly on the Transrec system, where a high capacity weir skimmer with internal pump is the most common high capacity recovery unit (100-250 m^3/h pumping capacity). For more viscous oils a so-called Hiwax skimmer (figure 5.4) could replace the weir skimmer. None of these skimmers have been designed to process ice, but both skimmers could be used under open ice conditions as long as ice is not obstructing the inflow of oil. Based on the need to develop equipment for larger oil spills in ice and the principle that already existing/verified equipment could be modified for use in ice, development of the Transrec system to be operational also in ice could be an interesting option.

Figure 5.4: The Hiwax skimmer developed by FRAMO

During the Prestige incident, two complete NOFO systems with Hiwax skimmers, each system operated by a supply vessel and a towing vessel, were hired by the Spanish authorities. Their contribution was much appreciated, although the equipment was not designed to combat spills of heavy bunker oil. As a consequence of the experience with their equipment during the Prestige spill, the manufacturer has further developed the Transrec system with a maneuverable Super-HiVisc skimmer to recover Prestige type emulsion in arctic winter conditions, with free water as a transport medium. To handle this mixture on board the recovery vessel (a large supply vessel), the system also incorporates containerized process equipment including steam boiler, debris strainer, heat exchangers for recovered product prior to storage and in the storage tanks. Even though the new skimmer is not designed for ice processing, this development is a step in the right direction as far as mechanical recovery of oil in ice. At present the heating capacity for this design is sufficient to melt about 30 tons of ice per hour.

A new principle for oil recovery in ice is motivated by the preparation for oil production in ice in the Sakhalin area and for the Prirazlomnoye offshore oil field, which is close to the loading terminal in Varandey. This design is based on the Transrec system from Framo and the intention is to operate the system under ice through the moon pool of a supply vessel. It is much too early to know whether this will be a useful tool, but it is appealing to have the possibility of operating in 100% ice coverage, even with pressure in the ice.

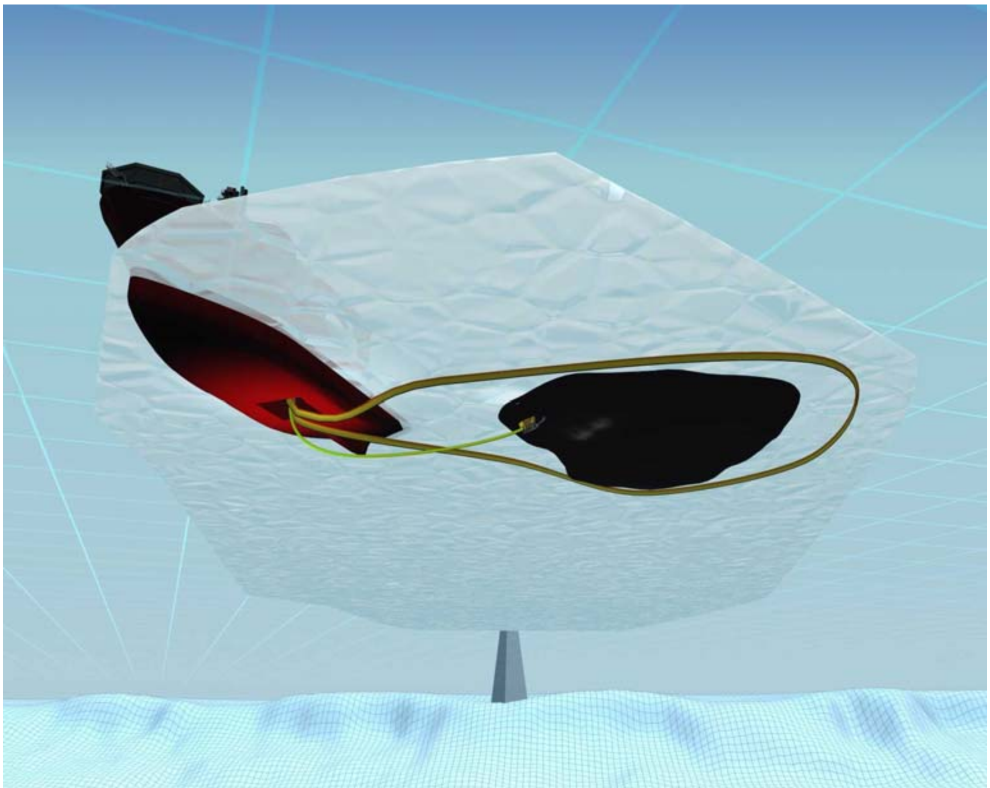


Figure 5.5 Possible principle for under-ice oil recovery (Illustration from Framo).

The MORICE (Mechanical Oil Recovery in Ice-infested Waters) project was initiated in 1995. Through several phases, organized as separate projects, MORICE included various participations from Norway, USA, Canada, Germany and Finland. The project was finalized in 2002 after testing the recovery system with oil and ice at the OHMSETT test tank in Leonardo, New Jersey (Jensen & Mullin, 2002).

The MORICE scenario included conditions that are fairly mild:

- Broken ice
- Up to 70% ice concentration on a large scale; locally up to 100%
- 0 - 10 m ice floe diameter
- Small brash and slush ice between ice floes
- Mild dynamic conditions (current, wind)
- Oil within a wide viscosity range

Based on the literature studies and the experience from the members of the project team, approximately 20 concepts were considered to have some potential for development, including concepts on ice processing, ice deflection and oil recovery. A number of concepts were proposed, of which ten were subjected to detailed discussions. The next step or phase involved qualitative small scale laboratory testing in oil and ice for most of the proposed concepts. Ice-infested water conditions were mimicked in a 5 by 8 meters test tank. These small scale studies reduced the number of concepts that warranted further evaluation and development to three. In the following phase, more carefully designed models of two of the concepts were constructed and brought to the Hamburg Ship Model Basin (HSVA), Germany, to evaluate their oil recovery and ice processing performance at a more quantitative level. In Phase 4 a full-scale harbor-sized unit was designed and constructed, comprising oil and ice processing components as well as a catamaran work platform. This unit was tested in ice conditions and modified in several phases starting in Prudhoe Bay during freeze-up in October 1999, in the Hamburg Ship Model Basin, in Prudhoe Bay, Alaska, during freeze-up in 2000 and a full-scale test of the MORICE unit at the Ohmsett facility in New Jersey.

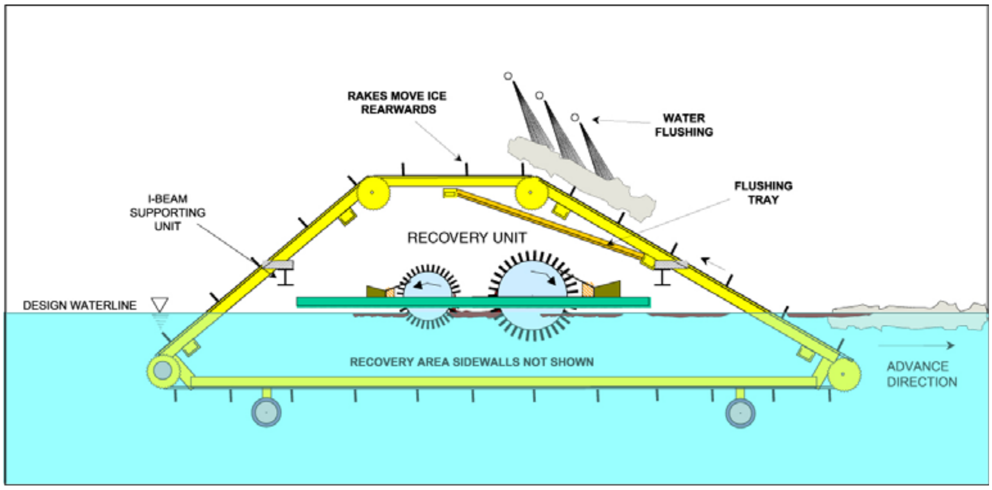


Figure 5.6 *MORICE ice processing and recovery principle. Larger ice pieces have oil flushed off while lifted out of the water by the grated belt, where after the ice is redeployed behind the unit. Oil and small ice goes through the grating and enters the recovery area where the oil is recovered (together with some ice).*

Figure 5.7 *Working platform with heated enclosure to avoid icing and freezing of equipment.*

Nearly all the ice processing and recovery components were sheltered from exposure to wind by a lightweight enclosure (Figure 5.7) that could be kept at temperatures around 30^{o}C even at outdoor temperatures around -20^{o}C. This proved to work very well, and solved the problems with icing and freezing. The MORICE concept was brought to a stage where it is ready for industrialization. The unit that was built is referred to as a harbor sized unit to indicate the conditions in which this particular size and strength of unit could operate. The choices made regarding cleaning of ice before redeployment also very clearly limit the operating speed and hence the encounter rate. For these reasons the developed system would be suited for thorough cleaning of a small spill in ice in harbor conditions. To combat a larger spill in offshore conditions, the scale of the unit would have to be increased accordingly, both regarding size and strength. The ice processing speed would have to be increased dramatically, which would require a wider and more heavily constructed belt.

5.1.4 Later R&D and present status in Finland

The Finnish Environmental Institute (FEI or SYKE) has encouraged development of oil recovery devices for cold and ice-infested waters, and the institute has also itself developed new technology for oil recovery. Several of the products developed over the years are now in operative use.

<u>LORI Ice Cleaner</u>
The Ice Cleaner developed in the early 1990s was a result of this effort. This unit is operated and pushed by a vessel through broken ice. The displacement is about 25 tons, and the operating principle is a combination of a submerging inclined plane and brush skimmer in two stages to separate ice from oil and water prior to the final recovery, see Figure 5.2 from Solsberg and McGrath (1992).

<u>Oil Recovery Bucket</u>
A rotating brush with a pump inside the bucket that could be used with typical excavators has been developed for cleaning up oiled shoreline or oil in ice (Lampela, 2001). The working principle of the Oil Recovery Bucket is that oil adheres to the stiff, rotating brushes of the equipment. As the drum rotates, the oil is scraped off the brushes and the oil enters the bucket. A screw pump transfers the oil to storage tanks. In tests conducted by the Technical Research Centre of Finland (VTT), the recovery efficiency in broken ice conditions was about 50%. This equipment designed by FEI has been used in some real spills with good results.

