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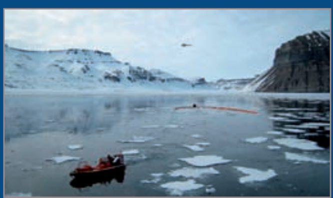

Oil in Ice - JIP

Report no.: 32

# Joint industry program on oil spill contingency for Arctic and ice-covered waters

## SUMMARY REPORT

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# JOINT INDUSTRY PROGRAM ON OIL SPILL CONTINGENCY FOR ARCTIC AND ICE-COVERED WATERS

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## PREFACE

**The Joint Industry Program on oil spill contingency for Arctic and ice-covered waters (JIP on Oil in Ice)** has uncovered important knowledge and developed new solutions for oil spill response in ice-covered waters. This will form the basis for further development of an improved oil spill contingency for the Arctic region.

From the start of 2006 to the end of 2009, the program has been carried out as a broad international cooperation in which the world's most experienced experts on oil spill R&D have participated. The program was completed according to plan with two large-scale field experiments in 2008 and 2009 as a most important verification for the outcome of the program.

Ice-covered waters and Arctic conditions possess other challenges for oil spill response compared to open and more temperate waters such as the remoteness of the area, the low temperatures, seasonal darkness and the presence of ice. At the same time we have experienced that ice can aid in oil spill response operations; it slows down oil weathering, it dampens the waves, it prevents the oil from spreading over large distances and it allows for more response time. In some cases oil spill response in an ice-covered area can be easier than in open water, although this does not imply that it will be simple.

We wish to give our sincere thanks to our cooperating partners, especially to the Norwegian Coastal Administration and the Norwegian Coast Guard, who provided significant support to the 2009 field experiment. We are also grateful to the Swedish Coast Guard, Alaska Clean Seas, MMS (US Dept of the Interior), the Governor of Svalbard and NOAA/CRRC, USA. The Oil Spill Recovery Institute (Cordova, Alaska), the Norwegian Clean Seas Association (NOFO, the University of New Hampshire, Boise State University, the University of Rhode Island and the University of Alaska, Fairbanks have all made important contributions to the program.

Trondheim, April 10th 2010

Stein Erik Sørstrøm
*Program Manager*

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# EXECUTIVE SUMMARY

The Joint Industry Program on oil spill contingency for Arctic and ice-covered waters was established in 2006 and completed by the end of 2009. Acknowledging the fact that the Arctic exhibits different environments in terms of ice conditions, water depth and the like, the results from this program represent a concerted industry effort for the improvement of oil spill response techniques for Arctic waters. Another important part of the program has been to gather more knowledge about the fate and behaviour of oil spills in ice and under cold water conditions.

Due to changes in oil's properties after being released into a marine environment, the opportunities for the use of various oil spill countermeasures such as mechanical recovery, dispersants and in situ burning changes with time. The time before we reach this point is termed the *window of opportunity*. The presence of ice on the sea surface will have a great effect on oil spill response. Whether the oil is spilled on or under the ice, the form and stage of the ice and other prevailing conditions (darkness, remoteness, and low temperatures) all have a significant effect on oil spill response operations.

**Key findings from the program:**

- The research program has provided a valuable knowledge base for the planning, implementation and further improvement of oil spill response in ice-covered waters.

- Each response tool evaluated during the program demonstrated some merit in responding to an oil spill in an Arctic environment.
- The availability of all the response options is considered as being the key to a successful oil spill response operation under Arctic conditions.
- A systematic way to predict the operational time frame for various response options was identified, thereby demonstrating that efficient spill response may be accomplished whether the techniques are used individually or in combination.
- Large-scale field experiments proved to be an important verification of results from a number of small- and medium-scale laboratory experiments being performed during the program.
- Laboratory and field experiments have verified that in situ burning and chemical dispersion can be highly effective response methods.
- Findings show that the presence of cold water and ice can enhance response effectiveness by limiting the spread of oil and slowing the weathering process.
- The window of opportunity for in situ burning and the use of dispersant operations in ice-covered waters can significantly increase compared to an open water scenario under certain circumstances.
- New technologies for mechanical oil spill recovery and dispersant application that, when combined with a large set of test data, will improve response planning and response operations.

As a result of this program, a significant data set has been collected that will aid in understanding more about oil in ice, including such issues as: oil weathering; the window of opportunity for various oil spill countermeasures; the interaction between oil-ice and water; the bio availability of released oil in ice; and information on oil-ice drift. This information will serve as the basis for model development; technical information to support further development of new technologies for oil spill countermeasures; and practical experience that will be used in spill response contingency planning strategies.

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# INTRODUCTION

**The present report summarises the key findings and highlights from the program presented in 31 separate scientific reports. Some of the conclusions in this report are, in addition to our own studies, based on previous national and international projects. References to these studies are given in the scientific reports from the program (see appendix).**

The Joint Industry Program (JIP) on oil spill contingency for Arctic and ice-covered waters (JIP Oil in Ice) started in 2006 and was finalised by the end of 2009. It represents a concerted industry effort to improve spill response operations in Arctic waters and to obtain more knowledge about spill cleanup in ice. The program's sponsors are the Norwegian Research Council and six oil and gas companies: Statoil, Shell, ConocoPhillips, Chevron, Agip KCO and Total.

The US Geological Survey (USGS) estimates that the area north of the Arctic Circle accounts for approximately 22% of the undiscovered technically recoverable oil and gas resources in the world. In order to improve the oil spill response to ensure that resources are produced in a safe manner, the oil and gas industry has established this JIP. The objective of the program is to develop and advance knowledge, methods and technology for oil spill response in Arctic and ice-covered waters.

As part of the R&D program, two large-scale field experiments have been carried out in the Norwegian part of the Barents Sea east of the Svalbard archipelago. Tests were conducted in ice with concentrations ranging between 50% and 95%. Mechanical recovery, in situ burning and dispersant application were tested on a large scale during these field trials. The two large-scale field tests verified both laboratory results and medium-scale experiments obtained during the program, and have provided valuable information about the behaviour of oil spills in ice and the development of state-of-the-art response techniques. The field experiments have given the participants a unique opportunity to test actual response techniques in a real-life Arctic environment. Several innovative response techniques were tested such as new skimmer concepts, the use of booms and herders[1] to enhance the in situ burning of oil in ice, and the dispersion of oil in ice as well as remote sensing and the detection of oil in the presence of ice.

The results of the research program may be used as the basis for oil spill contingency planning, improved spill response operations and the identification of additional applied research opportunities that will ensure the continuous advancement of Arctic oil spill response.

## 2.1 Program organisation and funding

The Joint Industry Program is divided into nine projects and a total of 25 sub-projects. SINTEF Materials and Chemistry has been coordinating the program, while SL Ross Environmental Research Ltd. (Canada) and DF Dickins Associates (USA) have been SINTEFs main R&D partners.

**The program has been organised in the following way:**

| | |
|---|---|
| • Steering Committee: | Representatives from the funding oil companies |
| • Program Management: | Stein Erik Sorstrom, (SINTEF) |
| • P1. Fate and behaviour: | Per Johan Brandvik, (SINTEF) |
| • P2. In situ burning: | Ian Buist, (SL Ross Ltd.) and Per Johan Brandvik (SINTEF) |
| • P3. Mechanical recovery: | Ivar Singsaas (SINTEF) |
| • P4. Dispersants: | Per S Daling (SINTEF) |
| • P5. Remote sensing: | David Dickins (DF Dickins Associates) |
| • P6. Oil spill response guide: | Ivar Singsaas (SINTEF |
| • P7. Program administration: | Stein Erik Sorstrom (SINTEF) |
| • P8. Field experiments: | Stein Erik Sorstrom (SINTEF |
| • P9. Oil distribution and bioavailability: | Liv-Guri Faksness (SINTEF) |

[1]Herders = Surface active components.

The Steering Committee comprises representatives from the funding companies. The total value of the project was approx. NOK 65 million, including support by the participating oil companies, funding from the Norwegian Research Council (Demo 2000 and Petromaks) and in-kind support from the cooperating organisations.

**2.2 The presence of ice**

Oil spill response in the Arctic ice-free season can be comparable to the response in other parts of the world with the exception of lower temperatures and seasonal darkness. The presence of ice on the sea surface will however have a great effect on oil spill response. If there is a solid sheet of ice on the sea surface, the oil spill response measures will depend on whether the oil has been spilled on or under the ice. If there is only a partial ice cover on the sea surface, the response will be affected by the amount of coverage and the properties of the ice. In pockets between larger ice floes, oil can be trapped in large quantities, enabling quite efficient mechanical recovery of oil.

The presence of ice will retard the rate of spreading for spilled oil in comparison to ice-free conditions. For that reason, the seasonal cycle of the freezing and melting of ice will have important practical implications in the selection of oil spill response method.

The presence of ice also modifies the wind-induced wave action at sea; short waves are damped by the presence of ice, while long swells from open water persist in the outer regions of broken ice fields. Waves are the driving force for the dispersion of dispersant-treated oil spills. Wave conditions at sea can be broadly related to wind speed, while the effect of waves on the dispersion process is greatly reduced in ice-covered areas.

The ice conditions will be different at different locations:

- In the shallow waters of most Arctic seas, the polar ice pack is never far away and the ice cover in the long winter will be characterised by a more or less continuous layer of ice broken up by tidal movements with ice attached to the shore in shallow water. Pressure ridges will be formed where the ice is forced upwards by the relative movement of the ice pieces.
- A large tidal range and fast currents, such as those that occur in Cook Inlet on the northern coast of the Gulf of Alaska, will rapidly break the ice into pieces in a wide range of sizes.
- At other more open ocean locations such as the Barents Sea the ice will be present as ice floes that have been formed as pack ice elsewhere and have been carried to the location by the influence of wind and currents.
- Arctic icebergs are created mainly from glaciers on the eastern and western coast of Greenland and from the glaciers of Ellesmere Island. They drift southward on the Labrador Current towards the Grand Banks of Newfoundland. Only about 400 icebergs, however, manage to complete the journey and appear at the Grand Banks and occasionally in the main North Atlantic shipping lanes.

A characteristic of some specific Arctic areas is lower seawater salinity. On average, seawater in the world's oceans has a salinity of approximately 35 psu (practical salinity units) to below 29 psu near river deltas, with seasonal variations depending on the freezing and melting processes. Because of its low salinity and resulting lower density, this freshwater remains close to the surface and is the first to freeze in the autumn.

An example of a pragmatic approach to sea ice characterization may be found in the Field Guide for Oil Spill Response in Arctic Waters.[2] In the Field Guide, the stages of ice development are defined in terms of seasons – open water, freeze-up, frozen conditions and breakup – each comprising certain possible ice forms (ice floes, broken ice, frazil/grease ice, slush, pancake ice, brash ice, ice hummocks, melt pools and leads). Different locations of oil are considered for the various seasons – oil on the sea surface, oil between broken ice, oil under the ice, submerged oil, and oil in melt pools as illustrated below. Some of the terms used here to define ice conditions are not included in the WMO[3] classification system.

*The oil spreads in between the ice floes and will follow the movement of the ice*

[2]The Field Guide was prepared for the Emergency Prevention, Preparedness and Response Working Group (EPPR) within the Arctic Environmental Protection Strategy (AEPS), which was adopted by Canada, Denmark/Greenland, Finland, Iceland, Norway, the Russian Federation, Sweden and the United States through a Ministerial Declaration in Rovaniemi, Finland in 1991.

[3]The WMO (World Meteorological Organization) ice code comprises three main parameters: ice concentration, stage of development and ice form or size, with each given numerical values according to a standardised system.

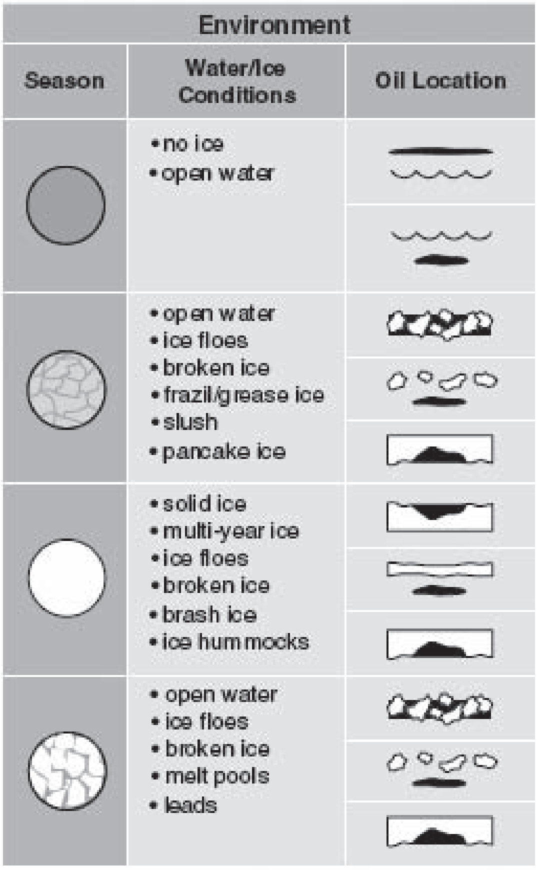



*Figure 2.1 - Ice conditions as defined in the Field Guide for Oil Spill response in Arctic Waters.*

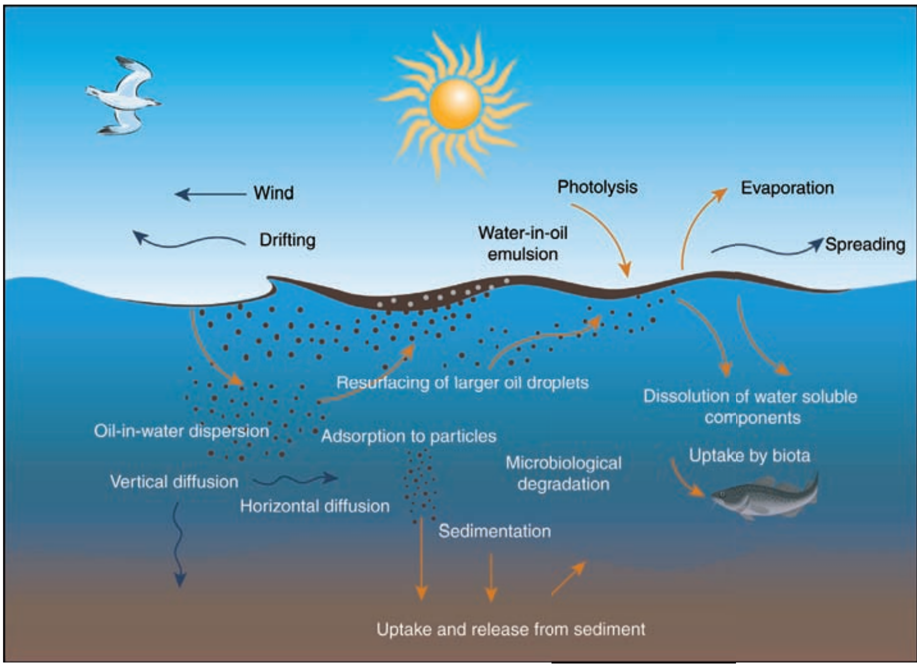



*Figure 2.2 A number of environmental processes take place which alter the properties of oil.*

**2.3 Oil weathering**

When crude oil is spilled at sea, a number of natural processes take place which change the chemical properties of the oil. These natural processes are evaporation, water-in-oil emulsification, oil-in-water dispersion, the release of oil components into the water column, spreading, sedimentation, oxidation and biodegradation. A common term for all of these natural processes is **weathering**, and the relative contribution of each process varies depending on the type of oil, the duration of the spill, weather and other factors.

Due to these changes in properties, the possibility for the use of various oil spill countermeasures, such as mechanical recovery, dispersants and in situ burning, changes. For example, after a certain time period the oil will no longer be ignitable due to water uptake. The time before we reach this point is termed the **window of opportunity.**

The effect of low temperatures on the rate and extent of oil weathering in ice-covered waters is known in general terms, although not in detail. Previous field and laboratory studies conducted in Canada and Norway indicate that the window of opportunity for both dispersant use and ISB can be much longer in Arctic conditions because of reduced rates of evaporation and emulsification. The ability to determine the window of opportunity for different response techniques as part of response planning is one key term in the present program.

Important weathering processes for oil spill operations such as evaporative loss, water uptake, emulsion stability and viscosity vary with oil type. Normally, these parameters change relatively quickly with increased weathering time in open water. In ice-covered waters, several studies have indicated that this time-dependent weathering can substantially slow down depending on ice type, ice coverage and energy conditions.

Compared to in-depth knowledge which exists regarding the behaviour of oil spills in open water and temperate conditions, our knowledge regarding Arctic oil spills has been rather limited. The laboratory and fieldwork reported here aims at closing these knowledge gaps and using this increased knowledge to improve our capability to predict the fate of oil spills in ice, as well as predicting the window of opportunity for the use of various oil spill countermeasures and techniques in ice.

### 2.4 Oil spill countermeasures

There are several possible ways to react to an oil spill in ice: mechanical recovery, in situ burning and chemical dispersion. Surveillance by remote sensing is regarded as a fourth method which may be a selected option under certain situations.

To select the best response option will depend on site-specific conditions (near shore, shallow water, sensitivity of the receiving environment, ice coverage, weather and ice drift forecasts, etc.) and the ability to assess the environmental impact from applying the different response options.

#### 2.4.1 Mechanical recovery

Mechanical recovery is presently considered to be the default response option of choice as it both removes and recovers the spilled oil. Mechanical methods are developed for open water conditions and have a number of limitations which will have to be overcome for operations in ice. Recovery values will be highly variable depending on a variety of oil weathering, natural conditions and logistical constraints. Some of the main challenges in ice vs. open water are: icing and freezing of equipment, limited access to the oil, limited flow of oil to the skimmer, separation of oil from ice and water, forces in the ice field and increased oil viscosity.

During the large-scale field experiments in 2008 and 2009, five different skimmers were tested under realistic conditions, and two of these skimmers have been developed as part of the R&D program (prototypes available by 2010).

#### 2.4.2 In-situ burning

Different crude oils can demonstrate very different ignitability due to their original chemical composition and the effect this has on the rate of weathering. The key to effective in *situ* burning (ISB) is thick oil slicks. Pack ice (70 – 90% ice coverage) can enable in *situ* burning by keeping slicks thick. In lower ice conditions, oil spills can spread and become too thin to ignite. The use of specific chemical surface-active agents (oil herders) to contain oil slicks on open water has been previously studied. Small quantities of these surfactants (50 mg/m$^2$) will quickly clear thin films of oil from large areas of the water's surface, contracting the oil into thicker slicks. Fire booms can collect and keep slicks thick in open water. The tests made during this program have shown that fire resistant booms may also be used with good effect in low ice conditions.

As part of the large-scale field experiments in this program several ISB tests were carried out: in situ burning of a weathered free floating slick in ice, tests with two different fireproof booms and a test of chemical herders on a free floating slick in low ice concentration.

#### 2.4.3 Chemical dispersion

The addition of a dispersant to spilled oil increases the potential for the oil to be dispersed as very small oil droplets in the water column. The smaller the oil droplets, the more available they are for micro organisms in the water mass to naturally biodegrade the oil. Mixing energy is required to create small oil droplets and to maintain the oil droplets within the water column. When breaking waves are present, which is a normal situation in open water, the crest of a breaking wave passing through a dispersant-treated oil slick possesses sufficient shearing action to convert the oil into small-sized droplets. Even a small vertical advection within the water column is sufficient to maintain the oil droplets in the water column and prevent the oil droplets from resurfacing. In ice-covered waters, the energy input from breaking waves may be almost zero, so in cases like these, it will be necessary to add extra mixing energy to enhance the dispersion process.

During the 2009 field experiment, a total of three different large-scale field experiments with the application of dispersants were conducted. A new application system developed under this program was also part of the 2009 experiment (commercially available by 2010).

#### 2.4.4 Remote sensing

Spill detection and mapping are particularly important for Arctic spills, as oil may be hidden under snow and ice during periods of almost total darkness. During situations in which weather or ice conditions can limit recovery operations, surveillance may be the only ongoing response activity. An ideal system would have the capability of operating in both airborne and ground-based modes and have the capability of determining whether oil is present, as well as to map the boundaries of contamination over potentially large areas.

During the 2009 large-scale field experiment, four different satellites plus Swedish Coast Guard surveillance aircraft were tested. In addition, a number of other techniques have been tested throughout the program period.

3

# FROM LABORATORY TO LARGE-SCALE FIELD EXPERIMENTS

The R&D strategy of the program has been to link small-scale laboratory tests with medium-scale tests in laboratories and the field, and to finally run large-scale field experiments to verify the results from the small- and medium-scale tests. It is a very challenging task to design reliable laboratory studies that recreate the situations we encounter in a real-life outdoor environment.

A large number of small- and medium-scale tests have been performed under controlled conditions in the laboratory facilities at SINTEF's SeaLab. Tests have been run with a number of combinations of oil types, ice conditions, temperatures and other important parameters which affect the behaviour of oil as well as the possibilities for efficient oil spill countermeasures with the various available techniques. Some important parts of the test program have been carried out at the outdoor test facilities at the Svea Research Station (Svalbard), and lastly, two large-scale field experiments have been conducted in the marginal ice zone in the Barents Sea.

**3.1 Laboratory tests**

The small-scale and basin tests have been performed in the laboratory facilities at SINTEF's SeaLab in Trondheim, Norway (weathering studies, the testing of dispersant, new application technology and new oil skimmers) and at S.L. Ross Laboratories in Ottawa, Canada (the testing of herders).

In an oil spill situation at sea, the weathering processes will occur simultaneously and affect each other. It is therefore important that oils are weathered under realistic conditions when studying the fate and behaviour of oil spills in ice. A meso-scale basin was used to study the weathering processes simultaneously under controlled conditions, and the basin experiments were performed using different ice conditions (0, 30, 50 70 and 90% ice coverage). Approximately 5 $m^3$ of seawater was circulated in the 10-meter-long flume basin, which is located in a temperature controlled room (0°C). Two fans placed in a covered wind tunnel allow for the control of the wind speed. The wind was calibrated to simulate an evaporation rate corresponding to a wind speed of 5-10 m/s on the sea surface.

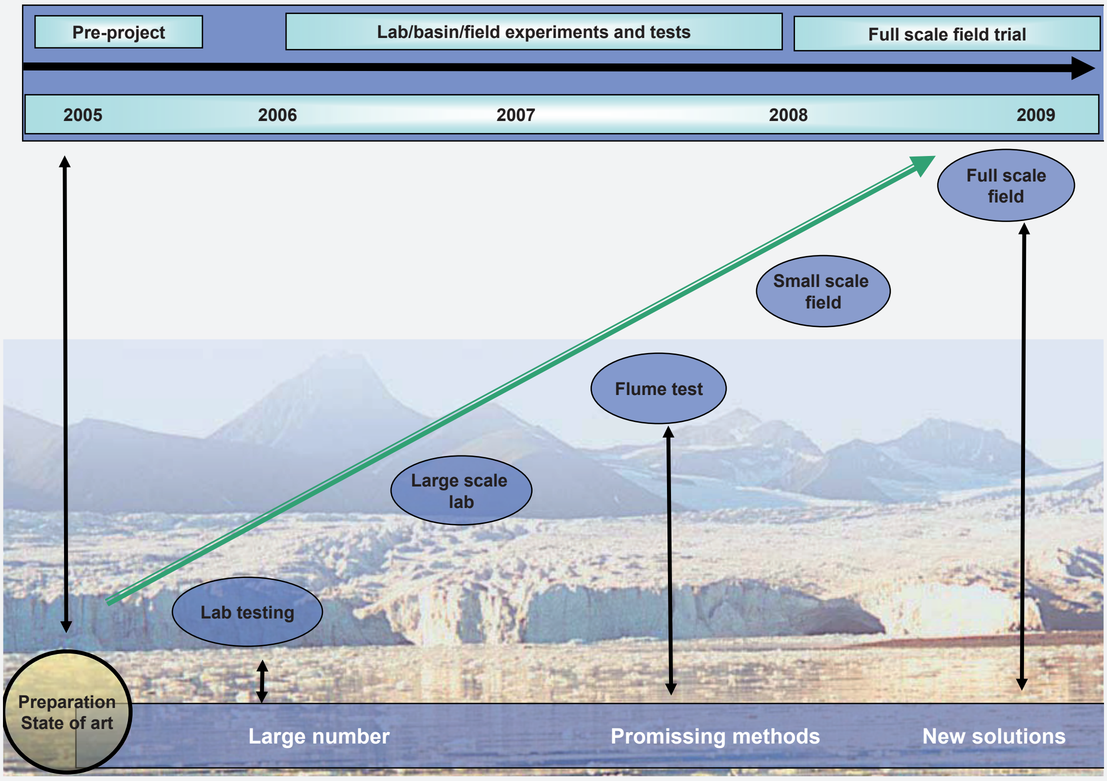


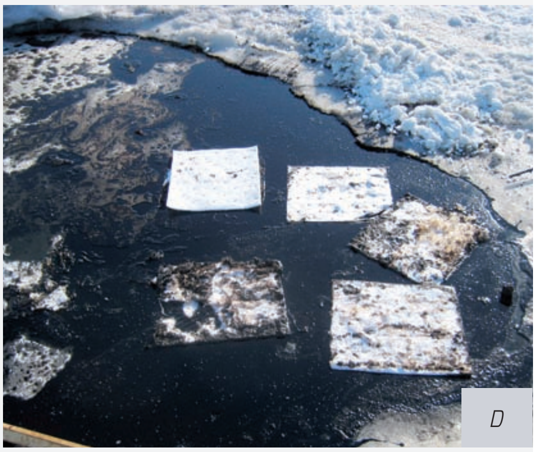

*Figure 3.1 - Illustration of the stepwise development from laboratory to field experiments*


### 3.2 Medium-scale field tests

The medium-scale field tests were carried out at SINTEF's field research station at Svea, Svalbard (78° North). Ice basins were constructed in the fjord ice and weathering studies similar to those run at SINTEF's SeaLab were performed. The experiments in Svea were performed on a larger scale (200 L of oil) compared to the experiments at SINTEF's SeaLab (9 L of oil).

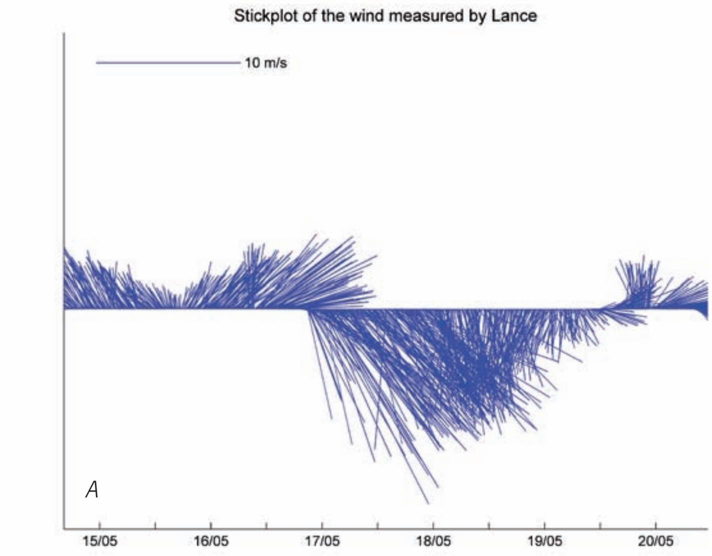
In the Svea area a number of remote sensing tests, including Boise State University's Ground Penetrating Radar (GPR) system, the Shell Light Touch system and specially trained dogs for detection of oil under ice/snow were also carried out.







*Figur 3.2 The burning cell at SINTEF Sealab (A), In situ burning tests at Svea Field station (B-D) and the flume basin at SINTEF SeaLab (E)*



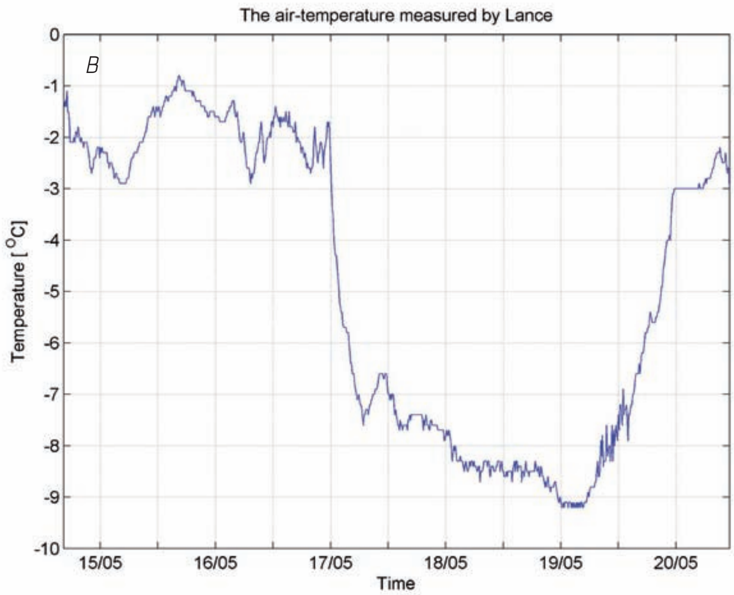




*Figure 3.3 Wind speed (A) and air temperature (B) during the 2009 field experiment.*

### 3.3 Large scale field experiments

Two large-scale experiments were carried out during the program. In 2008, the use of chemical herders were tested on a free floating crude oil slick (0.7 $m^3$) in low (10%) ice coverage, and two skimmers were tested on IF 30 bunker fuel in 30-50% ice coverage. The towing and handling of fire resistant booms in ice were also tested in preparation for the large-scale in situ burn tests in 2009.