<u>Air plume</u>
The pneumatic air method to steer oil under ice into a pre-selected direction was tested in Finland in 1993 with minor effects on the oil slick. In 2002 new experiments were conducted where the pneumatic air was released deeper under the ice, from 10 m to 30 m water depth (Rytkönen, 2003). This will cause a significant vertical water flow due to the rising bubble plume. When the vertical flow hits the ice cover, it bends and induces a horizontal, eddying flow. Higher air discharge and outlet depth both increased the velocities. The strongest measured flow was with 4 m^3 air per minute at 30 m deep, creating a maximum average water velocity of about 40 cm/s. This could be enough to clean oil from the subsurface of the ice, but will depend on the characteristics of the under ice surface. ExxonMobil have shown interest for this principle and are evaluating to fund further projects focusing on this approach.

<u>Arctic skimmer</u>
The Arctic Skimmer is a crane-operated system to be deployed vertically for recovering oil in broken ice. The skimmer incorporates static ice deflection pipes and rotating brush wheels for oil separation and collection. Recovered oil and small ice pieces are delivered into a collection hopper with screw conveyors that feed the material into an Archimedes Screw pump for transfer to storage. The idea is that by moving the skimmer in between blocks of ice, the ice surfaces can be cleaned and oil floating between the ice blocks can be recovered.

<u>The Vibrating Unit</u>
A novel Ice Vibrating Unit was designed for ice conditions by the FEI to be used in the presence of broken ice in shipping channel in Finnish waters. The idea of the ice vibrating unit is to submerge ice (and oil) by an inclined plane pushed through the ice field by a vessel. The inclined plane is a vibrating grid that forces the submerged rubble ice to move upside down and possibly to rotate by moving the grid. The unit is designed to withstand the forces from the rubble ice field in the shipping lanes when moving at maybe 3 knots. The ice vibrating unit was tested both in laboratory in 1997 and in full-scale with oil in rubble ice conditions in a shipping channel in 2001.

The main principle was confirmed and modified versions were tested both during spring 2002 and in March 2003 in broken ice (*Figure 5.8*). An up-scaled and improved version of this prototype is expected to be installed on two Finnish Coast Guard patrol vessels, Lampela (2003).

Figure 5.8: The Vibrating unit attached to the side of the vessel Linja.

The installations decided on the service and patrol vessels indicate the confidence in this system from the Finnish authorities. However, the vibrating unit system is not suitable for Arctic conditions found in e.g. the Pechora and Kara Seas. Ice conditions there are characterized by larger floes and drifting ice. This implies that unlike in the Baltic Sea, new shipping lanes may have to be broken all the time through fairly thick ice. The ice in such a shipping lane would be different from the rubble ice field found in the Baltic, and the typical size of ice pieces mixed with the oil would probably be larger.

5.1.5 Later R&D and present status in Russia

The main institution for marine oil spill response operations in the Russian part of the Barents region is the Murmansk Basin Emergency and Salvage Department (MBESD). MBESD is a state enterprise under the Ministry of Transportation of Russia. The activities are coordinated by the State Marine Pollution Control, Salvage and Rescue Administration of the Russian Federation. MBESD has to main responsibilities, rescue/salvage and oil spill response operations. MBESD implements oil spill prevention and response activities during reloading and shipment in Ob Bay, Varandey, Kolguev Island and Kola Bay (Bambulyak et al., 2005). In addition, there exist several other organizations that are responsible for oil spill prevention in different part of Russia which are supplied with oil combating equipments e.g.:

- Arctic Skimmer Company, Murmansk was founded in 2004 and attested as a salvage unit. The operational area is the Western part of the Russian Arctic.
- In Arkhangelsk port, the oil spill prevention and response service at the oil loading terminal are provided by the Marine Specialised Unit for oil spill response (MSU OSR).
- Specialised unit of the Rosneft-Arkhangelsknefteprodukt takes care of oil spill prevention and response operations at the oil loading terminal in Talagi
- The port of Vitino, in the White Sea, formed in 2003 a specialized oil spill prevention and response division (Vitino OSPR)

Russian scientists have in the last decades performed several research work regarding modelling (numeric analysis) of ice condition in the Arctic areas (Chmel et al., 2005, Marchenko et al.,2005, Makshtas *et al.* 2004, Makshtas *et al*., 2003 , Vasiliev *et al.*,1995, Marchenko, 1992). There is also performed experimental works related to sea ice modelling, e.g. ice tank experiments for meso-scale ice sea modelling (Ovisenko *et al*., 2005, Tuhkuri and Lensu, 1997). Russian scientist participates also in several major international programs and symposiums/congress to contribute with their knowledge to a mathematical approach related to ice drift and ice dynamics.

Models – sea ice drift and dynamics

Marchenko *et al*, 2005 have developed models describing sea ice dynamics accounting linear accumulation of the ice in ridges. Basic equations for the calculation of the sizes and the number of the ridges taking into account angular distribution of space orientation of the ridges are formulated and analyzed. Stress-strain relations of sea ice rheology based on deformation theory of plasticity are discussed. The using of elaborated approach is illustrated by numerical simulations of the number of ridges in the Arctic from 1950 to 2001. The fractality of sea-ice drift dynamics as revealed from the 'North Pole 32' monitoring are described by Chmel et al., 2005. The temporal characteristics of sea-ice motion were analysed using the database of field observations obtained during the drift of the ice camp.

Dynamic model of ice ridge build-up

Dynamic models of ice rafting and ice ridge build-up have been studied by Marchenko et al., 2005. The milestone of the models is the conception of a ridgeline accumulating in broken ice due to vertical displacements of ice blocks separated from the edges of compressed floes. The ridgeline is considered as a discontinuity line over which ice drift velocity is changed by a leap. The estimated characteristics of ice continuum along the ridgeline are the linear densities of volume, impulse, and energy. The equations describing the motion of the ridgeline and the growth of ridge volume are constructed. The expression for internal ice stress on the ridgeline is found in explicit form for arbitrary scenario of ridge build-up. Elaborated theory is used for the estimations of ice stresses for most typically observed scenarios of ice rafting and ice ridging. Simulated stresses are compared with the results of laboratory experiments and discrete particle modelling.

Ice modelling

The numerical method developed by Sergey Ovsienko and his team from the Russian State Oceanographic Institute is one of the variants of particles-in-cell method for quasi-two-dimensional compressible media with free boundaries. This method is used to find solution (calculate unknown values such as velocity of drift, compactness etc.) in areas with unknown configuration. Its typical situation, when ice cover only part of basin, this part is known in some moment (e.g. from satellite image) a necessary determine configuration of ice covered area in next period. This method was tested in a lot of numerical experiments in modelling of ice dynamics, oil dynamics, inter- thermocline lenses dynamics. It was investigated the accuracy, transport and numerical viscosity properties of method. This numerical scheme was used for ice modelling in Baltic Sea, Caspian Sea, Barents and Kara Seas and for modelling of ice tank experiments in Finland. Adaptive quasi-eulerian grids with different resolution and Lagrangian grid of particles are used. This numerical technology compatible with oil spill modelling.

Ice tank experiments – meso-scale sea ice modelling

The use of ice tank experiments for meso-scale modelling has been done to examine the representation and parameterization of ice mechanics (Ovisenko et al., 2005). The ice tank studies include elasctic-plactic rheology and a Lagrangian description for ice advection. This is ongoing research project and the coming conclusions will tell about the feasibility of the ice tank experiments for meso-scale sea ice modelling. However, an extensive series of ice tank experiments in ridging and rafting has been performed by the Arctic Marine Laboratory of the Helsinki University of Technology (HUT/AORC) during 1996-1998. Ice tank experiments are useful and promising approach to understand sea ice behaviour (Tuhkuri and Lensu, 1997).

Possible dynamic and thermal causes for the recent decrease in sea ice in the Arctic Basin
A dynamic-thermodynamic sea ice model with 50-km spatial and 24-hour temporal resolution was used to investigate the spatial and temporal variability of the sea ice cover and the surface energy exchange in the Arctic Basin (Makshtas et al., 2003). Daily surface level air temperature and pressure data from National Centers for Environmental Prediction for 1958–1997 and climatic data for cloudiness, relative humidity, snow precipitation, and the heat flux from the deep ocean in the Greenland, Barents, and Bering Seas were used as external forcing.

Oil behaviour in Ice Sea – under solid ice cover
The main factors affecting the spatial distribution of oil contamination under ice are currents, the degree of the lower ice edge roughness, and the possibility of ice capturing oil from water, based on the data of field and laboratory experiments and there has been suggested a theoretical model of under-ice movement of lenses (Ismailov, 1988). Specialists from St. Petersburg State Technical University have been involved in studies of oil spreading in water and under ice for more than 15-10 years, respectively Ahlimenko, 1989 and 1995. Experiments in Gulf of Finland have been performed in 1996 with participants of Russian specialist (Ahlimenko et al., 1997).

Modelling of behaviour and spreading of oil in cold water and ice condition
Brief description of the physical basis, mathematical formalization and original numerical technique for oil spreading model are presented. The governing equations for oil spreading at the water surface are supplemented by the additional terms describing the viscous stresses in oil slick. The boundary of oiled area is considered to be unknown, and is determined in the process of solution. The particles-in-cell technique on quasi-Eulerian adaptive grids is used. The problems of the model developing and tuning are discussed. The results of modeling are discussed to estimate a validity of derived equations in oil behavior description (Ovisenko et al., 2005).

Oil loading of tankers
A research work package by developing a roadstead loading system of tankers has been carried by Krylov Institute in St. Petersburgh in their ice test tank. The purpose was providing the ice conditions for tanker mooring, mooring and loading hose connection with the tanker, stable operation of the system as a whole during loading operating, and mooring and loading hose disconnection and tanker unmooring.

Figure 5.9 The general arrangement of export system of road loading of tankers.

Krylov Institute has in addition performed development work considered to change the PLEM (Pipe Line End Manifold /submarine manifold), and bow loading system design by increasing the loads and improve the reliability of the machinery (figure 5.10). As a result, a fundamentally new and unique technology of tanker loading from non-equipped shore in ice conditions was developed (patent for invention) (Moreinis et al., 2005).

Figure 5.10 Overview of PLEM – a gravitational anchor with a manifold and oil swivel. This special stationary device is mounted on the sea bottom.

<u>Institutes of possible collaborators</u>

MMBI
The Murmansk Marine Biological Institute (MMBI) is a research institute in the frame of the Kola Scientific Center of the Russian Academy of Sciences. MMBI solves for instance applied problems within marine biology, oceanography and ecology. In 2004-2005, SINTEF engaged MMBI to prepare a research work regarding an overview of Russian oil properties and routes for its transportation for export through the port on the Barents Sea and the White Sea. SINTEF and MMBI will probably during the first quarter of 2006 make a letter of intent between these two organizations.

CNIIMF
Central Marine Research and Design Institute in St. Petersburgh has been a central contributor to the ARCOP (Arctic Operational Platform) program during the period from 2003 to 2005. The ARCOP project is a research and development project supported by the European Union, which was part of the ”Competitive and Sustainable Development” program. SINTEF has previously co-operated with research scientists at CNIIMF, Semanov in 2003 regarding characteristics of Russian oils.

AARI
The Arctic and Antarctic Research Institute in St. Petersburgh is a Federal Service for Hydrometeorology and Environmental Monitoring of Russian Federation. Center for Ice and Hydrometeorological Information (CIHMF) is an operational sub-division of AARI and it is engaged in acquisition and processing of complex hydrometeorological information (including satellite data), generating ice charts and maps, forecasting the ice coverage and meteorological conditions at the NSR, and also in distribution of operational and prognostic information products to users. AARI provides centralized services mainly for shipping and coastal and harbour activities within the Northern Sea Route, for the Central Arctic Basin and Arctic seas – Greenland, Kara, Laptevs, Eastern-Siberian, Chukha as well as for the seas with the seasonal ice cover – Baltic, White, Bering, Okhotsk and also Antarctic seas.

Selected participant programs
- INTSOK, 2005: Similar to more temperate areas the oil spill contingency planning in Barents Sea is mainly focused on mechanical response.
- EPPR Emergency Prevention, Preparedness and Response) a Program of the Arctic Council:
    - Russia has informed EPPR about the fleet activity NSR (Northern Sea Route).
    - A field Guide for Oil spills in Arctic water was produced in accordance with funding by the eight participating circumpolar countries.
- AMAP (Arctic Monitoring and Assessment Program)
- EMERCOM of Russia. Energy source control management and spill prevention strategies of high priority risks
- PAME members include National Representatives of the 8 Arctic Council States (Canada, Denmark, Finland, Iceland, Norway, Russian Federation, Sweden and United States).
- The Environmental Working Group (EWG). This working group was established in June 1995 under the framework of the U.S.-Russian Joint Commission on Economic and Technological Cooperation. In order to expand scientific understanding of the Arctic, the EWG Arctic Climatology Project compiled a set of three atlases for Arctic oceanography, sea ice, and meteorology. The Arctic and Antarctic Research Institute (AARI) in St. Petersburg participated to this program (V. Smolyanitsky, V.N Smirnov)

- International Assossiation of Hydraulic Engineering and Research (IAHR): Makshtas, A., Marchenko, A., Shoutilin, S., 2004: New schemes of accounting ice ridges in models of sea ice cover dynamics. 17th International Symposium on Ice. St.-Petersburg, Russia, 21-25 June 2004, IAHR,
- 5th International ISAAC Congress, July 25-30, 2005
  Department of Mathematics and Informatics, University of Catania
  Sicily, Italy.

5.2 Dispersants

A dispersant consists of a mixture of surfactants (surface active agents) in a solvent. When applied to an oil slick the surfactants will be oriented at the oil-water interface and contributes to formation of small oil droplets that easily will be mixed into the water column and rapidly diluted and later biodegraded (Figure 5.10).

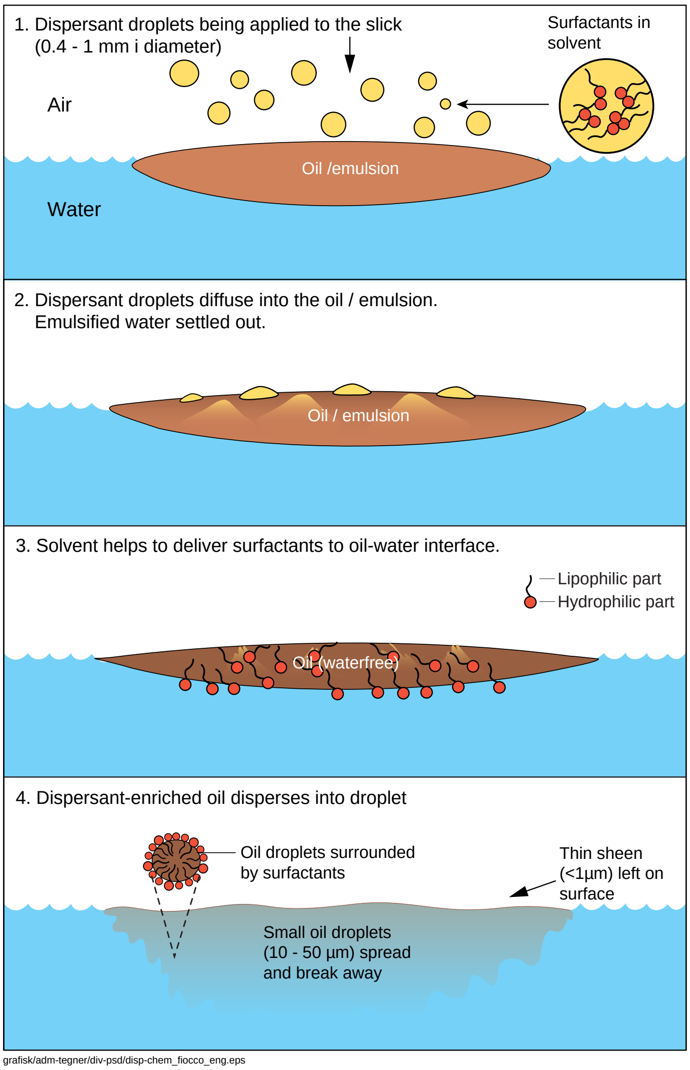


Figure 5.10 Simplified mechanisms for dispersant action.

Limited laboratory and field work has been performed with dispersants and oil in ice. Most of the studies with dispersants under "arctic" conditions have been performed through the Norwegian ONA-program (Daling et al., 1990) and the DIWO-program (Brandvik et al., 1993). "Arctic" conditions are in this context defined as low temperatures (0 to -20°C) both in the presence of ice and without ice. Later cold water dispersants studies have also been performed by S.L. Ross Environmental Research on Sakhalin/Hibernian/North Slope oils (S.L. Ross, 2001, 2002) and at SINTEF/CEDRE on North Sea crudes (Nedwed et al., 2006).

The effectiveness of dispersants is dependent on:

1. Oil properties or oil type
2. Type of dispersant
3. Oil weathering (window of opportunity)
4. Sea water and air temperature (oil and dispersant properties)
5. Sea water salinity (surfactant leakage)
6. Energy conditions (to initiate chemical dispersion)
7. Oil availability for dispersant application

5.2.1 Oil dispersant combination and weathering

The first three subjects on the list above are similar to temperate open water use of dispersants. However, lab./field experiments (Sørstrøm et al., 1994, Brandvik et al., 2004) show that the oil weathering can be slower with high ice concentration and low wave energy. Evaporation, water uptake and viscosity increase will take place at a lower rate in ice. Therefore, the “window of opportunity” for use of dispersants can be significant wider under Arctic conditions than in the North Sea. The meso-scale experiments performed by UNIS and SINTEF on Svalbard in 2005 included weathering experiments with the Statfjord crude under different ice conditions. A simple field test was performed to estimate the dispersibility of the emulsions versus weathering for these experiments.

5.2.2 Low water/air temperature

The effect of low temperature on dispersant effectiveness will vary for different dispersants (Daling et al., 1990). Some products are not very sensitive to temperature reductions, and even positive effects have been registered. Changes in physical/ chemical properties of the oil (pour point etc.) as a result of low temperature can be more significant. The physical/chemical properties of the dispersant itself can also be important for the effectiveness. Especially the viscosity of the dispersant at low temperatures will be important, for instance during application by a helicopter bucket at low temperatures. During later years (2001-2004) are dispersant experiments with low water temperatures and with presence of ice performed by MMS in the Ohmsett facility to test dispersibility at low temperature and under low energy conditions (Mullin, J.V. 2004).

5.2.3 Varying salinity

Dispersants that earlier have shown high effectiveness at North Sea salinity (3.5%) can give very low effectiveness at low salinity (0.5%) (Brandvik et al., 1993). This is an important aspect under arctic conditions as the salinity of the surface water can vary e.g. during melting periods. The effect of low salinity is explained with changes in surfactant interactions on the oil water interphase and surfactant leakage to the water phase. Experiments with leaching of dispersants from the oil phase to water (Daling et al., 1991), have shown that dispersants can remain in the oil phase for a longer period than previously suggested. It is important to study this effect more in detail, as it is important for defining the potential for use of dispersants under different low energy "arctic" conditions. An ongoing joint industry project at SINTEF/CEDRE (PERF) headed by ExxonMobile is focusing on delayed dispersion after application of dispersants (Nedwed et al., 2006). This can be possible with an oil-in-ice scenario where treated oil at a later stage enters into (more) open water and sufficient energy for chemically enhanced dispersion. The project studies both dispersant effectiveness as a function of oil and soaking time. A limited number of experiments will also be performed with oil on ice.

5.2.4 Energy conditions

Dispersant effectiveness experiments have been conducted on Alaskan and Canadian crude oils in cold water and with low energy at the Ohmsett test facilities in New Jersey, USA (Mullin, 2004). Two series of experiments were conducted, the first in February-March 2002 and the second in February 2003. The chemical dispersants Corexit 9500 and Corexit 9527 were applied to fresh and weathered oils. The 2002 test series gave dispersant effectiveness ranging from 82-99% and the 2003 series effectiveness ranging from 74-100%. Two of the oils in the 2003 test series were not dispersible. A total of approximately 25 tests were performed during 2002 and 2003. The results demonstrate that both dispersants were effective in dispersing the crude oils tested in very cold water.