In 2009, a total of 11 different tests were performed over a period of eight days. 7 $m^3$ of oil was released in 70-80% ice cover and tracked for six days with a comprehensive sampling and monitoring regime. The sampling program involved oil weathering and oil-ice-water interaction studies, monitoring of ice, oil distribution and drift and spreading. The testing of ignitability and dispersibility over time were also part of the test program. Finally, the slick was treated with dispersants as part of the test program.

The dispersant studies involved the testing of a new concept for the application of dispersants on oil in ice. The in situ burning studies were comprised of three different tests: one 2 $m^3$ slick was released in 80% ice coverage and weathered for 10 hours before ignition and two slicks of 4.5 $m^3$ were used in the two tests with fire resistant booms. Two new skimmers were tested on emulsified IF 30 bunker fuel over a period of several days. The entire operation was kept under surveillance by various remote sensing techniques.


*Pictures from the field activities in 2009*

4

# THE WEATHERING OF OIL

**Key findings about the weathering of oil**

- Oil spills in ice spread much slower and occupy a much smaller area than a similar spill in open water.
- Oil will have a slower weathering in ice which can be an advantage and contribute to the enhancement of response effectiveness for certain types of oil spill scenarios. Still, the window of opportunity is limited and rapid decision making and action are required to make use of the available windows of opportunity for the three response options.
- The Oil Weathering Model (OWM) created by SINTEF can be used to predict the behaviour of various types of oil in ice in order to help plan for different response scenarios.
- SINTEFs OWM is the only model verified by large-scale field experiments with oil in ice.

Prior to this R&D program, the existing knowledge with regard to weathering processes in Arctic oil spills, and in broken ice in particular, was limited. Experimental studies had been performed in laboratories, but only to a limited degree in the field. The major parts of previous studies have been performed in North America, Finland and Norway.

The complexity of an oil spill in ice can be larger than a similar spill in open water, with a large number of possible scenarios. Seasonal variations such as freezing and thawing as well as the uneven distribution of oil in ice, between ice floes and in slush ice represent different challenges in predicting the fate and behaviour of oil in comparison to open water conditions. In the present program focus has been on the large quantities of oil that are usually assembled in leads between the ice floes.

The rate of the weathering process is usually reduced when oil is spilled in ice compared to a spill in open water which is caused by less energy input, higher oil film thickness and lower temperatures. By comparing an experimental oil spill in open water to a similar experiment in broken ice, it has been shown that the water uptake under the Arctic scenario is significantly lower.

This has large operational consequences related to the volume of oil remaining on the surface as well as the properties of the oil, the total influence area of the oil slick, the lifetime of the slick and the window of opportunity for the use of various oil spill response techniques.

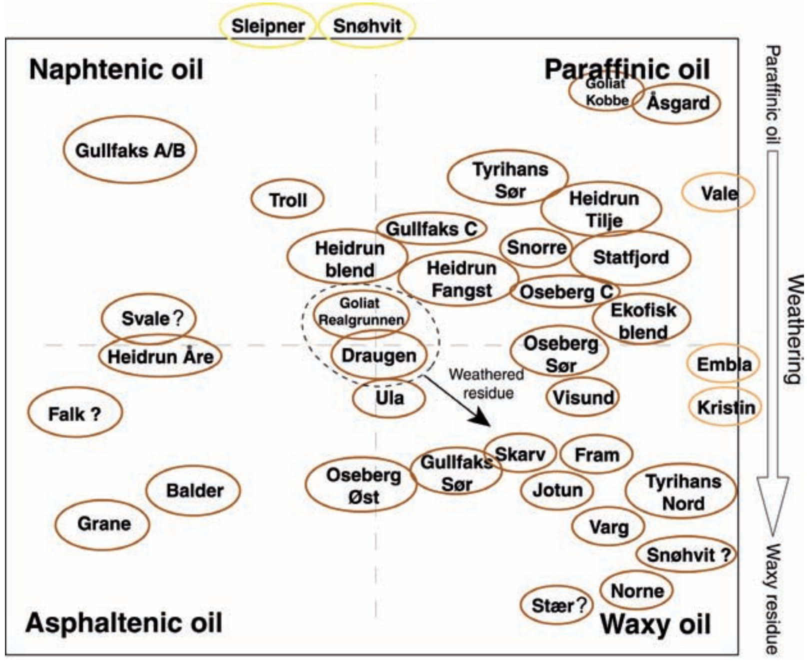
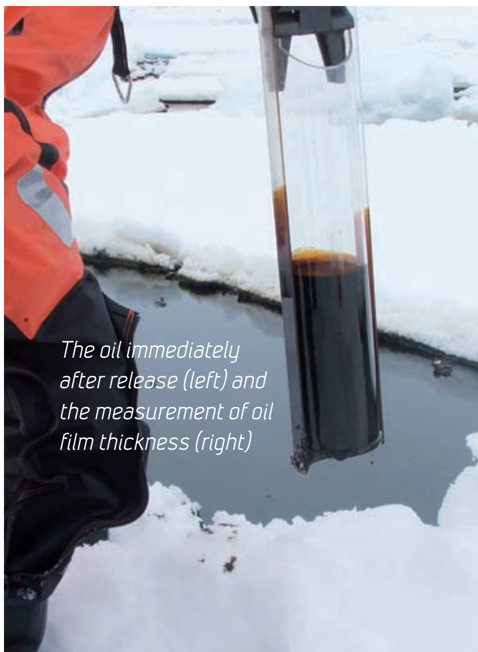



*Figure 4.1 - Illustration of different crude oil properties based on earlier weathering studies performed at SINTEF*

**4.1 Objectives**

The main objective of this part of the program was to generate new knowledge on the behaviour of oil spills in ice for a representative range of oil types. The second goal was to develop new and improved algorithms that describe oil weathering for selected oil-in-ice scenarios, and the third and final goal was to implement these algorithms into the SINTEF Oil Weathering Model.

The upgraded oil weathering model will improve the ability to give more accurate predictions of oil weathering in ice as basis for more precise contingency planning and response operations.



*The oil immediately after release (left) and the measurement of oil film thickness (right)*

### 4.2 Five different oil types

Five different crude oil types were selected for the basin and field weathering experiments. The selected oils represent four different groups of oil type (asphaltenic, naphtenic, waxy and paraffinic) and were selected based on the fact that they represent a large variation in oil properties. The results from these studies form a representative data set which can be used to calibrate the weathering model. In addition to these oils, a very light oil (Kobbe) representing oils from gas/condensate fields was included.

### 4.3 Laboratory experiments

During the test program, a large number of weathering experiments with different ice conditions (open water, 30, 50, 70 and 90% ice coverage) and different oils were carried out at SINTEF's experimental basins in Trondheim.

Both the asphaltenic (Grane) and naphtenic oils (Troll) demonstrated a rapid and high water uptake, while the more waxy/paraffinic oils (Statfjord, Kobbe and Norne) revealed a significantly reduced water uptake.

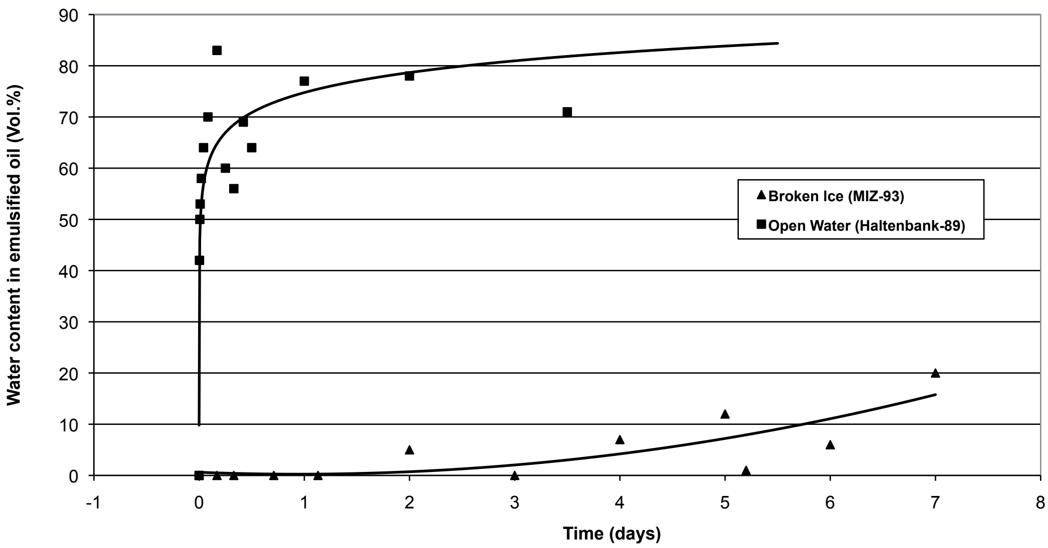



*Figure 4.2 - Example on variations in water content for crude oil as a function of weathering in ice covered and open water.*

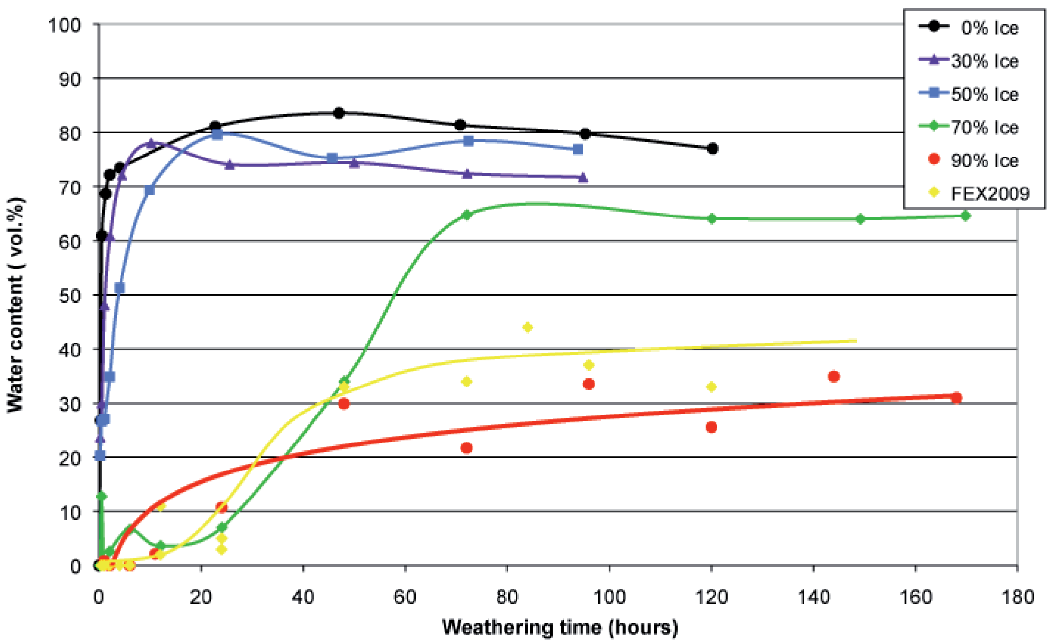



*Figure 4.3 - Water content (vol.% water in emulsion) for the Troll B crude for different ice conditions (0, 30, 50, 70 and 90% ice coverage) as a function of weathering time in the meso-scale flume. The water uptake measured during the field trial in May 2009 (FEX2009) is also plotted in the figure.*

### 4.4 Large-scale field experiment

During the field experiments (FEX) in 2009, 7 $m^3$ of fresh Troll B crude (napthenic oil) were released uncontained between the ice floes to study oil weathering and spreading in ice. The ice concentration in the area varied between 70 to 90% during the experimental period of six days.

GPS trackers, under-ice current monitors, large volume water samplers, in situ oil-in-water monitoring systems and passive absorption devices were installed on the ice floes in and around the oil slick area to enable a detailed monitoring of oil-ice-water dynamics and interaction throughout the experiment. Samples of oil were regularly taken to study weathering processes and assess the potential for in situ burning and the use of dispersants.

The data from the large-scale weathering experiment in the Barents Sea was used to verify the dataset from the laboratory and small-scale field tests. The results show that the water uptake from the field experiment matches the water uptake from the basin experiment with corresponding ice coverage.

### 4.5 Oil weathering model

The extensive data set collected during the experiments (small-, meso- and large-scale results) was used to describe the weathering of oil in ice as a basis for establishing algorithms which describe weathering properties of different oil types as a function of ice conditions. These algorithms have been used to improve the SINTEF Oil Weathering Model.

This new capability of the SINTEF OWM is very valuable for oil spill contingency planning, tabletop training and real response operations.

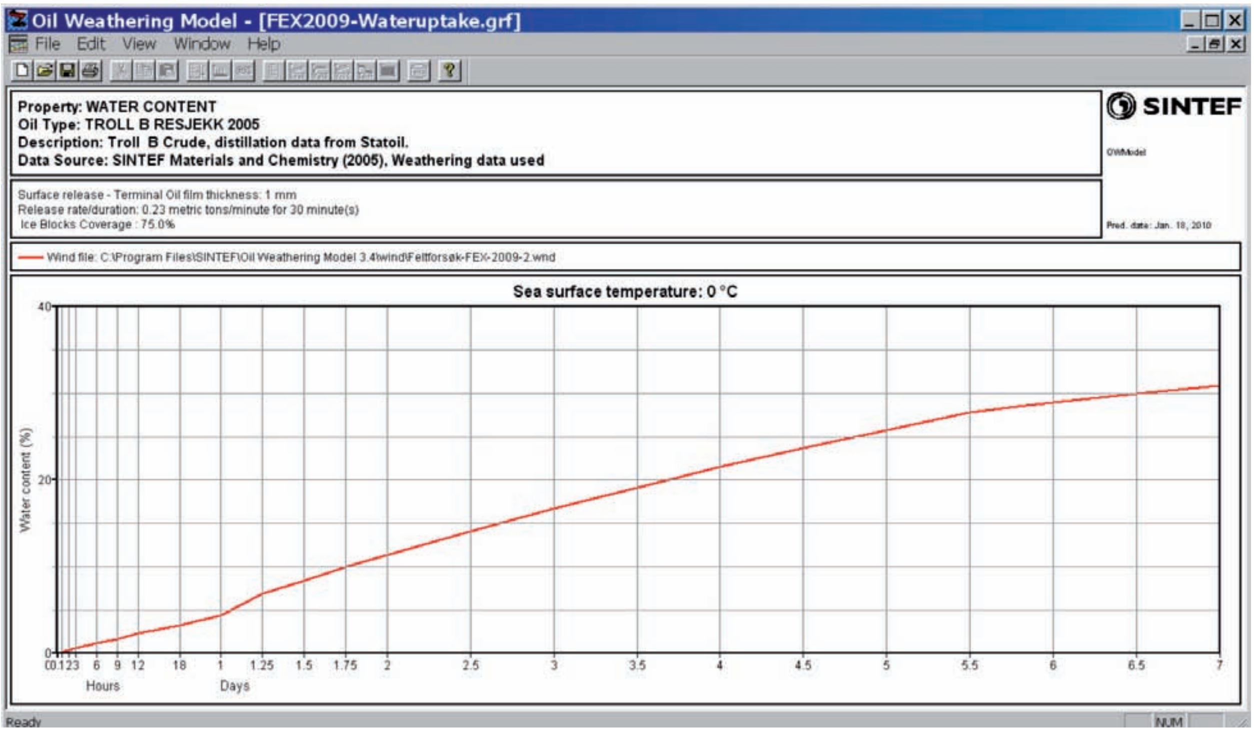



*Figure 4.4 - Water content predicted with the SINTEF Oil Weathering Model improved for predicting oil weathering in ice. Predictions are for Troll B with ice conditions and wind from the field experiment in May 2009 (FEX2009).*

5

# IN SITU BURNING

**Key Findings for in situ burning**

- The window of opportunity for the use of in situ burning in the Arctic can be larger than in the open sea.
- In situ burning has been tested and proven to be effective for the elimination of both free floating oil in ice and oil collected in fire resistant booms.
- Findings show that the presence of cold water and ice can enhance the effectiveness of in situ burning by limiting the spread of oil and slowing weathering processes.
- The field experiments verified in situ burning as an efficient technique, with a burn efficiency rate above 90%.
- Fire-resistant booms and herders proved to be effective in drift ice.
- A small-scale laboratory burning cell to map ignitability as a function of oil type and weathering degree is established and verified against meso- and large-scale field experiments.
- The operational time window for the in situ burning of oil spills can now be predicted using the SINTEF OWM.