Modern icebreakers and ice classed oil field support vessels are being designed with Azimuthal Stern Drive (ASD) as the propulsion mechanism. With the ability to rotate the propeller pods, a large area behind the vessels may be exposed to turbulent mixing resulting from the propeller wash. ExxonMobil is currently planning a series of lab experiments to test the feasibility of using an ASD vessel to apply dispersant onto an oil spill in ice and use the propellers to provide the mixing energy required for dispersion. Initial basin tests were performed in December 2005 in Helsinki by ExxonMobile.

Conclusions have been drawn from different studies concerning the effect of ice on the use of dispersants (Daling et al., 1990). Both ice floes and slush ice have a wave damping effect. This can reduce the energy to a level below what is required to disperse oil treated with dispersant. With a wind direction towards the ice edge, the energy created by waves will probably be sufficient to start a chemical dispersion process some distance inside the ice edge. Pumping movements between ice floes can also be a mechanism which promotes both natural and chemical dispersion in ice. Another limiting factor for use of dispersants on oil spills in ice is the reduced accessibility for application of dispersants. This is due to the fact that the oil will be found on a limited area between ice floes, especially at high ice concentrations.

5.2.5 Oil availability for dispersant application

Standard methods for dispersant application (spraying booms mounted on boat, helicopter or fixed-wing aircraft) could have limited application in oil in ice scenario due to limited availability of the oil. However, helicopter application has been tested several times during experimental field trials in the North Sea. During last years field trial a large bucket (3 m^3) was successfully used (Brandvik et al., 1995) (figure 5.11). The capacity can be improved if the helicopter is operating from a platform or a supply ship. The good maneuverability of a helicopter makes it a good response tool for application of dispersant in ice-covered waters. Even with an ice concentration up to 50% it should be possible to maneuver the helicopter so that most of the dispersant will hit the oil between the ice floes. Using spraying arms from boat or fixed wing aircraft will probably have limited usefulness in most oil-in-ice scenario, but could be applicable in more open water e.g. outside an ice edge or during melting in the spring.

Figure 5.11: On-land testing of the spraying pattern of Norwegian Response 3000D helicopter bucket with dyed dispersant (from Brandvik et al., 1995).

5.3 In-situ burning

In-situ burning as a spill response technique is not new and has been used for a variety of oil spills. Since the late-1960s both laboratory, tank and field studies have been conducted in order to support drilling operations in arctic waters. Extensive laboratory and field trials have been performed especially in US and Norway. Ian Buist (2000) has made a comprehensive literature survey on in-situ burning of oil spills in ice for the International Oil and Ice Workshop 2000. This review paper contains a description of the fundamental in-situ burning issues and much of the text in this chapter is from this review paper, but only aspects with specific interests for in-situ burning of oil in ice are included in this chapter.

In-situ burning is particularly suited for use in ice conditions, sometimes offering the only option for removal of surface oil. In-situ burning of thick, fresh oil slicks can often be initiated very quickly by igniting the oil with simple devices such as an oil-soaked sorbent pad. Oil from the water surface can be removed by in-situ burning efficiently and at high rates. It is reported that removal efficiency for thick slicks can exceed 90%. Oil removal rates of 2000 m^3/hour can be achieved with a fire area of about 10 000 m^2. Mechanical recovery comprising transfer, storage, treatment and disposal is more complex compared to the use of towed fire containment boom to capture, thicken and isolate spilled oil, followed by ignition.

The fundamentals of in-situ burning are described briefly in the following sections:

1. Oil properties or oil type
2. Oil weathering (“window of opportunity”)
3. Environmental condition (especially wind and waves)
4. Safety hazards (human and the environment)
5. Oil availability for ignition/burning
6. Igniters
7. Fire-proof boom systems

The last years have scientist at S.L. Ross in US performed promising work on the use of chemical herders to thicken surface oil slicks. The intention is to perform in-situ burning without using booms to increase film thickness. This can especially be interesting in oil in ice scenario with low ice coverage.

5.3.1 Oil properties and oil type

Very few oil types are not suitable for in-situ burning, but some oil types are lacking low molecular, volatile components and are difficult to ignite and burn with sufficient effectiveness. Heavy bunker fuels (IF-340 and higher) have a very high initial flash point and are usually not considered suitable for in-situ burning.

5.3.2 Oil weathering (“window of opportunity”)

There are limitations for in-situ burning when the surface oil slick starts to weather. The light components evaporate (increasing flash point) and the water is emulsified into the oil as small droplets. Both these two processes complicate ignition and lower burning effectiveness. Different percentages of evaporative loss (20-30%) and water uptake rates (25-50%) are reported in the literature as “rule of thumb” for defining the window of opportunity for in-situ burning. Ignitability is however not dependant on how much of the light components that are evaporated, but on the flash point of the residue. Two different emulsified crude oils, with the same water content, can also show very different ignitability due to their chemical composition. Further research is needed to overcome this limitation and more precisely define the window of opportunity for in-situ burning.

5.3.3 Environmental condition (especially wind and waves)

Wind could dilute the hydrocarbon vapour above the oil slick and complicate both ignition and burning. Successful ignition of large burns has been performed in wind speed of 10 to 12 m/s, but this will be very dependant on weathering degree. Flame spreading during the ignition phase could also be dependant on wind speed. Heating of the “upwind” areas of the oil slick could be reduced resulting in insufficient flame spreading. The presence of waves (or swell) could reduce flame spreading probably due to reduced thickness (stretching of surface oil slick) and blending of cold underlying oil with the burning surface oil.

5.3.4 Safety hazards (to humans, installations and the environment)

The temperature during burning of large oil pools is in excess of 1200ºC. Precaution must be taken with respect to human activity and physical installations in the area. Even in controlled burning experiments, equipment has been lost (burned) due to miss calculations of the amount of released energy. This aspect must be handled by using well prepared and controlled operational procedures for in-situ burning. The environmental aspects are mainly linked to the smoke emissions and to the burning residue. The composition of burn emissions varies with the type of oil burned and the size of the burn. Smoke and particulate material is the main concern and is dealt in more detail.

Carbon smoke particles are responsible for providing the characteristic black colour of the plume rising from an in situ burn. The smoke is unsightly, but more important the smoke particles can cause severe health problems if inhaled in high concentrations. In addition, carbon smoke particles serve to carry other adsorbed toxic materials (e.g., PAHs; PAH = polycyclic aromatic hydrocarbons) deep into the respiratory tract. From a health perspective the focus is on those particles that are small enough to be inhaled into the lungs, that is, those smaller than 10 μm in diameter. Health scientists call these PM-10s (PM stands for "particulate matter"). PM-10s make up approximately 90 percent of the mass of particulate emitted from an in situ burn. The average particle size of the soot is about 1 μm. One exposure standard that exists for PM-10s is the U.S. National Ambient Air Quality Standard (NAAQS) which states that PM-10 exposures of more than 150 μg /m^3, averaged over a 24-hour time period, can cause mild aggravation of symptoms in persons with existing respiratory or cardiac conditions, and irritation symptoms in the healthy population. In the absence of any data, however, in situ burn experts, health experts and regulators have agreed to adopt a more conservative standard for in situ burning requiring that concentrations averaged over <u>one hour</u> should not exceed 150 μg /m^3.

A successful in-situ burning leaves a viscous, usually floating, residue representing 5% or less of the initial oil volume. The chemical toxicity of this burn residue appears to be low. In tests conducted at NOBE water taken from beneath the oil slick contained only low concentrations of hydrocarbons (<13 ppb total oil) and were not toxic to bivalve larvae or juvenile fin fish (EVS 1995). More recently, Environment Canada scientists developed methods for conducting toxicity tests on water accommodated fractions from burn residues. Results showed that these water-accommodated fractions were not toxic to a variety of standard test organisms, including sea urchin gametes and three-spine sticklebacks (Blenkinsopp et al., 1997). Sinking residues could impose an environmental risk. In the M/T Haven case (Italy, April 1991), an area of the seabed of some 141 km^2 was measurably contaminated with sunken residue (Moller, 1992), to the extent that it was abandoned by most local trawl fishermen for a period of two years (Martinelli et al., 1995).

5.3.5 Oil availability for ignition/burning

In-situ burning has been considered as a primary arctic spill countermeasure, from the start of offshore drilling in the Beaufort Sea in the mid 1970s and during oil exploration on Svalbard in 1980-94. Many basin studies and field trials have been undertaken to investigate and document burning of large crude oil slicks (both fresh and emulsified) in open water, slush ice, and broken drift ice. In broken ice the applicability of in-situ burning will be strongly influenced by the concentration and types of ice present. Present knowledge can be summarised in the "rule of thumb" below:

1. Open water to 30% coverage (no oil confinement by ice, but booms can probably be used)
2. 30-60 % ice coverage (limited oil confinement by ice, booms can not be used)
3. 60-90+ % ice coverage (oil can be confined by ice)

In the lowest range, the oil's spreading and movement will not be greatly affected by the presence of the ice, and open water in situ burning techniques can be applied. In ice concentration range from 30-60% is the most difficult from an in situ burning perspective. The ice will reduce the spreading and movement of the slick, but not yet to the extent that it is containing the oil. The deployment and operation of booms in this ice concentration would be difficult, if not impossible. In the highest ice concentrations, the ice floes are touching and contain the oil; if slicks are thick enough they can be burned effectively in these ice concentrations (SL Ross and Dickins, 1987, Singsaas et al., 1994, Brandvik and Faksness 2005). In -situ burning of oil spilled in broken ice during break-up will likely be easier than in the same ice concentration during freeze-up. During break-up, there is much less slush and brash ice present, the ice floes are deteriorating and melting, there is 24-hour daylight, and finally the temperatures are increasing.

Both oil on ice (melt pools created in the spring by vertical migration from an encapsulated oil layer) and oil in snow can be burned with high effectiveness if oil type and weathering degree is favourable. There is a high degree of knowledge on the ignition and burning melt pools and oil in snow. For large melt pools, helicopters deploying igniters would be used to ignite individual pools of oil. Oiled snow with up to 70% snow by weight can be burned in situ. For higher snow content mixture (i.e. lower oil content) promoters, such as diesel fuel or fresh crude, can be used to initiate combustion. In many cases, waiting for the snow to melt could result in thin oil films incapable of supporting combustion and spread over a large ice area. For this technique, the oiled snow is scraped into a volcano-shaped pile, with the centre of the volcano scraped down to the ice surface. A small amount of promoter is ignited in the centre of the pile. The heat from the flames melts the surrounding inside walls of the conical pile, releasing the oil from the snow which runs down into the centre and feeds the fire.

5.3.6 Igniters

These are divided into two types: igniters for use from a vessel or on the ice, and igniters for use from helicopters.

The simplest form of an igniter to be used directly on the ice would typical be sorbent pads soaked in diesel, ignited and thrown onto the oil slick. A variation on this kind of sorbent igniter was used in experiments in the 1980s and involved sorbent wrapped around a short piece of styrofoam, dipped in diesel or crude oil, and then sprayed with dimethyl ether (also known as starter fluid). This ignited easily and burned for a long time. The more advanced Dome-igniter measures approximately 25 cm by 15 cm by 10 cm and weights about 500 g. The unit consists of solid propellant and gelled kerosene between two metal floats. The Dome unit is intended as a hand-thrown device, with an automatic starter and a 45 second fuse before ignition. Once ignited the solid propellant burns intensely for about 10 seconds with temperatures in excess of 1200°C. During this initial burn, the gelled kerosene begins to burn, producing temperatures of 700° to 800°C. The total burn time for the igniter is about 10 minutes.

The Heli-torch is a field-proven, helicopter-deployable, gelled fuel igniter commonly used for burning forest slash and for setting backfires during forest fire-control operations. Three models are available with gelled-fuel capacities of 110, 210 and 1100 litres, respectively. Of these, the 210-liter model has been most extensively tested for use on oil spills. The ignition system is self-contained units consisting of a gelled-fuel drum, pump, and motor assembly slung beneath a helicopter and controlled with an electrical connection from the Heli-torch to a panel in the cockpit. The burning gel falls as a highly viscous stream and quickly breaks up into individual globules before hitting the ground. Experience has shown that the Heli-torch should be flown at altitudes approximate 10-20 m and with speeds of 40-50 km/h. The Heli-torch ignition system is approved by both the U.S. Federal and Norwegian Aviation Administration. One Heli-torch unit (210 litres), owned by SINTEF is stationed at Longyearbyen, Svalbard and is a part of the local Governmental oil spill contingency. Another unit used for field in-situ burning experiments is located at SINTEFs field station in Svea, Svalbard.

5.3.7 Fire-proof boom systems

Some fire containment booms are heavy and difficult to handle. At the same time they are also durable and able to survive burning for long periods in an offshore marine environment. These are typically metal booms. Others are lighter and easier to handle and deploy, but are not designed for long-term deployment offshore or long-term exposure to fire. These usually employ fire-resistant, mineral-based fabric and ceramics. Water-cooled booms are initially relatively light, but become extremely heavy when soaked. As well, the additional complexity of water filtering and pumping must be accommodated with water-cooled booms.

The commercial available booms are divided into three categories:
1. Steel booms (Fireguard boom, Festop boom, Pocket boom and Sandvik Steel Barrier)
2. Booms made of fire-resistant (3M Fire boom, Sea Curtain Fireguard and Autoboom)
3. Booms with active water cooling (Oil Stop and two boom systems made by Elasteck/American Marine and Env. Marine Techn. Associates)

Many of the booms listed above have been tested by the U.S.C.G. for oil containment (Bitting and Coyne, 1997) and fire resistance in waves, conducted in the fall of 1997 and the fall of 1998 by NIST, in Mobile, AL (Hiltebrand, 1997; Walz, 1999). Further details concerning these booms are given in these publications.

5.4 Monitoring and remote sensing

When handling oil spills in open water a wide variety of remote sensing tools are available to monitor the oil trajectory, the distribution of the oil and the film thickness of the oil on the sea surface. These tools are used to both estimate the physical dimensions of the spill and to locate the thickest (often emulsified) parts of the oil slick for contingency operations. This is possible through a combination of sensors located onboard satellites, airplanes/helicopters and even operated from boats. Fingas and Brown (2000) review the possibility of using current remote sensing detectors in different oil-in-ice scenario.

5.4.1 Micro-wave radars

The most frequently used sensors are microwave radars inboard airplanes or satellites. The detection principle is detection of loss of reflection from surface capillary waves due to wave damping from the oil slick. The radar does not give any information regarding film thickness but is very sensitive to detecting oil on the sea surface. It is often used for regulatory surveillance of offshore oil exploration/production installations due to the high sensitivity. The potential of these systems in case of oil-in-ice is limited due to the lack of open water and the strong wave damping effect of frazil and slush ice in smaller areas with open water.

5.4.2 IR sensors

A combination of micro-wave radar and infra red sensors are often used to estimate the dimensions (MW) and the thickness distribution within the oil slick (IR) in open waters. Several attempts have been made to use IR sensors to estimate oil film thickness with oil in ice. The main limitations are the low temperature difference between surface oil and the surrounding water/ice. Several attempts were made during the oil-in-ice experiment in MIZ-93 and also on earlier experiments in US without success. Also in US and Canada have IR sensors been tested to map oil in broken ice at the Nova Scotia experiment in 1986 (Ross and Dickins, 1987) and during the Kurdistan tanker spill off Nova Scotia in 1979 (C-CORE; 1980). When the oil was trapped between ice sheets with a high ice coverage it was very different to distinguish between ice with water in the leads between the sheets and ice with oil. In periods was the ice fields opens up to possible detect signature differences between oil and water (see figure 5.12). Further development of IR sensors the last years have made new and promising models available for possible field testing with oil in ice. Sensors have improved both with respect to resolution and sensitivity. Also the price and physical size of equipment have been drastically reduced the last decade. Surface temperatures of thick oil layers trapped between ice sheets have been measured by UNIS as a part of their annual oil-in-ice experiments in the Barents Sea (2001-2005). These measurements, only published in students reports, show variations from -1.8ºC (night) up to 9ºC (daytime, overcastted). Testing of new IR sensors should be included in a possible field experiment with oil-in-ice.

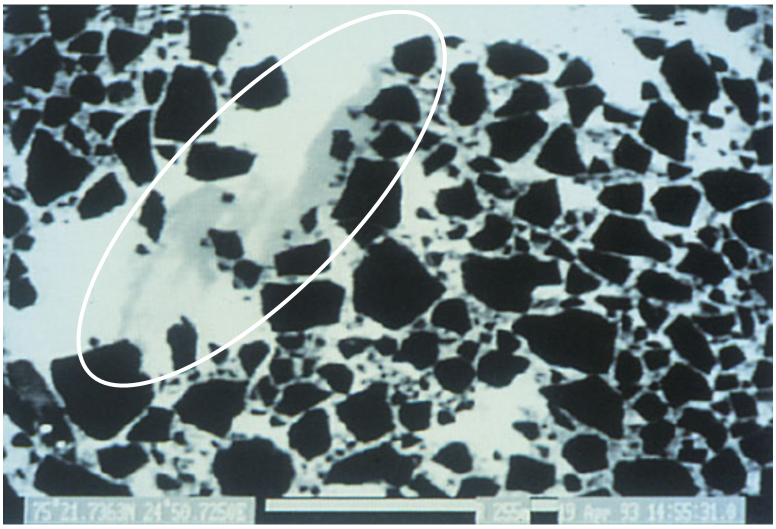


Figure 5.12: Example of an IR image showing oil drifting in ice from the MIZ-93 experimental oil release in broken dynamic ice in the Barents Sea.

5.4.3 Fluorescence detector

Based on Fingas and Brown (2000) review it is likely that the most acceptable method of detecting oil spills on snow and ice surface is the method based on measuring fluorescence spectra from a powerful laser source.

A Laser Fluorosensor system (LFS) was integrated in an aircraft operated by the German Ministry of Transport in 1993 and has shown promising results. A project for development of a new generation LFS was initiated in Canada in 2001/02. Ground testing of the Scanning Laser Environmental Airborne Fluorosensor (SLEAF) was one of the activities, but was hampered by hardware and software problems. The SLEAF has been integrated into Environment Canada's DC-3 remote sensing aircraft. The potential and limitation for both systems should be tested/verified during oil in future oil-in-ice field experiments.

5.4.4 Ground penetrating Radar and acoustic systems

Considerable efforts have gone into projects studying various methods to detect oil trapped under or in first year sea ice. Especially in US and Canada several different methods have been investigated during the 1980 and 90ties (Goodman et al., 1985). Later work performed by DF Dickins and Boise State University have again focused on radars and acoustic systems to detect oil under ice (Dickins, 2000 and 2005). Utilising new and improved technology regarding high frequency ground penetrating radars (450 – 1200 MHZ) have made it possible to detect oil layers under ice in basins studies (Dickins 2005). UNIS has performed several studies trying to use lower frequency GPRs (200 – 500 MHz) to detect oil under ice or to estimate ice thickness without success (Paste, 2003) probably due to signal attenuation in saline first year ice. This new and promising concept to use helicopter mounted high frequency radar and fly low transects (height: 3-10 m) to map oil under ice. Further field testing and verification of this system is planned as cooperation between DF Dickins, Boise State University and SINTEF on Svalbard during spring 2006. 3500 litres of oil will be trapped under approx. 1 meter of sea ice.

5.4.5 Methane detectors ("sniffers")

Shell Global Solutions LightTouch system is an ethane gas sensor which can be used to detect methane gases from oil trapped in or under ice. The system is further described in Hirst et al., (2004). These sensors uses a Tureable Diode Laser Spectrometer (TDLS) that are specified to measure real-time concentrations of methane down to 50 part per trillion (10^{-12}). The system has been tested with oil under ice in the Cold Region Research and Engineering Laboratory (CRREL) in US in 2004. The system detected methane originating from the oil under ice in ice samples with an ice thickness of 35 cm (Dickins et al., 2005).

At present the system is dependant on analysing methane content in ice cores sampled on site and transported to the laboratory. Testing of the present version under real field conditions is expected to be challenging due to the demand for liquid nitrogen, temperate operating environment etc. However, this concept is hopefully developing in a direction of a smaller, portable unit which, in a later stage, can be incorporated in field tests.

6 Conclusions

This chapter summarises and concludes from the previous chapters. Contingency planning regarding oil-in-ice should be focused to the following subjects:

- Response time
- Oil spill response techniques (mechanical recovery, *in-situ* burning, dispersant)
- Combating equipments (booms, skimmer etc.)
- Training (personnel, mobilization and equipment technology)
- Environmental risk analysis
- Mapping natural resources (include use of Net Environmental Benefit Analysis (NEBA) and oil spill risk assessment tools)
- Fate and behaviour of transported oil (properties, type of oil products, amount of oil transported)

Generally, oil spills in ice are far more complicated to combat compared to oil spills in open waters. Apart from the normally long distances from existing infrastructure, the oil is less accessible in ice-covered waters. The oil can be spilled on ice/snow, in open pools between ice floes, in open channels behind vessels or even under the ice as shown in figure 1.1 in chapter 1.