In situ burning (ISB) is one of the response techniques with the highest potential for the removal of oil spills in Arctic conditions, especially in snow and dense ice. ISB is well proven and established as part of the oil spill contingency in many Arctic areas. The effectiveness of ISB is verified by previous field experiments performed in the US, Canada and Norway, showing removal efficiencies over 90%.

The suitability of ISB depends on the initial oil characteristics and the weathering state of the oil. Several factors such as slick thickness, oil weathering (particularly emulsification), igniter temperature, swell/waves and wind conditions are important for a successful burning.

### 5.1 Objectives

The main focus in this part of the program has been to study the ignitability of an oil spill as a function of oil properties and the degree of weathering, and to establish algorithms that enable the prediction of the window of opportunity for using ISB.

These new algorithms have been implemented in the SINTEF Oil Weathering Model to allow for more precise decisions on when to use ISB as a countermeasure against oil spills.

The second part of this project has tested whether ISB can be improved by the use of chemical herders to help increase film thickness and by the use of fire resistant booms in partially ice-covered water.

### 5.2 Mapping ignitability versus oil type and weathering degree

The laboratory measurements of ignitability were performed with a laboratory burning cell developed from a previous project and improved as the first part of the oil in ice JIP. This testing of ignitability as a function of weathering was performed on oil samples taken from the meso-scale weathering flume. 0.1 l of oil was used in each test and the laboratory cell contained all the required parts for operation in an ordinary chemical laboratory (water cooling, smoke trap, exhaust filters, etc.).

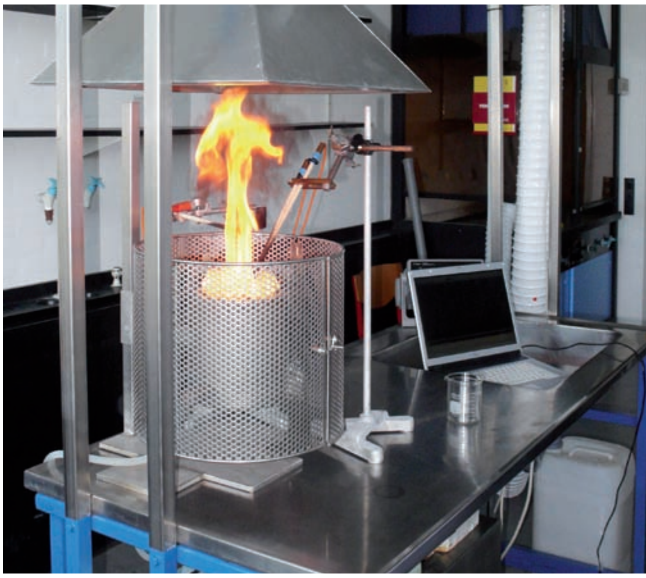


*Figure 5.1 - The new laboratory burning cell during initial testing*

The mapping of ignitability as a function of weathering was performed on a broad selection of oil types and under different ice conditions (open water, 30, 50, 70 and 90% ice coverage), as well as in combination with the studies of weathering properties previously described in this report.

A selection of oils was also tested at the SINTEF field research station in Svea (Svalbard), where larger volumes of oil per experiment (400-600 litres) were used. At the end of the weathering period, the entire batch of weathered oil was transferred to a burning basin and ignited, and the burning efficiency was quantified by collecting the semi-solid burning residue.

The objective of the larger scale experiments performed in Svea was to verify the results from the small-scale laboratory burning cell experiments. The results showed that the drastic drop in ignitability that was recorded during the laboratory tests was identical to findings from experiments in the real Arctic environment conducted in Svea, which verified the validity of the results from the laboratory burning cell.

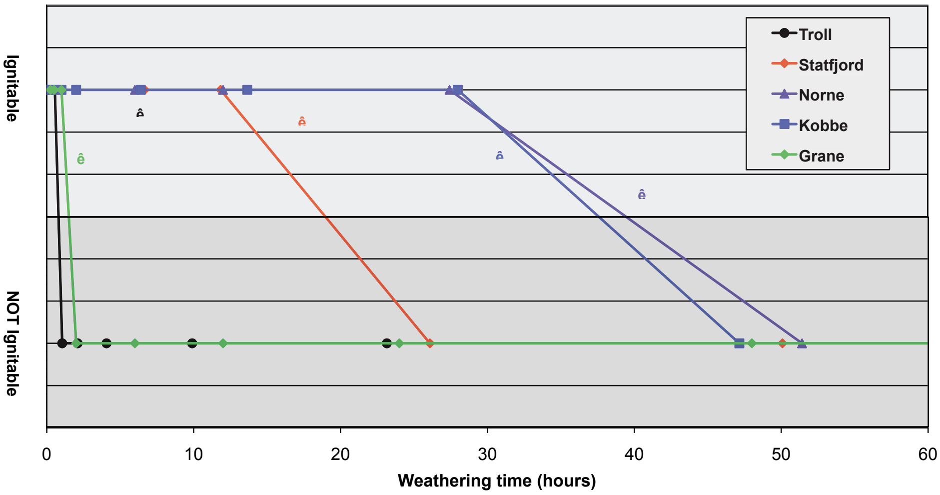



*Figure 5.2 - Ignitability measured with the laboratory burning cell as a function of weathering time for the five different oil types used in this study. All were measured at 50% ice coverage.*

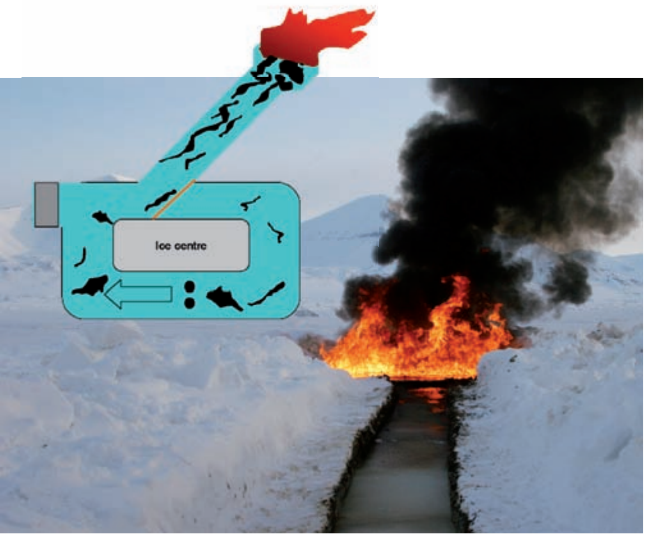



*Figure 53 - In-situ burning of weathered oil. The system consisting of a burning basin connected to the weathering basin with a channel (see earlier figure) in operation.*

**5.3 Large-scale field verification**

To ensure the validity of the extensive dataset generated with the laboratory cell, an experimental oil release was performed during the 2009 large-scale field experiment. Two cubic meters of fresh Troll B crude were released uncontained between the ice floes, weathered for six hours and then ignited using 500 ml plastic bags containing gelled gasoline with emulsion breaker. The ice concentration during the experiment was 70 to 90%.

Ignitability was also measured for the large experimental oil release (seven cubic meters of Troll B crude) used for studying the weathering of oil in ice. This oil slick was ignitable until five days of weathering at 70-90% ice coverage.

The peak burning intensity occurred 10-12 minutes after ignition and the total burn time was 26 minutes. The residue after burning was collected using adsorbents, and the test area was treated with bark to immobilise the traces left on the water. The burn efficiency was estimated at more than 90%.




*Figure 5.4 - Large-scale field experiment in the Barents Sea, May 2009. Peak burning intensity (A, the collecting of residue (B) and final treatment with adsorbents (C).*

The main deliverable from this part of the program is a new module in the SINTEF Oil Weathering Model which predicts the operational window for ISB as a function of weathering.

**5.4 Using chemical herders**

A two-day field research program was conducted off Svalbard in May 2008 to test the efficacy of a chemical herding agent in thickening oil slicks on water among very open drift ice for subsequent in situ burning. The objective of this study was to further evaluate the use of chemical herding agents to thicken oil spills in broken ice to allow them to be effectively ignited and burned in situ. Two meso-scale field burn experiments with crude oil slicks of approximately 0.1 and 0.7 $m^3$ in open drift ice were performed.

Prior to conducting the field experiments, two series of small laboratory tests were carried out with two crudes (Heidrun and Statfjord). The purpose of the field experiment in 2008 was to determine the ability of the USN herder to contract slicks in a larger scale experiment.

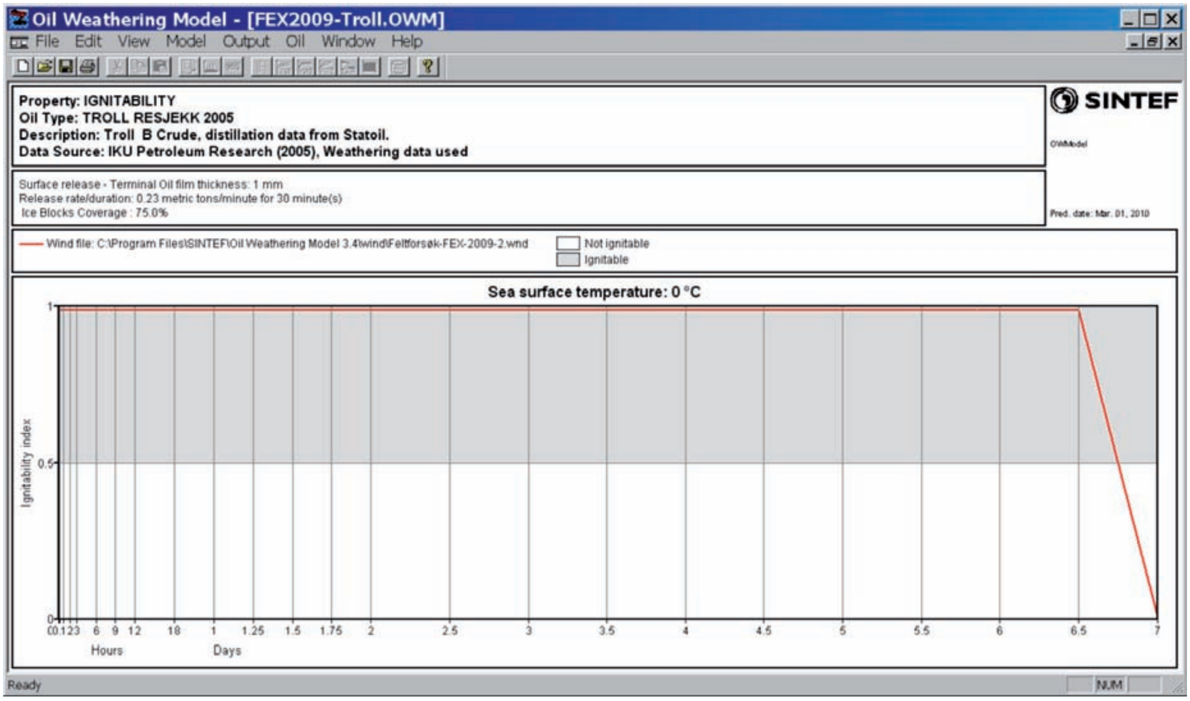



*Figure 5.5 - Example of prediction of "Ignitability" from SINTEF OWM simulating the conditions from the large-scale field experiment in May 2009 (FEX2009)*

Heidrun was chosen based on its low wax content and associated pour point to avoid any solidification of the oil and problems using the herder.

The main test involved releasing 630 L of fresh Heidrun crude onto the water from the edge of a floe. The oil was allowed to spread on the water for roughly 15 minutes, after which a total of three litres of herder was applied by personnel on the ice floe and then along the sides of the slick by personnel in a boat. The igniters were placed on the upwind edge of the herded slick approximately 10 minutes after the first herder was applied, and the burn finally extinguished nine minutes later after a large, intense burn travelling the length of the herded slick.

The residue and unburned oil were recovered using pre-weighed sorbent pads and sorbent booms using the small boats. The estimated burn efficiency based on the amount of oil released and residue recovered was approximately 90%.

**5.5 Testing fire-resistant booms**

The objective of this part of the program was to determine whether fire-resistant booms could be used to facilitate an effective burn in low concentrations of drift ice. Two tests were planned in two different situations of drift ice, using two different fire-resistant booms.

In both tests, the basic elements of the plan were to deploy the boom, tow it through a field of 10-30% drift ice, monitor boom performance, collect and concentrate a 4 $m^3$ spill of crude oil, ignite the oil and contain it while burning, collect and measure the residue, and retrieve the boom. As a prelude to the tests in 2009, both booms were tested in 2008 to study the capability of the booms to operate in low ice concentrations in terms of their strength, durability and the towing forces on the booms.

The boom was prepared for deployment by flaking it out, with all connections made, on the heli-deck of the K/V Svalbard. The towing operation was carried out by the K/V Svalbard and one of its rescue boats.

The intention was to tow the boom into the wind and through an area with ice concentration varying from trace to 50%. With the boom in a U-shape and ice filling its apex, a total of 4 $m^3$ of oil was discharged into the boom. The oil was ignited with a number of small zip lock bags containing gelled gasoline. The igniters drifted back into the oil, and the oil was soon ignited.

The ensuing burn lasted for approximately 25 minutes for the first test and as much as 2.5 hours for the second test.

Following the burn, sorbent pads were used to recover the residue. Based on the residue mass estimated following the burn, the burn effectiveness was in excess of 95% for the first test and approximately 90% for the second test.