Traditional use of booms and skimmers can be difficult. However, there are also some advantages with oil spills in ice compared to open waters. The weathering rate is normally much slower for an oil spill in ice. This means that emulsification rate and hence viscosity increase may be slowed down resulting in an increased window of opportunity for use of most response techniques (e.g. the Marginal Ice Zone (MIZ) experiment in 1993, Brandvik et al., 2004). The spreading of oil will be normally also much slower resulting in a large oil film thickness that may be favourable for the oil spill response.

The ice concentration can become a governing factor in making decisions about equipment selection. The advantage of spill in ice is that the ice can act as a natural containment in a variety of ice features such as floes, snow and ridge. In a case of a spill the oil can be located on ice, among ice floes and oil under ice, which also requires a different approach to the problem.

Table 6.1 gives an indication of expected effectiveness of different response methods as a function of ice coverage. Few of these methods have actually been tested in ice-infested waters, so there are large uncertainties attended with the listed technologies. It should also be mentioned that there are major differences in capacity (e.g. amount oil removed per time unit) between the different methods.

Table 6.1 Indication of expected effectiveness of different response methods as a function of ice coverage (Evers et al., 2006).

		Ice coverage									
Response method	Open water	10 %	20 %	30 %	40 %	50 %	60 %	70 %	80 %	90 %	100 %
Mechanical recovery:											
- Traditional configuration (boom and skimmer)											
- Use of skimmer from icebreaker											
- Newly developed concepts (Vibrating unit; MORICE)											
In-situ burning:											
- Use of fireproof booms											
- In-situ burning in dense ice											
Dispersants:											
- Fixed-wing aircraft											
- Helicopter											
- Boat spraying arms											
- Boat "spraying gun"											

Mechanical methods to deal with spills in moving broken ice in general have serious limitations, especially for large oil spills, and recovery values will be highly variable depending on a variety of natural conditions and logistics constraints. Most mechanical methods at hand are technology developed for open water conditions. The largest potential for improving mechanical oil recovery in Arctic and ice-infested waters may be to further improve and adapt existing concepts.

A significant usefulness of dispersants in an oil-in-ice scenario has not been demonstrated by a low number of earlier laboratory or field trials. Questions are raised if necessary energy is present in such scenarios to initiate the chemical dispersion process. If dispersants are applied and necessary energy will be available later. Laboratory testing at low temperatures have shown that only dispersants type 3 (concentrates) are actual for use under arctic conditions. Strict requirements concerning physical properties have to be applied in order to avoid problems with high viscosity or precipitation at low air temperatures. Many dispersants show quite low effectiveness at low temperatures and salinity compared to North Sea conditions, and only products tested and approved for "arctic" conditions should be used. To our knowledge use of dispersant is not an operational response method for ice-infested waters in any areas today.

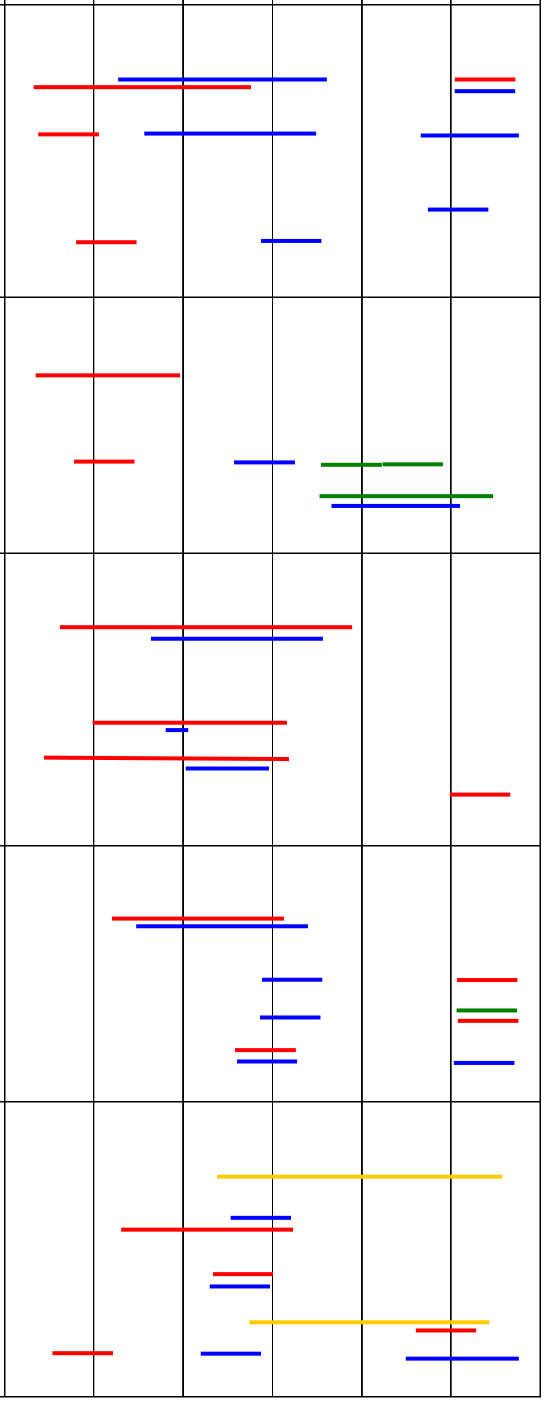
The technology to perform in-situ burning has developed during the last decade. New types of fire resistant booms (actively cooled) have been developed and tested in the past few years, but none have been tested in actual arctic conditions. Most burning projects have been conducted in small-medium test tanks. At the same time there are certain tactics and techniques that can only be accomplished through an in-the-field exercise. Testing both inside and outside the ice edge could be included. Information from such experiments will be used to make justifiable, scientific-based decisions on the suitability of *in situ* burn packages for the intended operating environment. *In-situ* burning is not an operational response method for any ice-infested waters today, even if its principle can be used e.g. at Svalbard were a Heli-torch igniter system is stored.

6.1 Approximate timeline for Arctic oil spill related R&D

Testing and development of Arctic related oil spill technology have been important activities in most circum polar countries. This activity has been induced by ship traffic through ice oil spill incidents (Finland/Russia) or Oil exploration in Arctic areas like in US, Canada and Norway. The table below is a summary of this activity organized as a timeline.

Table 6.2 Approximate timeline indicating Arctic oil spill related R&D activities in North America (US and Canada), Finland, Norway and Russia.

US/C: —— Fin: —— N: —— Russ: ——	**Approximate timeline**					
Arctic oil spill R&D activities	1980	1985	1990	1995	2000	2006
Weathering processes of oil-in-ice • Basin experiments (evap/emul….) • Small-scale field exp. (evap/emul/long time weathering…) • Leakage of water soluble components in ice • Full-scale field experiments						
Mechanical recovery • Winterization of exist. equip (boom/skimmer) • Handling of viscous oils at low temperature • Field testing of equipment with oil in ice • New concepts (Vibrating unit; MORICE)						
In-situ burning • Burnability vs. weathering – basin studies with oil (evaporation/emulsification/wind/waves) • Fire proof booms - development/testing with oil • Ignitors - development/testing with oil • Herders lab/basin testing with oil						
Dispersants use oil-in-ice • Effectiveness testing – lab • Effectiveness testing – meso/full scale facilities • Low energy ice conditions • Leakage of surfactants - dispersants/oil in ice						
Modelling oil-in-ice processes • Sea ice dynamics • Drift, spreading of oil in ice • Oil weathering processes (evap./emul.) • Oil-ice interactions • Field verification						



NB! Duration of activities on the timeline is only approximate.

7 Knowledge gaps and R&D recommendations

This chapter identify and summarise the most significant knowledge gaps and list R&D activities that can be initiated to develop new knowledge to overcome these knowledge gaps.

7.1 Fate and behaviour of oil in ice infested areas

Present knowledge regarding weathering processes in case of an oil spill in ice is limited, both with respect to different ice scenarios and different oil types. We have data with varying quality from a few experimental releases with crude oil and from accidents causing spills of mainly bunker fuels in ice. Knowledge regarding oil-ice interaction with different ice types during freezing/thawing is also limited. This is due to limited number of meso-scale and full-scale field experiments with different oil types and ice scenarios.

R&D recommendations:

1. Perform systematic meso-scale experiments simulating several different oil-in-ice scenarios using different oil types (asphaltenic, naphtenic, waxy, bunker fuels etc.) to quantify operational important weathering processes e.g. in SINTEFs new meso-scale ice laboratory in Trondheim (SeaLab).
2. Performing long-term weathering field experiments (up to five months) with oil encapsulated in ice and oil-under-ice scenarios in the stable first year fjord ice in Svea, at SINTEF field station on Svalbard.
3. Perform full-scale field trials to verify findings from meso-scale experiments for a limited selection of oil-in-ice scenarios (1-3) on suitable locations in Canada, Norway or possible NW Russia.
4. Build a larger ice-tank for freezing first year sea ice with realistic properties. UNIS have a tank 600 litre tank in Longyearbyen but a 2-3 m^3 tank should be established in Trondheim for long term experiments with oil encapsulated in ice (leakage of water soluble components, vertical migration during thawing etc.)
5. Based on laboratory and field verifications establish a calibration set for developing and calibration of numerical models describing oil weathering processes of oil spills in ice, replacing older parameterizations with process-related algorithms where possible.

Recommendation	Priority	Status (previous work)	Time needed (years)	Cost (ranges)	Prob. for success
7.1.1: Meso-scale experiments	1	Builds on ongoing work	2	2	Very good
7.1.2: Long term weathering	2	Builds on ongoing work	2	2	Good
7.1.3: Full-scale field trials	1	Builds on earlier work	3	3	Good
7.1.4: Ice-tank	3	New Innovative	2	1	Good
7.1.5: Calibration data for OWM	1	Builds on ongoing work	2	1	Very good

Costs ranges: 1: <100 kUS$ 2: 100-500 kUS$, 3: >500 kUS$

Of these activities are 1, 3 and 5 evaluated as critical to be able to advance our capability of predicting the weathering behaviour of an oil spill in ice.