Peat moss was distributed over the remaining residue and the ice/residue mixture released. The boom was observed to be in good condition and could have been used in a subsequent burn.


*Large herder test burn in 2008*


*Ice contained within the boom*

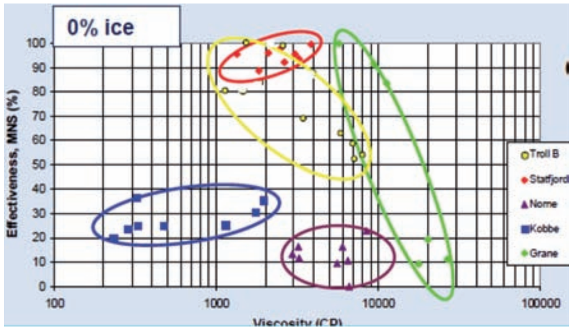

*3M American Marine boom*

6

# CHEMICAL DISPERSION OF OIL

**Key findings – the use of chemical dispersants**

- Laboratory and field experiments have verified that oil spilled in ice-covered waters is dispersible by use of oil spill dispersants.
- The tests conducted during this R&D program have systematically verified that the weathering process is slowed down when ice is present, enabling a larger window of opportunity for dispersant application. Some oils spilled in ice remain dispersible over a period of several days.
- Tools have been developed to define the window of opportunity, as well as methods and technology for applying dispersants effectively on oil spills in ice.
- Reliable predictions on the "operational time window" for the use of chemical dispersants can be given by using the SINTEF Oil Weathering Model.
- A new dispersant spray unit developed through this research program opens up the possibility of new strategies for the operational use of dispersants in high ice coverage (80-90%).
- The energy input in the oil-ice system will be reduced with increasing ice coverage. Adding extra mixing energy extends the operational possibilities. The use of the thrusters from the main vessel, and the water jet of the mob boats to create turbulence, proved to be effective.
- The results from the large-scale field trials verify the potential for the use of dispersants in ice-covered areas, which gives the potential for new strategies as well as new and improved systems for dispersion of oil in high ice coverage.



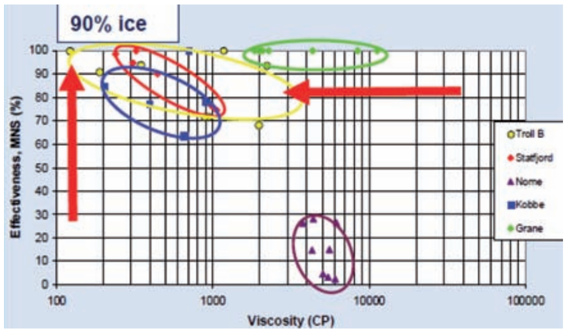




*Figure 6.1 - Weathering of oil vs. dispersibility and ice coverage. The figure shows that the "clusters" of the viscosity range for the different oils are generally lower when weathered in high ice conditions compared to no ice, and that this results in a higher dispersant effectiveness for some of the oils.*

The addition of dispersants to spilled oil increases the potential for the oil to become dispersed. Mixing energy is required to create small oil droplets to maintain the oil droplets within the water column, finally causing them to spread, dilute and naturally biodegrade.

While there have been a few studies which have used laboratory test methods with various combinations of low temperature, the absence or presence of ice and variations in water salinity, no field scale experiments have been conducted with dispersants under realistic ice conditions prior to this program. The main question with regard to the results obtained in the laboratory studies is how accurately these tests simulate the actual conditions that will be observed in real field conditions. Because of this question, the main emphasis of the program has been to design reliable tests in the laboratory and to link previous tests and results with the flume tests at SINTEF SeaLab with results we can observe under realistic field conditions.

After being released on the sea surface, oil will start weathering, causing changes in the oil's properties. Weathered, emulsified and more viscous oil is normally less dispersible than fresh crude. The possibility of carrying out an efficient dispersant operation will therefore be reduced at a certain point after the release of oil. In a systematic way, the program has documented that oil weathering slows down, thus enabling an increased window of opportunity with increasing ice coverage (see Chapter 3).

**6.1 Dispersant spray systems**

Ice will alter the distribution of spilled oil on the sea surface, and the presence of ice will set limits on the operation of spraying dispersants onto the oil slick. Dispersant spraying systems have currently been developed for use on spilled oil in open water conditions. In open water, the oil will spread rapidly and cover a large area of the sea surface shortly after being released. Together with the rapid changes in the oil's properties, the strategy is therefore to spray the dispersant as early and quickly as possible before the window of opportunity for dispersion application has been closed.

In ice, we are facing many different challenges, as the remoteness of the area and the ice itself sets limits on the operation. The distribution of oil between ice floes and the reduced level of energy (due to ice having a dampening effect on wave action) both reduce the natural dispersion process.

An efficient spraying system for ice-covered waters should be able to distribute as much of the dispersant as possible on the oil in between the ice floes in order to optimise the use of dispersants and target the application. One of the goals of the dispersant project has been to develop a new dispersant application system with optimised spraying properties suitable for Arctic conditions.

This development has been carried out in cooperation with a Norwegian engineering company (Jason Engineering), and the concept is based on an idea that resembles the de-icing system used at airports: A flexible arm with a hydraulic operation and spray nozzles that can be changed, depending on the operating conditions.

**Design, construction and laboratory testing of prototype**

The new spray system is characterised by a manoeuvrable arm divided into two 2.5 m long sections with three joints that can be bent individually by means of hydraulic cylinders. The arm can rotate 300 degrees horizontally, and in the front of this arm there is a nozzle section that can be rotated 360 degrees. The nozzle section can be replaced to achieve different spray patterns depending on the actual conditions encountered during the spraying operation.

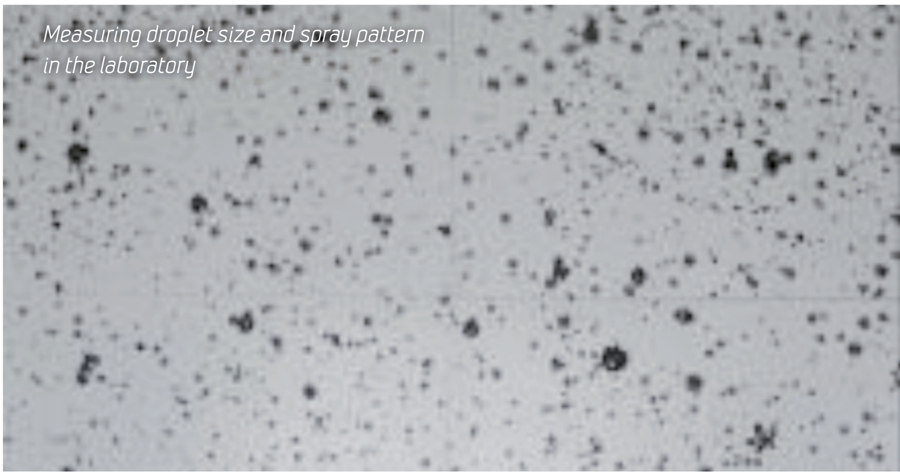
**Test of basic components in the laboratory at SINTEF SeaLab**

Preliminary tests were carried out at SINTEF SeaLab to study the flow rate, spray pattern and pressure drop through the test rig, in addition to determining the dispersant droplet size distribution.

**Field validation of the spray arm proto type during FEX 2009**

The main objective of the field tests was to verify the applicability of the system under realistic field conditions. Three large-scale tests were performed on 0.5, 2 and 7 m$^3$ of oil, respectively. These slicks were weathered for 1 h, 6 h and 6 days before dispersant application. A comprehensive sampling scheme was carried out in order to document the effectiveness, with two different dispersants being used during these tests: Corexit 9500 and Dasic Slickgone NS.


*Testing of spray arm in SINTEF laboratories*


*Measuring droplet size and spray pattern in the laboratory*


*Testing of dispersant application system during FEX 2009*

*Extra energy added by use of thrusters and water jet of the MOB-boat.*

### 6.2 Adding extra energy

Breaking waves in open water force the oil slick to disperse into small droplets. The presence of ice causes a dampening of the wave action inside the ice field which results in reduced mixing energy compared to open water, thereby reducing oil droplet formation.

If dispersants are sprayed onto spilled oil from a vessel, mixing energy can be added by, e.g. the use of the vessel's propellers or the use of high pressure water systems. The intention of using additional energy after dispersant application is to create small oil droplets with a very low rising velocity, thus allowing the prevailing local currents to dilute the cloud of dispersed oil. A small droplet will have a larger surface-to-volume ratio as compared to a large droplet, allowing more oil degrading bacteria to work on the surface of the droplet. For that reason, the additional effect of chemical dispersion is to enhance the natural bio-degradation of dispersed oil.

### 6.3 Field tests

A series of three separate large-scale dispersant tests were carried out during FEX 2009. The first test was a pre-test to verify that the systems were operating as required and to ensure that the second test could be carried out in a safe manner. The third test was performed on an oil slick weathered for six days (See Chapter 4.4).

#### Pre-Test: Release of 0.5 $m^3$ crude oil

0.5 $m^3$ of Troll B crude oil was released in ice coverage of 70-80% and weathered on the sea surface for approximately 30 minutes before the application of the dispersant Corexit 9500. There was no wave action during this operation.

Fifteen minutes after the dispersant treatment, the thrusters on board the research vessel Lance were used to create extra energy to enhance the dispersion process. This resulted in a very effective, immediate and significant dispersion of the treated oil, and the estimated dispersion efficiency was above 90%.

**Main test: Release of 2 $m^3$ crude oil**

2 $m^3$ of Troll B crude oil was released in ice coverage of 70-80% and weathered on the sea surface for approximately six hours before application of the dispersant Corexit 9500. There was no wave action during this operation. Concentrations of dispersed and dissolved oil in the water column were monitored by in situ UV Fluorescence, LISST droplet size distribution measurements and water sampling.

The spraying operation lasted for 30 minutes. 300 L of Corexit 9500 was applied and the thick part of the slick was covered with dispersant, with priority given to applying the dispersant along the ice edge where the oil thickness was 2-3 cm. In this area, the dosage was estimated at 200-300 ml / $m^2$. By adding extra energy by use of the thrusters on board the Lance, we achieved an estimated dispersion efficiency of more than 90%.

**Clean-up operation: Release of 7 $m^3$ crude oil**

7 $m^3$ of Troll B crude oil was released in ice coverage of 80-90% and weathered on the sea surface for six days before application of the dispersants Dasic Slickgone NS and Corexit 9500. There was no wave action during this operation which took place 6 and 7 days after oil release.

To enhance the dispersion process after the dispersant treatment, it was decided to use the water jet of the MOB boat to create artificial turbulence, while the Lance focused on the dispersant application operation. The water jet of the MOB boat proved to be highly efficient, especially in the narrow leads between the ice floes. The dispersant operation, including the work with the MOB boats,[4] resulted in an estimated dispersion efficiency of above 90%.

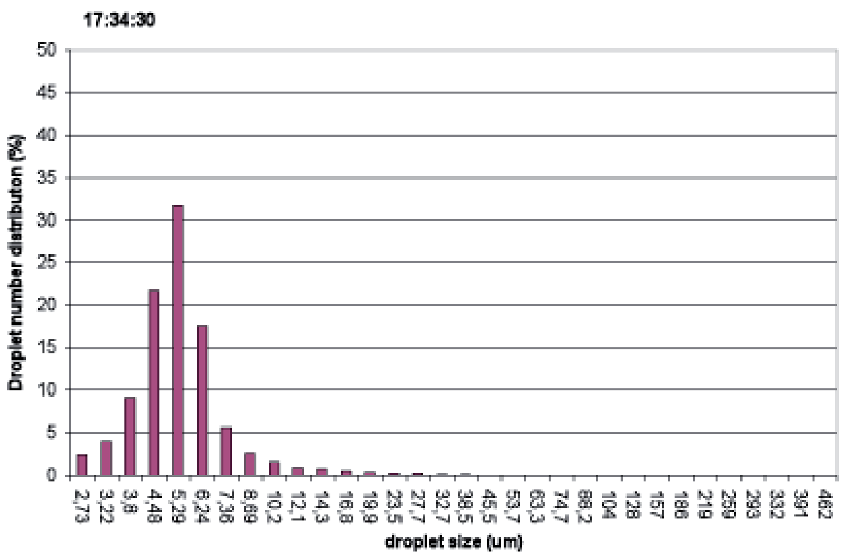



*Figure 6.3 - Droplet size measurements document that the oil is broken down into small particles (5-30 um) with extremely low rising velocity*

[4]MOB boat= man over board boat

# 7 MECHANICAL RECOVERY OF OIL

**Key findings for the mechanical recovery of oil**

- The research program demonstrated that the mechanical recovery of oil spills in ice-covered waters is possible. The efficiency of the available recovery technology may vary depending on the type of ice and its concentration.
- Brush drum skimmers can combine ice processing with oil recovery capabilities in a positive manner. The use of thrusters on the skimmer improves the ability to recover oil in ice fields that are not disturbed by vessels.
- An existing state-of-the-art skimmer for oil recovery in ice was tested, and two new prototypes were developed.
- An increased understanding of the challenges related to the use of mechanical containment and the recovery of oil in ice-covered waters was obtained, and ideas forfuture innovative developments were identified.
- In some cases, oil can be recovered with an efficiency rate similar to that of open water conditions, especially in open leads and pockets between large ice floes. However, a reduced efficiency should be expected in the presence of smaller ice floes and slush ice.

In open waters, mechanical oil recovery is normally conducted using booms to confine the oil and skimmers to collect and pump the oil back to a recovery vessel. Mechanical recovery in ice-covered waters constitutes some additional challenges compared to open waters. It is difficult to use booms when the ice coverage exceeds 10-20%, while in higher ice coverage the ice itself can act as a boom to confine the oil. A skimmer working in ice-covered waters needs to be able to deflect the ice in order to gain access to the oil (referred to as ice processing). It is also necessary to deal with low temperatures, and the skimmers should therefore be protected and/or heated to avoid freezing.

Several methods of separating oil and ice have previously been evaluated. These methods include lifting or submerging the ice or the lateral deflection of ice in the water.

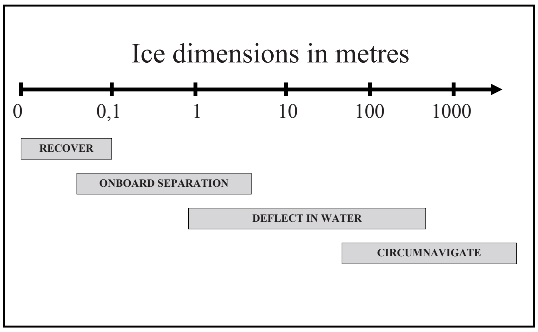
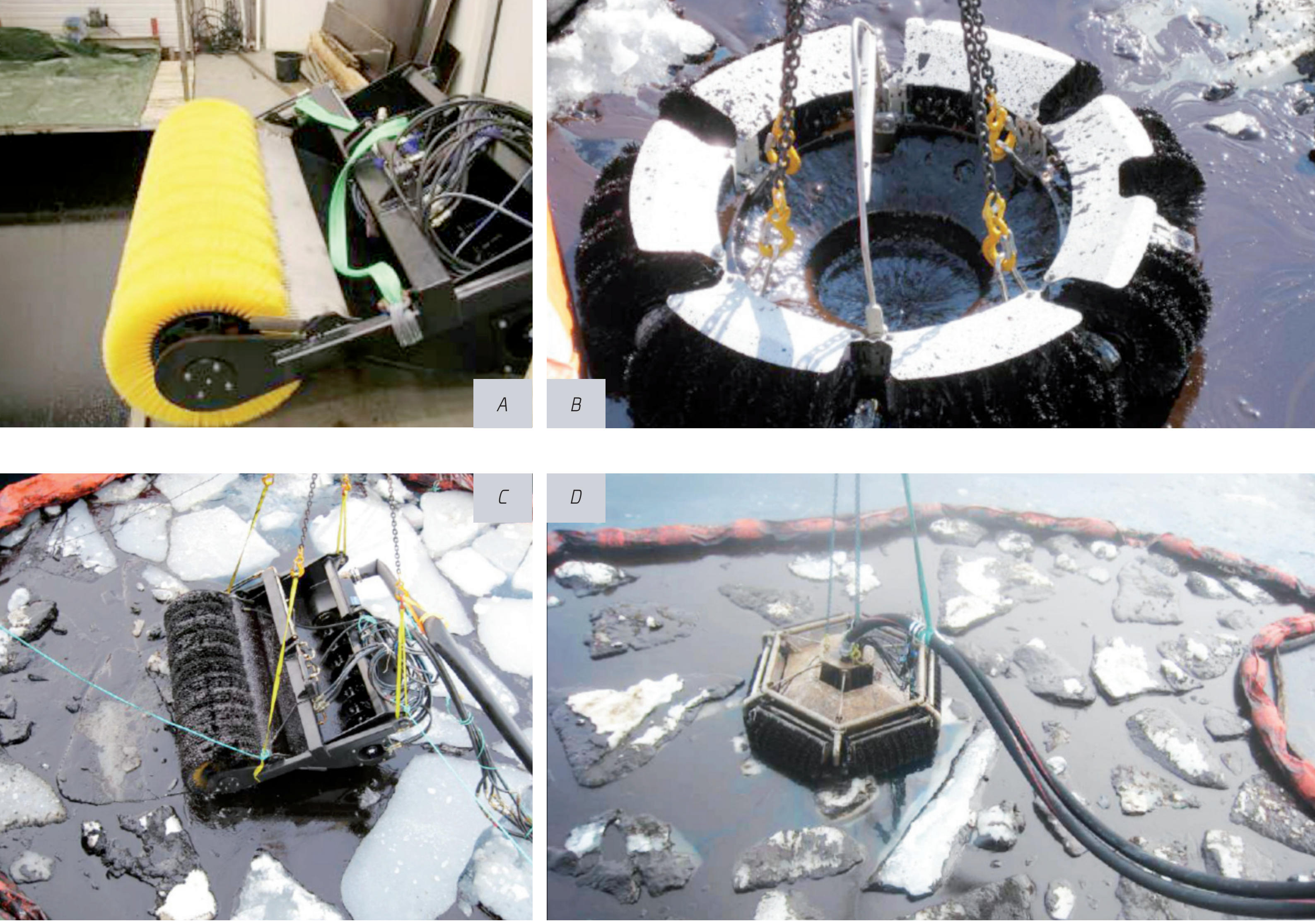



*Figure 7.1 - Main ice processing principles roughly related to ice dimensions (metres)*

The capacities of these vertical deflection methods are limited by the weight and dimensions of the ice forms. Small pieces of ice up to 10 – 15 cm, in addition to slush ice, can be recovered by some skimmers and pumped to a receiving tank together with the oil. One existing concept submerges the ice, thereby releasing the oil to the water surface, while another system lifts smaller ice floes out of the water, allowing the drum unit under the skimmer to recover the oil from the water surface. In an area with large ice floes (>50 - 100 metres in diameter), circumnavigation may be the only option.

### 7.1 Objective

The overall objective has been to improve and develop technology for oil recovery in ice-covered waters in cooperation with skimmer manufacturers. This includes documentation of their capabilities and limitations, as well as improvements to existing skimmers and the development of new types of skimmers. At the beginning of the program, 15 manufacturers worldwide were invited to nominate skimmers with the potential for oil recovery in ice, with the intention to perform testing in basin and field tests. The manufacturers were also invited to submit ideas for new concepts to be developed through this program.




*Figur 7.2 Testing of skimmers in laboratory and field experiments. A) Lamor LRB 150 Brush drum skimmer (SINTEF Sealab) B) Ro-Clean Desmi Helix (FEX 2008) C) Lamor LRB 150 Brush drum skimmer (FEX 2008) D) Ro-Clean Desmi Polar Bear (FEX 2009)*

**7.2 Technological development and testing**

In 1992, the Canadian Petroleum Association presented a state-of-the-art review on Oil-in-Ice Recovery, which was further evaluated through the MORICE project (Mechanical Oil Recovery in Ice Infested Waters) in 1996. It was concluded that brush and brush-drum skimmers seemed to have the highest potential for a combination of ice processing and oil recovery in ice. Brush-drum skimmers consist of a large number of bristles installed on the surface of a rotating drum.

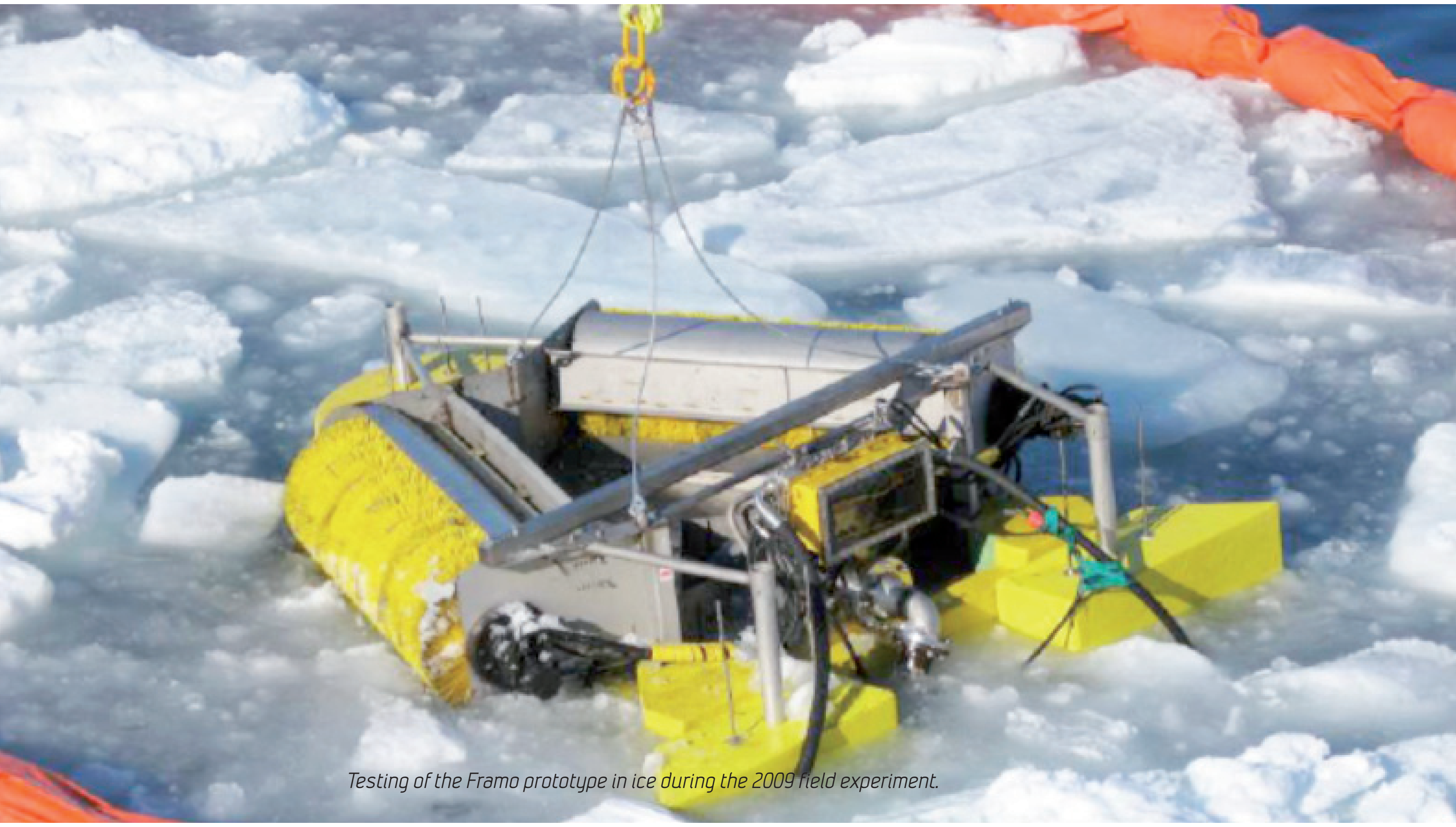
Bristles must be fabricated from a flexible and durable material so as to prevent them from being permanently damaged when encountering ice. Parameters such as bristle length and stiffness, drum diameter, angle between the brush drum and surface, the number of brush drums and rotational speed are expected to be important factors for both oil recovery and ice processing. Due to the long bristles and irregular geometry, brush skimmers are not as affected by the presence of small ice pieces as most other types of skimmers. Its ability to recover oil depends on a combination of adhesion of the oil to the bristles and the mechanical lifting by the bristles. The skimmers are normally equipped with a scraper mechanism which removes the oil from the bristles to a hopper for pumping to a vessel.

In total, five existing skimmers were tested in the SINTEF Ice Basin in the presence of small ice floes (up to 1 metre in diameter) and slush ice at air temperatures down to -18°C. Two of these skimmers (Helix 1000 and LRB 150) showed promising capabilities in ice and were included in field testing in the Barents Sea in May 2008.

The Ro-Clean Desmi Helix 1000 skimmer is dependent on a crane, and it was decided to develop this concept further in order to build in buoyancy elements and attach all hoses through an umbilical on top of the skimmer.

The Lamor LRB 150 skimmer is normally operated by an excavator crane and today is part of the oil spill contingency for ice-covered waters in Finland.

From four new skimmer concepts evaluated by an international reference group involved in the project, two were chosen for support through the Joint Industry Program and the Norwegian Research Council's DEMO 2000 Program.



*Testing of the Framo prototype in ice during the 2009 field experiment.*

The Ro-Clean Desmi Polar Bear skimmer consists of six brush drums in a hexagonal shape and is a further development of the Helix 1000 skimmer. An early prototype was tested in the SINTEF Ice Basin, and the final prototype was tested and verified during the experimental field trial in May 2009.

A brush-drum cassette built for the Framo skimmer was tested in the SINTEF Ice Basin, and an early prototype of the skimmer was tested during the 2009 field experiment.

### 7.3 Main findings

The target ice cover in the basin and field experiments performed was comprised of 30-70% of broken ice pieces and floes, in addition to the slush ice scenario used in basin testing. The recovery rate from the testing of the Helix 1000, LRB 150 and Polar Bear skimmers was recorded as a function of the presence of small ice (width < 1.5 m) and slush ice.

The results indicate a general trend that recovery effectiveness decreases with the increased coverage of small ice, and that the actual ice regime will have a major impact on skimmer recovery effectiveness.

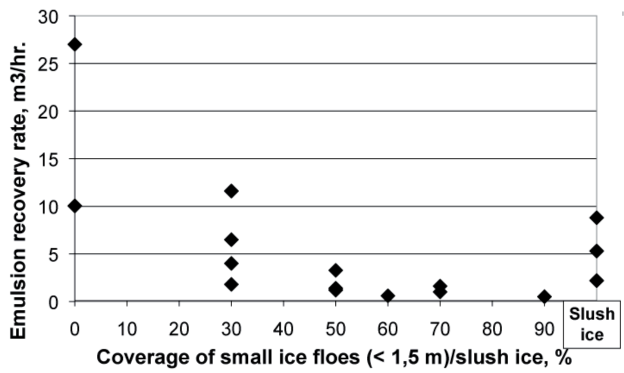



*Figure 7.3 -Calculated recovery rates as a function of increased coverage of small ice floes*

***Ice coverage*** or **ice concentration** normally describes the ice conditions in a larger area with ice floes from several metres up to several hundreds of metres in width. However, the *type of ice* is an equally important parameter in regard to oil spill countermeasures. Pockets and leads between larger ice floes can be free of smaller ice, which

enables mechanical recovery in between the ice floes with a recovery effectiveness similar to that under open water conditions. If these pockets and leads contain smaller ice floes or slush ice, reduced efficiency should be expected. Among existing skimmers, the LRB skimmer represents state-of-the-art technology for the recovery of oil spills in ice, but if it is going to be used under extreme Arctic conditions, there may be a need for the further winterisation of the skimmer.

The results from the testing of the Polar Bear Skimmer, both in the ice basin and in the field, indicate that it can be effective in collecting oil in ice. The skimmer works best in the presence of low concentrations of smaller ice pieces and slush ice (< 50%) and could also have the potential for application alongside larger ice floes. It is a medium size skimmer that should recover 10-20 $m^3$/hr in low ice concentrations provided that the oil is contained in thicker layers (tentatively > 5 cm). The rotating brush drums works well in small ice forms and in the open water between larger floes. The skimmer has no thrusters and will consequently have to be repositioned by a crane or similar device during operation. The improvement of the skimmer's buoyancy will increase the capability of the skimmer, and plans to include thrusters on the skimmer are also thought to be beneficial.

The Framo Skimmer is still under development and focuses on basic skimmer components such as brush quality and buoyancy in addition to minor general improvements, and the tested prototype of the skimmer exhibited good ice processing capabilities. The triangular vessel shape of the skimmer, together with its thrusters, was a successful combination which allowed the skimmer to move very well in ice. This approach appears to have some merit in being able to access and remove oil from in between ice floes and pieces. Further developments and improvements on these parts will result in a functional skimmer based on an interesting concept.