7.2 Modeling of drift and weathering of oil-in-ice

Modeling of oil weathering in the presence of sea ice remains at an *ad hoc* level, limited in part by the state-of-the-art in modeling (or parameterization) of sea ice morphology and physics at the appropriate scales, and in part by limitations in our understanding of oil-ice interactions. Advances have been made in our understanding of oil spreading and weathering processes in the presence of sea ice. This new understanding has come primarily through field work, the results of which have corrected misconceptions introduced through prior laboratory-scale weathering studies. Significant advances in oil-ice interaction modeling will require that oil behavior and fates, ice formation and drift, and hydrodynamic models be coordinated to take advantage of new knowledge in both ice cover and oil-ice interaction modeling. The establishment of nowcast-forecast met-ocean model systems that include both oil fates and ice cover components will facilitate this coordination, and provide a basis for continual improvement in this area.

R&D recommendations:

1. Use presently available ice formation and drift models, coupled to hydrodynamic models, to supply dynamic input to oil spill contingency and response models. This would use today's technology to replace the use of static ice-cover datasets based solely on historic observations, an over-simplified methodology that has been in use for the past 30 years. The result would be a significant improvement in Arctic oil spill planning, risk analysis, and hind-casting model applications.
2. Improve ice formation and drift models to represent a variety of ice types, based on today's knowledge of the weather conditions under which these different types form. Ice type has a significant effect on oil-ice interactions, and therefore on oil weathering and realistic alternatives for oil spill response.
3. Calculation of wave-damping as waves enter an ice field is key to computing oil weathering processes, such as emulsification and dispersion, which in turn determine the window of opportunity for burning or eventual dispersant application, or selection of skimmer or pump systems.
4. Couple oil spill and ice cover models into nowcast-forecast met-ocean model systems to provide support for oil spill contingency plans and actions in Arctic areas. Using today's technology, a relatively "transportable" system could be developed to supply tailored forecasts, either on a regular basis for support of daily operations, or as-needed, for oil spill response support.

Recommendation	**Priority**	**Status (previous work)**	**Time needed (years)**	**Cost (ranges)**	**Prob. for success**
7.2.1: Ice & hydrodynamic models	1	Builds on earlier work	3	2	Very good
7.2.2: Include different ice types	2	New Innovative	2	2	Good
7.2.3: Energy input - wave-damping	2	New Innovative	2	2	Good
7.2.4: Nowcast-forcast	1	New Innovative	3	2	Good

Costs ranges: 1: <100 kUS$ 2: 100-500 kUS$, 3: >500 kUS$

7.3 Mechanical recovery

Most of the oil activities in areas with sea ice (shipping, exploration, production etc.) take place in remote areas with long distance to land and without good infrastructure for oil spill response. Parts of the year low temperatures and little daylight will also give additional challenges to oil spill response operations. Generally, oil spills in ice are far more complicated to combat compared to oil spills in open waters. Apart from the normally long distances from existing infrastructure, the oil is less accessible in ice-covered waters. The oil can be spilt on ice/snow, in open pools between ice floes, in open channels behind vessels or even under the ice. Traditional use of booms and skimmers can be difficult. However, there are also some advantages with oil spills in ice compared to open waters. The weathering rate is normally much slower for an oil spill in ice, especially at higher ice concentrations. This means that emulsification rate and hence viscosity increase may be slowed down resulting in an increased window of opportunity for use of most response techniques (e.g. the Marginal Ice Zone (MIZ) experiment in 1993, Brandvik et al., 2004). The spreading of oil will normally be much slower resulting in a large oil film thickness that may be favourable for the oil spill response.

The main challenges for oil recovery in ice vs. open waters are assumed to be:

- Icing/freezing of equipment
- Limited/difficult access to the oil
- Limited flow of oil to the skimmer
- Separation of oil from ice and water
- Pressure in the ice field
- Detection/surveillance of the oil slick, potentially over long time

There have been some recent developments for mechanical recovery of oil in ice (see chap. 5.1) both in Finland (e.g. Arctic skimmer and Vibrating Unit) and Norway (e.g. MORICE concept). However, most of the equipment recommended for use in ice-infested waters today is made for recovery of relatively small amounts of oil. Some of this equipment has been tested in laboratory- or meso-scale with oil present, but there is generally a lack of performance data with regard to recovery effectiveness under different ice conditions and operations under cold conditions.

The potential for improvement and/or further development and “winterisation” of existing equipment is probably higher than the development of new concepts. Due to the remoteness for many of ice-infested areas and lack of infrastructure it is important that equipment for combat of oil in ice also can be used in open waters. There is also a need for equipment with a potential pumping capacity capable of handling larger oil spills.

Based on the challenges with oil recovery in ice and earlier and ongoing developments a set of recommendations has been worked out. NOFO and the Norwegian Coastal Administration have also given input in this process. Some of the challenges with oil recovery in ice are the same as for oil recovery in open Arctic waters (e.g. darkness, cold conditions etc.).

R&D recommendations:

1. Winterisation of existing concepts. This includes measures to avoid icing/freezing of equipment and potentially other elements that could reduce the effectiveness due to low temperatures and wind. Promising existing concepts should be examined systematically. Testing should be perform under relevant conditions, necessary modifications carried out followed by tests under controlled conditions and demonstrations in field trials.
2. Improve ice processing. The challenge is to improve the access to the oil. The MORICE concept is lifting the ice floes by a grated belt allowing the oil to flow to the skimmer head. The Vibrating Unit pushes ice pieces under a grid and by use of oscillation the oil is washed of the ice blocks and rises to the water surface for recovery. Similar modification should be suggested for other existing concepts.
3. Separation of ice and water. Considerable amounts of water are normally recovered along with the oil, as free water or water in emulsion, even in open waters. In ice-infested waters one should expect that in addition, ice will be recovered together with the oil. In order to utilize the tanks onboard the recovery vessel for storage of recovered oil the aim should be to separate out as much water and ice as possible. Use of heat by e.g. steaming could be one solution to melt the ice. Addition of emulsion breaker could be used to remove water from the recovered emulsion. Work is reported to be ongoing related to a containerised steaming facility.
4. Darkness and low visibility. The main challenge related to darkness is to find the thick oil while light sources onboard the recovery vessel can be used when recovering the oil. This is one of NOFOs priorities and work is ongoing to develop equipment for monitoring of oil in darkness and low visibility, with focus on open waters.
5. Equipment with the capability to respond to larger oil spills. Most of the equipment dedicated for oil recovery in ice has limited pumping capacity. Equipment with potentially higher pumping capacity that also can be used in open waters outside the ice edge should be developed. The NOFO TransRec system has high pumping capacity built to operate offshore in open waters. However, the weir system that the TransRec is based upon has not shown promising results in ice and needs to be modified for operation in ice-infested waters.
6. Oil recovery under ice. It is expected that many of the future developments in ice-infested waters can be sub-sea developments with the risk of under-water accidental oil releases. There is a need to look into the potential of oil recovery under ice. A concept has been sketched in Norway with the use of an under-water boom and a ROV to operate the boom and an under-water pump. This concept should be further investigated.
7. Techniques for deflection of ice to create open channels. The idea is to create open channels in the ice for more easy recovery by skimmers. Open channels can be created e.g. down-wind oil platforms or by used of large icebreakers.
8. Further development of the MORICE concept. The MORICE concept was brought to a stage where it is ready for industrialisation. However, the existing unit built is referred to as a harbour sized unit and there is a potential for increasing the unit both with regard to size, ice processing speed and strength.
9. Regular field trials with oil inside and outside the ice edge in order to:
    a. Train response personnel
    b. Testing and verification of different strategies and equipment
    c. Get acquainted with the different conditions to meet in the Arctic.

Recommendation	Priority	Status (previous work)	Time needed (years)	Cost (ranges)	Prob. for success
7.3.1: Winterisation exist. concepts	1	Builds on earlier work	2	2	Very good
7.3.2: Improve ice processing	1	Builds on earlier work	2	2	Good
7.3.3: Separation of ice and water	1	New Innovative	2	2	Good
7.3.4: Operation in darkness	2	Builds on earlier work	2	1	Good
7.3.5: Large capacity equipment	1	New Innovative	3	2	Good
7.2.6: Oil recovery under ice	1	New Innovative	2	2	Good
7.3.7: Ice deflection	2	Builds on earlier work	2	2	Good
7.3.8: Further R&D morice concept	2	Builds on earlier work	3-5	3	Good
7.3.9: Training exercises, oil-in-ice	2	New	3-5	2	Very good

Costs ranges: 1: <100 kUS$ 2: 100-500 kUS$, 3: >500 kUS$

7.4 Dispersants

Earlier studies carried out in Norway (ONA report 1995/ AKUP report 1996) conclude that use of dispersants can be a suitable response method, either as an independent response method or in combination with e.g. mechanical recovery, to a number of scenarios in Arctic waters-both in open water and in ice coverage up to around 50 %. Application could be performed from aircraft /helicopter /boat on oil spill in open water (outside the ice edge), from e.g. helicopter or boat (use of artificial mixing energy) in relative open ice or e.g. preferable from helicopter in pond of melted ice or oil in high coverage. This could have a positive influence upon enhanced dispersion rate when oil is drifting out in open/turbulent water.

For obtaining an effective dispersant operation in Arctic areas, it is important to evaluate the following critical parameters:

- Access (contact) of the dispersant to the oil.
- Sufficient mixing energy for the dispersion process.
- Oil properties at low temperature (weathering degree), with special focus on viscosity and pour point.
- Dispersant performance and properties under the relevant conditions (salinity, temperature, oil type).

Dispersants application has been studied extensively for over 30 years (Owens, 2004) and dispersants have been used successfully in many actual oil spills. However, little laboratory and field work has been performed with dispersants and oil in ice and the potential for use of dispersants under arctic conditions has been little demonstrated.

There is need to establish a better understanding for the potential in operational use for dispersants in various scenarios under Arctic conditions, define the limiting cases for applicability of dispersants in cold and/or ice covered waters, explore the capabilities of the dispersants to effectively disperse various oil in cold water, in the presence of brash and slush ice and with different levels of mixing energy. The key concerns for use of dispersants in cold -water environments with ice have been centred on lack of natural mixing energy due to the damping effects of the ice, and the tendency for oil to become viscous at low temperatures. The use of icebreakers or other vessels to introduce the necessary mixing energy, in combination with dispersant formulates for longer retention by viscous oils, could lead to dispersants becoming a practical response option for oil spill in ice. However, research in this area is at an early stage and much more work needs to be done before a definitive answer is available (Dickins 2004).

R&D recommendations:

1. Improved documentation of effectiveness under various Arctic conditions. There is a need to provide better documentation on effectiveness of the present generation of dispersants on various oils under relevant weathering degrees and different Arctic conditions (low temp., presence of ice etc.). The results should be used as input to improvement of weathering models.
2. Improvement of application technology. For effective use of dispersants the application technology is important. Both vessel and helicopter based equipment should be further evaluated and developed also with regard to winterisation.
3. Extended time window for use of dispersants. The effectiveness by use of dispersants on paraffinic and waxy crude oils with high pour point and heavy bunker fuel oils can often be low, especially at low temperatures.
4. Optimize dosage needs for various oil types. The optimal dosage (dispersant to oil ratio = DOR) can vary from oil type to oil type. An optimal DOR is important for the maximum effectiveness under different Arctic conditions and the costs.
5. Fate and degradation of dispersed oil in cold and ice-covered waters. The fate and degradation of dispersed oil in the water column can be very different in Arctic waters compared to more temperate areas. Optimisation of experimental design and generation of data should be focussed, and the data should be compared to natural dispersion and to similar data obtained from earlier studies in temperate waters.
6. Biological effects in the water column from dispersed oil droplets and water soluble oil components. The objective should be to quantify the effects of chemically dispersed oil relative to mechanically dispersed oil, both short-term (acute) and long-term (chronic) effects on species of different tropic level. The results should give input to model tools as a basis for NEBA analyses.
7. Injection of dispersants from the sea bed. A potential injection of dispersants into a blow-out at the sea bed could lead to a dispersion of the oil into the water column and reduce the trapping of oil under the ice. The concept has been evaluated but work remains to be done in order to establish whether this could be a realistic concept.
8. Development of dispersant for long-term retention in viscous oils. This include development of a new type of dispersant formulated for long-term retention to remain within the oil as the oil/ice moves from low energy (e.g. pack ice) to a higher energetic (e.g. ice edge) environment.
9. Artificial turbulence to start the dispersion process. The objective is to identify and test methods in order to introduce energy to start a dispersing process in low energetic conditions in ice-covered waters. Work is ongoing in USA/Canada.

Recommendation	Priority	Status (previous work)	Time needed (years)	Cost (ranges)	Prob. for success
7.5.1: Effectiv. testing -Arctic cond	1	Builds on earlier work	2	2	Very good
7.5.2: Imp. application technology	1	Builds on ongoing work	2-3	2	Very good
7.5.3: Ext. time window	2	Builds on ongoing work	3	2	Good
7.5.4: Optimize dosage	2	Builds on earlier work	1-2	1	Very good
7.5.5: Fate and degradation - Arctic	2	Builds on earlier work	3	2	Good
7.5.6: Biological effects - Arctic	2	Builds on earlier work	3-5	2	Good
7.5.7: Injection from seabed	2	New Innovative	3-5	3	Good
7.5.8: Long-term retention	2	New Innovative	3	2	Good
7.5.9: Artificial turbulence	1	Builds on ongoing work	2-3	2	Good

Costs ranges: 1: <100 kUS$ 2: 100-500 kUS$, 3: >500 kUS$

7.5 In-situ burning

Improvement of igniters and fire proof booms will increase the window of opportunity for in-situ burning. As demonstrated through several larger programs in North America and Norway, in-situ burning has the potential to be an effective oil spill response technique in arctic and/or remote spill scenarios. However, operational capability is difficult to quantify without doing real burning experiments. There is a large need for operational field testing of in-situ burning to verify knowledge established trough laboratory and basin studies. There is also a large potential in refining existing and developing new igniters and fire proof booms for in-situ burning.

A standard approach to predict the “window of opportunity” for in-situ burning should also be established in the same manner as we today used knowledge on dispersant effectiveness to predict “window of opportunity” for dispersant use. A laboratory method to test ignitability/burnability versus initial oil properties and weathering should be established. Results from laboratory experiments should be compared with results from meso-scale systems and verified through field experiments. The data from these tests and experiments should be used with existing oil weathering models to predict the window of opportunity for the use of in situ burning for a variety of oil types. The objective is to establish how the physical/chemical properties of oil, the oil weathering/emulsification and environmental factors will affect the ignitability and burning efficiency of both crude oils and refined petroleum products for in situ burning in arctic spill scenarios.

R&D recommendations:

1. Establish a laboratory methodology based on oil properties, weathering behaviour, measured ignitability/burning effectiveness, measure the "window of opportunity" for in situ burning.
2. Based on the data from laboratory burnability testing on different oil types and weathering degrees, implement the ability to predict the "window of opportunity" for in-situ burning in SINTEF OWM and other oil weathering models.
3. Test/verify existing fire-proof booms with oil in different ice conditions trough basin and field testing with oil
4. Test the potential of using herders to increase oil film thickness with different ice conditions trough basin and field testing
5. Laboratory and field testing to verify existing and develop new igniters also including the use of surfactants for enhancing breaking w/o-emulsions

Recommendation	Priority	Status (previous work)	Time needed (years)	Cost (ranges)	Prob. for success
7.4.1: Window of opportunity	1	Builds on ongoing work	2	2	Very good
7.4.2: Implement into OWM	1	New innovative	1	1	Good
7.4.3: Testing - Fire-proof booms	1	Builds on earlier work	1	2	Very good
7.4.4: Testing - Herders	1	New innovative	1	1	Good
7.4.5: R&D - Igniters	2	Builds on earlier work	1	2	Good

Costs ranges: 1: <100 kUS$ 2: 100-500 kUS$, 3: >500 kUS$

Of these activities are 1 and 2 evaluated as critical to be able to predict "window of opportunity" for in-situ burning of oil spills in ice. However, operational activities involving testing and development of booms and igniters are also important, both to develop new technology and to give realistic training/experience to oil spill personnel.

7.6 Remote sensing

There are 3 main levels of remote sensing in open waters:

- Use of satellite and microwave radar to decide yes or no concerning the presence of oil on a large scale. The system is based on reflection from surface capillary waves and damping in the presence of oil and is very sensitive in open waters but the potential in ice-infested waters is limited (see paragraph 5.4).
- Use of fixed wing aircraft or helicopter. Potential sensors are e.g. microwave radar, IR sensors, UV sensors etc.
- Use of vessels. Potential sensors are e.g. ships radar, IR and UV sensors etc.

It is expected that traditional use of microwave radar from satellites for detection of oil in ice-infested waters has limited potential. The “yes” or “no” detection may be moved from satellite to aircrafts/helicopters. However, the use of existing multi-spectral satellite data and satellite and airborne active optical probes may have a potential. This will probably need some considerable R&D effort and should be subjected to development in dedicated programs. Satellites will be useful for monitoring of ice drift and tracking of buoys and drifters.

The coupling of modelling tools with drifters has been used at several occasions in open waters. Use of models coupled to different kind of monitoring equipment should be further developed to track and follow the oil and drift of oil and ice over a long time. The AIS (Automatic Identification System) system currently used e.g. to track and follow vessels has a potential for further development of use in drifters (AIS based drifters).

Although some remote sensing systems have been tested in previous experimental oil spills in ice (e.g. the IR sensor during MIZ-93 – see 5.4.2) there is a still a large need for testing of currently operating systems during field experiments. Further testing of the German and Canadian Laser Fluorosensors should also be included into future field experiments.

The Ground Penetrating Radar being tested at Svalbard spring 2006 should also be included in future field trials. Further development and testing of this system will be suggested based on the results and experience from the Svalbard testing. The Shell Global Solutions LightTouch system developed for methane detection from oil in or under ice should also be incorporated in future field tests.

R&D recommendations:

1. Based on the results and experience with testing of the Ground Penetrating Radar (GPR) at Svalbard during the spring 2006, it is expected that further development and testing of the system will be suggested. This should also include testing of the system through experimental field trials in ice-infested waters.
2. The Shell Global Solutions LightTouch system should be included in future spill experiments for detection of oil in and under ice. This could be a ground-based evaluation of the level of gas emissions from oil spills and the range of detectability of such spills remotely and from what range this may be feasible.
3. Coupling of modelling tools with different kind of monitoring equipment including drifters. When oil is covered by snow or frozen into the ice this could be one of few options to follow the oil over long time as it drifts towards open waters or the ice melts.
4. Testing of Laser Fluorosensor (LFS). For detection of oil on ice and between ice floes the LFS system is regarded to be a good tool. For testing of this system in Norwegian ice-infested waters it is suggested that the German Ministry of Transport is contacted through the Norwegian Coastal Administration. For testing in Canadian waters is must be evaluated whether the system presently available in Canada can be used. The LFS system should be tested during experimental field trials.

5. Testing of Infrared (IR) sensors. Further development of IR sensors has made new and promising models available. These should be tested during a field experiment.
6. Existing and recently developed systems for multi-spectral satellite data and airborne active optical probes should be evaluated with the aim to perform testing during oil spill experiments.
7. Testing of AIS based drifters during experimental field experiments for tracking of oil in ice over a long period of time. This testing could be included in future experimental field trials.

Recommendation	**Priority**	**Status (previous work)**	**Time needed (years)**	**Cost (ranges)**	**Prob. for success**
7.6.1: Further R&D / testing – GPR	1	Builds on earlier work	2-3	2	Good
7.6.2: Further testing of LightTouch system	1	Builds on earlier work	2-3	2	Good
7.6.3: Coupling models - drifters	1	Builds on earlier work	2-3	2	Good
7.6.4: Testing – Laser Fluorosensor	1	Builds on earlier work	1	1-2	Good
7.6.5: Testing – IR	2	Builds on earlier work	1	1-2	Good
7.6.6: Testing of multi-spectral satellite data and active optical probes	2	Builds on earlier work	2-3	1-2	Good
7.6.7: Testing - AIS based drifters	2	New	2-3	2	Good

Costs ranges: 1: <100 US$ 2: 100-500 US$, 3: >500 US$

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