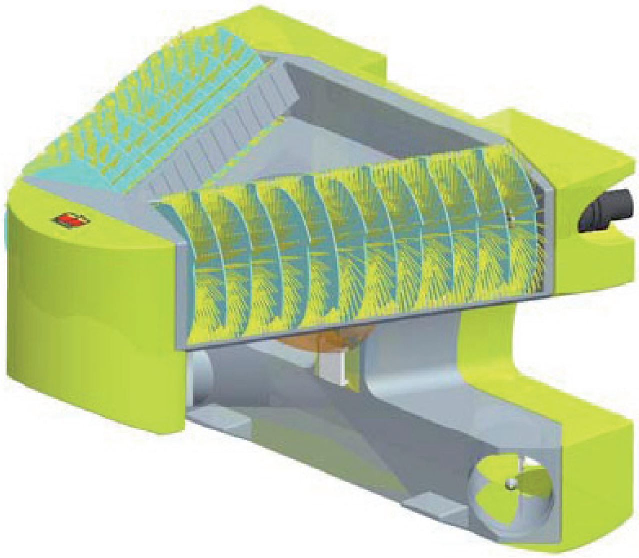


*Figure 7.4 - Sketch of the Framo skimmer concept under development*

Further development of the Framo skimmer will commence in 2010 (as part of the DEMO 2000 project). This development will be based on recommendations from the field trial, including a new frame, a new bristle type and improved buoyancy.

The final version of the skimmer is expected to have the potential to recover oil in small ice and slush ice in ice coverage up to 70%.

# 8 REMOTE SENSING

**Key findings for monitoring and remote sensing**

- A flexible combination of sensors operating from aircraft, helicopters, vessels, satellites and the ice surface is recommended for future Arctic oil spill emergency preparedness.
- The most useful remote sensors and systems applicable to Arctic spills are: Side-Looking Airborne Radar (SLAR); Satellite-based Synthetic Aperture Radar (SAR); aircraft and vessel-based Forward Looking Infrared (FLIR); Trained dogs; and Ground Penetrating Radar (GPR) operated from helicopters and/or from the ice surface.
- The current generation of all-weather SAR satellites can play a valuable support role in mapping detailed ice conditions and directing marine resources.
- Existing commercial GPR systems can be used from a low-flying helicopter to detect oil trapped under snow on the ice and to detect oil trapped under solid ice.
- Detecting isolated oil patches trapped among closely packed ice floes is a major challenge with any current remote sensing system, particularly during periods of extended darkness.
- Trained dogs are able to reliably detect very small volumes of oil and to map oil boundaries on solid ice and in sediments on Arctic shorelines under cold conditions.

## 8.1 Airborne remote sensing

Multispectral airborne remote sensing supplemented by visual observations by trained observers remains the most effective method for identifying and mapping the presence of oil on water. Many of the existing airborne sensors will theoretically detect and map oil among ice in certain situations, but their capabilities in these conditions are not well understood. At some point, the presence of ice will significantly affect slick behaviour by reducing the spreading rate, increasing the equilibrium oil thickness, and damping wind waves and swells. All of these factors can greatly affect the capabilities and usefulness of various sensors.

The airborne remote sensing programs in 2008 and 2009 provided a real-world demonstration of the capabilities and limitations – both technical and operational – of airborne surveillance. In 2008, a Norwegian surveillance aircraft was forced to abort its mission on four hours notice in order to respond to a real spill from an offshore platform, while the Swedish Coast Guard participated with their advanced new Dash 8 aircraft in 2009. Nonetheless, another marine emergency at Bear Island permitted only one flight over the experimental spill site, just after the oil was discharged. Within the closely packed ice conditions, the spill area was too small for detection with airborne SLAR or satellite SAR, and the low clouds prevented the high-resolution Wescam optical FLIR camera system - the most capable sensor for viewing small spills - from acquiring the spill.  Airborne SLAR, which is the least weather dependent sensor, provided a wide swath regional view on either side of the flight line, but lacked the resolution to identify the spills contained within the ice.

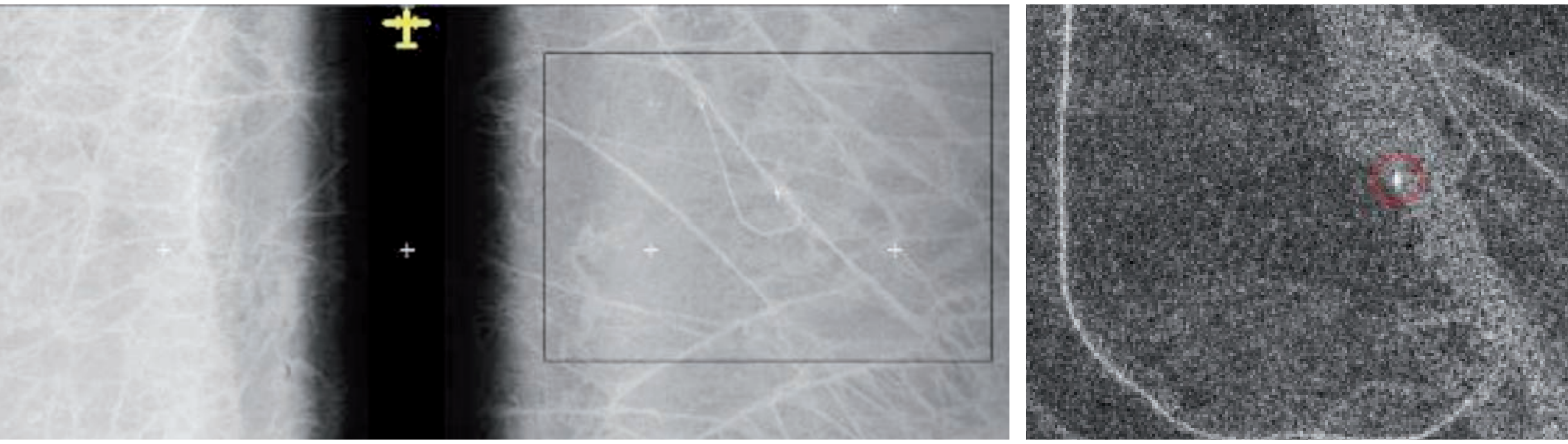


*Figure 8.1 - A) Segment from airborne SLAR imagery acquired four hours after oil release. KV Svalbard is slightly to the NW of the Lance. Individual ice features and floe outlines are clearly visible. B) Cosmo-Sky-Med image. The tracks of the ships are clearly visible in the ice.*

The main conclusions from the 2009, and previous field experience, are that airborne systems are likely to have a great potential for large spills in very open drift ice, a moderate potential in open drift ice and a limited potential in close to very close pack ice. Available airborne sensors are constrained by a combination of low cloud, fog and darkness (UV/IR line scanners and FLIR), and pixel resolution (SLAR/SAR). The operational constraints of long transit distances and few alternatives in terms of airports may result in very short stays at the scene of a spill.

**8.2 Satellite Systems**

SAR satellites can resolve small targets down to 1 metre or less in darkness and clouds. A series of satellite images were acquired by KSAT, Tromsø, to determine if the latest generation of high-resolution (surface features down to 1 metre or less) radar satellites (e.g. Radarsat 2, Cosmo SkyMed) could detect the 2009 experimental oil spills in ice.

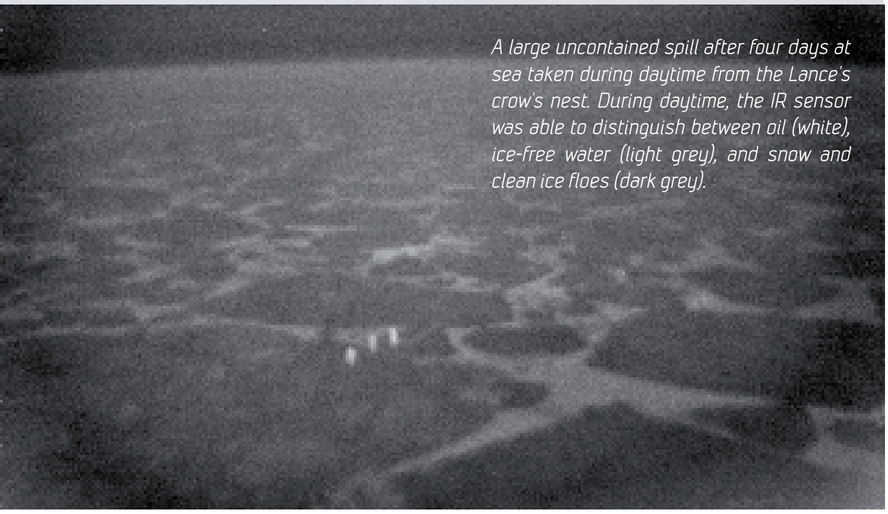
The oil spills were not detectable on the imagery primarily because they were effectively constrained from spreading by the close pack ice cover. Objects that could be identified included: the ice-filled booms alongside the vessel being used for skimmer tests, the ice-filled fire-resistant boom being towed behind the *K/V Svalbard*, and the telescoping dispersant spray arm that extends out from the side of the *R/V Lance*. Ship tracks through the ice could be seen for some days after the ship had passed, depending on the motion of the ice.

**8.3 Surface Systems**

**Ground Penetrating Radar:** A series of previous tank tests and field experiments demonstrated that surface-based ground-penetrating radar (GPR) can clearly detect and map the presence of oil films as thin as 1-3 cm underneath the ice and trapped as layers within the ice. Numerical modelling indicated that the same system operating at low altitude from a helicopter should be able to detect thin oil layers under cold ice in mid-winter, as well as oil on the ice surface buried under snow. This capability was tested and validated in an experimental on-ice spill at Svea in April 2008.

*Preparation of GPR field test with 400 litres of oil at Svea Field Station*


*The radar system was suspended from the helicopter's cargo hook mount and flown across the test cells at altitudes from 5 to 20 metres and forward speeds of up to 20 knots.*



*A large uncontained spill after four days at sea taken during daytime from the Lance's crow's nest. During daytime, the IR sensor was able to distinguish between oil (white), ice-free water (light grey), and snow and clean ice floes (dark grey).*

The results indicate that readily available, commercial GPR systems can be effectively used to detect crude oil spills within or under snow in the Arctic environment.

**Hand-held IR:** Low-cost, non-cooled, hand-held IR systems can detect oil under certain conditions, as demonstrated by a collection of images obtained from the RV Lance in 2009. Performance is more reliable during daylight and without fog.

**Optical gas sensors (Shell LightTouch):** Shell Exploration and Production collected baseline data on methane emissions from oil on the ice surface at Svea in April 2007. The primary goal was to obtain a usable estimate of the hydrocarbon emission rate resulting from oil spills into icy water and to use the data to assess the potential for detecting and locating such spills, using the ultrasensitive LightTouch™ system.

The results indicate that a hypothetical spill onto open drift ice would emit detectable methane for a relatively short time period (likely much less than 100 hours) over distances up to several km using current generation sensors from a low-flying aircraft. This conclusion is highly dependent on the speed of weathering of the actual spill.

### 8.4 Combination of surface and airborne systems

Depending on the ice conditions (floe size, thickness, stability), it may be possible to deploy a variety of remote sensing systems to work directly from the ice surface or from the deck or bridge of a nearby vessel. Surface-based sensors may include: hand-held IR, specially trained dogs, X-band Marine Radar, and integrated systems combining IR and low light level camera technologies, e.g. the Aptomar SECURUS system.

*Dachshund Tara on the ice with a GPS real time tracking system*

**Trained dogs:** The training and field assessment of dogs in detecting oil in snow and on ice was a highly successful part of the JIP remote sensing program.  Field tests conducted in April 2008 at SINTEFs research station near Svea on Svalbard followed positive early trials in Trondheim in 2007, and confirmed that dogs can be used to detect oil spills covered with snow and/or ice in Arctic winter environments. The dogs maintained their large concentration and operative sensitivity for several days, even after being transported in cages while strapped on scooter sledges and exposed to bumpy rides and exhaust.

The dogs also verified the bearing to a larger oil spill (400 litres, on top of the ice covered in snow) at distances up to 5 km.

**Marine Radar, X-band (short and medium pulse):** In the 2009 field experiment, Rutter Sigma 6 radar was tested on background oil sheen on the water, although no discernible spill target was visible on the radar screen. These radar systems have proven their ability to detect slicks at sea and there is no technical reason why similar results would not be possible in very open to open drift ice (10-50% ice coverage).

**8.5 Evolving Technologies**

The JIP focused on technologies that already exist in a "proven" state. Nevertheless, there are a number of new technologies or new applications of rapidly evolving technologies that could play an important role in expanding remote sensing capabilities to a wide range of oil-in-ice scenarios such as Nuclear Magnetic Resonance (NMR), Unmanned Air Vehicles or (UAVs), Autonomous Underwater Vehicles (AUVs), and next generation GPR optimised for the problem of oil-in-ice.

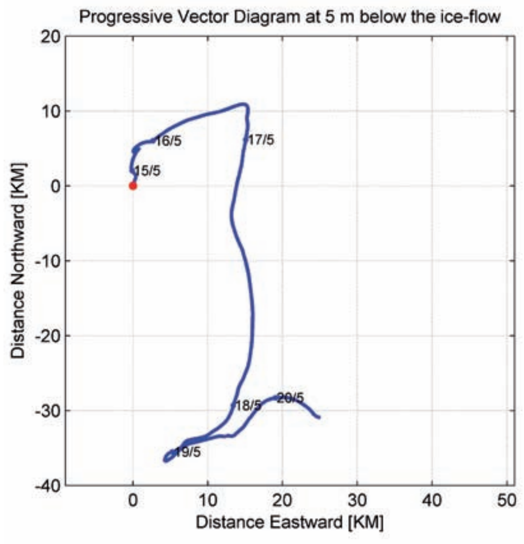



*Figure 9.1 - Drift of the oil slick during the field experiment*

# 9 OIL DISTRIBUTION AND BIO AVAILABILITY

When oil is released into an area with ice, spill responders face a complex interaction between oil, water and ice. The oil will be absorbed by snow on the ice edges, it may be trapped in the ice in brine channels and it may be moved underneath the ice. As such, the ice field will also be under a constant transformation driven by wind, currents and temperature. The result over time is that the individual ice floes may change their relative position and may melt or freeze. Some ice floes may be transported relatively far from both their original position and from their original neighbours. Altogether, this may be a strong driving force for the drift and spread of oil after oil has been released in an ice field, and it is necessary to understand these processes as a basis for realistic studies of oil-ice-water interactions and for exposure studies in the laboratory. Acquiring data on these aspects is also of great importance for the upgrading of present oil drift models for ice-covered areas. The knowledge derived from the data sampling program under FEX 2009 will be used to assess the effects of oil spills in Arctic marine environments.

Various data were collected during the 2009 field experiment. These data will be used as the basis for developing models that predict oil distribution in ice and give extended knowledge on the interaction between oil, ice and water.

The data analyses from this project are part of an extension of the R&D program and will therefore be reported on in a separate report. The following is an extract of some of the measurement program.

**9.1 Measurements during FEX 2009**

The processes of the drift, spreading and weathering of oil have been monitored by multiple sampling throughout the six-day experiment. Some of the important measurements are:

- Data on the potential bioaccumulation of oil components in the water column were collected by passive SPMDs. [5]
- Dissolved hydrocarbons in the water column were sampled by an in situ large volume water sampler (KISP) that concentrates the dissolved hydrocarbons onto filters and XAD resins, and is supplemented by on-line UV-fluorescence measurements both beneath and close to the oil slick.
- Oil droplet size distribution was measured by an on-line in situ laser diffraction instrument.
- Meteorological and oceanographic data were recorded for the monitoring of wind speed and direction, and air temperature and pressure in addition to currents, tide and wave height recording.
- The recording of ice drift and ice field deformation was carried out by deploying a large number of GPS recorders on selected ice floes in and around the oil slick.

[5] Semi Permeable Membrane Devices (SPMDs) mimic biological systems to provide a measure of bio available pollutants in the seawater. Its passive transport mechanism is similar to that of fish gills. SPMDs accumulate water soluble oil components by the use of diffusion.


*Fig. 9.2 - Examples from FEX 2009 measurment program A) Seaguard - current measurements B) Mini Seawatch – waves in ice field C) Deployment of SPMD D) Deployment of KISP*

**9.2 Observations**

Ice floe movement was monitored using an accelerometer and a Seawatch Mini Buoy, and the instruments were placed on two ice floes. The measurements were all close to the lower measurement limit of the instrument, but there was more movement along the horizontal plane than along the vertical. The movement in the horizontal plane was in the range of −13 to +16 cm during the measurement period.

The ice field drifted nearly 80 km during the experimental period, and the oil drifted with the ice and remained contained between the ice floes, thereby enabling continuous experimental work. The weather and wind direction changed at day 3 (May 17), while the wind speed increased to 23 m/s (near gale) and both the ship and the ice field drifted more than 35 km in a southward direction for the next 24 hours.

Preliminary results show measurements of low, but detectable concentrations above background level using the large volume water sampler and SPMDs. The concentration level of total extractable hydrocarbons (THC) in the seawater was below 30 ppb, and the content of water soluble oil components was lower than 1.5 ppb.

A 2 $m^3$ oil slick was dispersed six hours after release (described in Seq. 6.3). Two hours later, measurements of oil in water were performed at a depth of 1, 2 and 3 m. The maximum concentration of oil in water was measured at 5.5 ppm (at a depth of 2 m) with an oil droplet size smaller than 10 µm 30 minutes after mixing energy was added by the ship thrusters. The oil droplet measurements show that effective chemical dispersion did indeed take place.

The chemical monitoring data collected during the field experiment will be used to perform a limited number of controlled experiments with realistic exposure concentrations in the laboratory in order to compare the biological effects of various cleanup technologies by measuring the body burden and biological effects on Arctic amphipods. The met-ocean parameters recorded will be used to improve and verify existing oil spill contingency and ice drift models. These activities will be initiated in 2010.

Altogether, these data constitute a dataset for various follow-up analyses within biological effects, oil-ice-water interactions and how the presence of ice affects the drift and spread of oil in high ice coverage. The large set of data, results and conclusions will be presented in a separate report in 2010.

An ongoing activity is the project "Behaviour, biodegradation, and potential exposure of oil in ice", which will be finalised in late 2010 and reported separately. The project includes controlled laboratory studies on the transport of water soluble oil components in ice, the biodegradation of oil in ice, and the development of an oil in ice submodel. Collaborating partners are the Coastal Response Research Center (CRRC), the University of Rhode Island (URI) and the University of Alaska Fairbanks (UAF).

# 10 OIL IN ICE RESPONSE GUIDE

One of the objectives of this program has been to prepare a generic Oil Spill Response Guide (OSRG) for Arctic and ice-covered waters, which is based on a number of selected ice regimes typical of the Arctic region. The Guide shall give recommendations to response measures given a defined scenario and will contain information and findings from this program as well as previous R&D activities, and the Guide will be used internally among the oil companies in oil spill response planning and training.

The development of the web-based guide is co-financed between this program and the Norwegian Research Council (DEMO 2000). The DEMO 2000 financing stretches into 2010 and a final version of the guide will be launched in July 2010. A pilot version of the guide was presented during a workshop in October 2008 and a revised version during a workshop in November 2009.

### 10.1 Objective

OSRG is a generic tool that is independent of any specific location and applicable to the conditions that we may expect to find in the Arctic regions covered by this project. The Guide shall give oil spill response recommendations for ice-covered waters and because it is intended to be used in connection with planning activities, the user has to define a scenario as input to the Guide. Environmental sensitivity, as well as economically valuable resources, is not included in the OSRG. In order to gain the acceptance of the response recommendations given by the Guide, they will be based on an evaluation by international experts through a peer review of input data.

The output from the OSRG will be in the form of recommendations with regard to potential response measures related to the selected scenario. The tool is intended for use during internal training, at courses and in the preparation of oil spill contingency plans, and includes all relevant results from the current R&D program plus relevant information from previous studies. However, it will never replace local knowledge and experience.

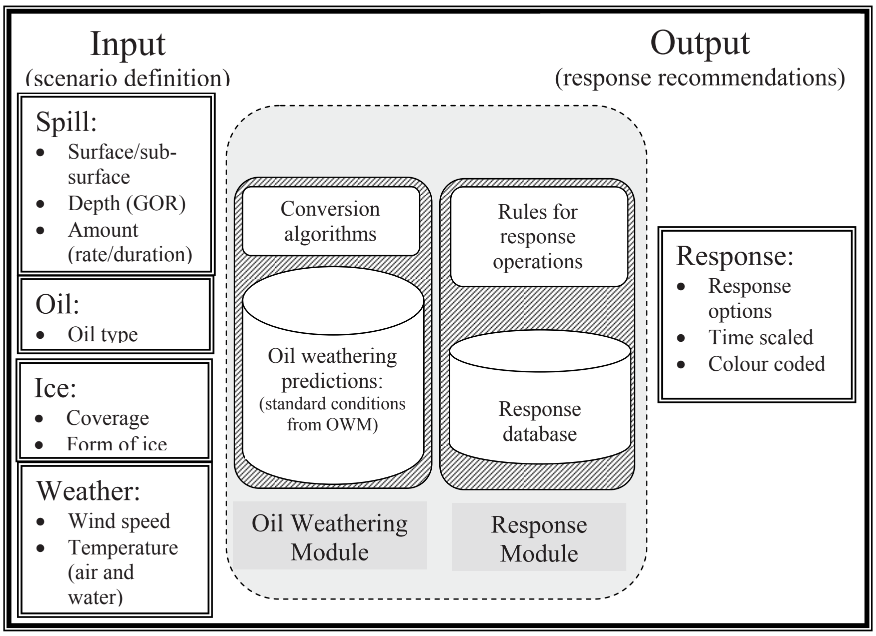



*Figure 10.1 - Basic architecture of the OSRG system*

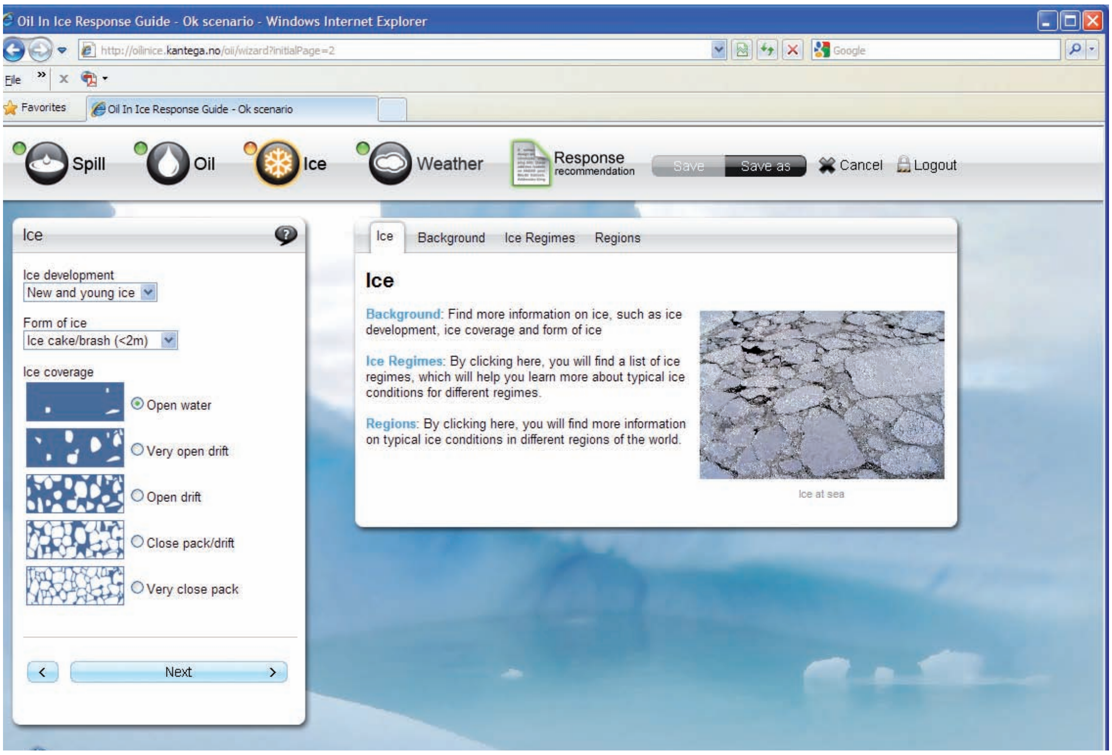



*Figure 10.2 - Example on definition of ice conditions as input to the Guide*

## 10.2 System description

There are three main input data to be specified for each scenario: oil spill information, weather conditions and ice conditions. The output from the OSRG is a recommendation on the appropriate response to a given spill scenario.

OSRG is linked to SINTEF's Oil Weathering Model (OWM). If the oil in question cannot be found in the OWM database, the guide has a search function that allows the user to search for a similar oil type in the database which can then be used as a realistic substitute for the given scenario.

Ice characteristics (ice coverage and ice form) are very important. The success of, for instance, mechanical recovery is dependent on whether there are pockets of ice-free water between the larger ice floes, or if these are filled with small ice pieces or slush ice.

The user also has to define the expected weather conditions as input to the scenario description, which includes wind speed, sea and air temperature. Precipitation and visibility will also exert an influence upon the effectiveness of response methods, but are not included in this version.

OSRG capitalises on the latest enhancements of the OWM being performed as part of this program, and these enhancements include improvements to the models for oil-in-ice weathering and a new oil ignitability prediction capability.

The Response Module takes into account both oil spill data and environmental data. While in situ burning and dispersants are based on oil weathering predictions, mechanical recovery is based on threshold values in the response database. These threshold values are derived from previous literature on skimmer testing and results from this program. Moreover, the guide includes multimedia content regarding oil spill contingencies in ice-covered waters, ice conditions, oil types and a description of different response options, which can be updated by individual users in a "Wikipedia style".

The OSRG is a generic, multi-purpose, web-based tool that is easy to use. No installation is required, and it is collaborative in the way that it shares scenarios, data and knowledge within the company. Response recommendations are displayed as colour-coded windows of opportunity presented on three levels. The output includes further information and justification for the recommendations given, and also includes a multimedia content system that shows text, graphics, pictures and video, based on and including state-of-the-art knowledge and research results.

# 11 FINAL COMMENTS

The JIP on oil in ice has focused on improving our understanding related to techniques for handling oil spills in ice. The program have focused on testing of existing technologies and their possibilities and limitations, and on the further development and improvement of these technologies.

**Important conclusions and findings are:**

**Knowledge**

- When crude oil is spilled at sea, a number of natural processes occur that change the chemical properties of the oil. In ice-covered waters this time-dependent weathering is significantly reduced depending on ice type, ice coverage and energy conditions. This can be an advantage and contribute to the enhancement of response effectiveness for some oil spill scenarios.
- The results and experience gained during this program will form an important basis for the further improvement of technology, as well as for the tactics used for oil spill contingencies in ice-covered waters.
- A significant data set has been collected that will aid in understanding more about oil in ice, including such issues as: oil weathering; the window of opportunity for various oil spill countermeasures; the interaction between oil-ice and water; the bio availability of released oil in ice; and information on oil-ice drift.
- Two new skimmers, a new dispersant application system and an internet based oil spill response guide have been developed and tested based on the results from the program. This work is partly funded by the Norwegian Research Council and will be completed in 2010.

**Operational aspects**

- A systematic way to predict the operational time window for various response options has been identified, thereby demonstrating that efficient spill response may be accomplished whether the techniques are used individually or in combination.
- Each response tool evaluated during the program demonstrated some merit in responding to an oil spill in an Arctic environment and the availability of all the response options is considered as being the key to a successful oil spill response operation under Arctic conditions.
- The window of opportunity for in situ burning and the use of dispersant operations in ice-covered waters can significantly increase compared with an open water scenario under certain circumstances. Both techniques have been tested and proven to be effective for the elimination of oil in ice. In some cases the energy input in the oil-ice system will be reduced with increasing ice coverage. Adding extra mixing energy extends the operational possibilities for use of dispersants.
- The research program demonstrated that the mechanical recovery of oil spills in ice-covered waters is possible. In some cases, oil can be recovered with an efficiency rate similar to that of open water conditions. However, a reduced efficiency should be expected in the presence of smaller ice floes and slush ice.
- A flexible combination of sensors operating from aircraft, helicopters, vessels, satellites and the ice surface is recommended for detecting oil in ice. The optimum choice of remote sensing technologies will depend on the spill characteristics, ice regimes and prevailing weather conditions.

# APPENDIX A. LIST OF REPORTS FROM THE PROGRAM

| REP.NO | PROJECT | TITLE |
|---|---|---|
| 1 | P0 | Short state-of-the-art report on oil spills in ice-infested waters |
| 2 | P1/P2/P5 | Field report from experiments Svea, April 2008. Description of activities and data |
| 3 | P2 | Static and dynamic testing of the USN oil herding agent on Statfjord crude at 0°c in ice (included in report no 6) |
| 4 | P2 | Static and dynamic testing of the USN oil herding agent on Heidrun crude at 0°c in ice (included in report no 6) |
| 5 | P2 | Testing of fire-resistant boom in low concentrations of pack ice |
| 6 | P2 | Field testing of the USN oil herding agent on Heidrun crude in loose drift ice |
| 7 | P3 | Testing of Ro-Clean Desmi Ice Skimmer and Helix skimmer in the SINTEF ice basin. "Oil in ice" JIP, task 3.1: Testing of existing concepts. A technical report. |
| 8 | P3 | Testing of Lamor GT 185 Skimmer and LRB 150 Skimmer in SINTEF ice basin. "Oil in ice" JIP, task 3.1: Testing of existing concepts. A technical report. |
| 9 | P3 | Testing and verification of oil skimmers during the field experiment in the Barents Sea, May 2008 |
| 10 | P3 | Testing of Ro-Clean Desmi Polar Bear Skimmer in the SINTEF ice basin. "Oil in ice" JIP, task 3.2: Testing of new concepts and units. A technical report. |
| 11 | P4 | A review of Studies of oil spill dispersants effectiveness in Arctic conditions |
| 12 | P4 | Evaluation of dispersant spray systems and platforms for use on spilled oil in seas with ice present |
| 13 | P4 | Development and testing of containerized dispersant spray arm for use in cold and ice-covered areas |
| 14 | P5 | Using dogs to detect oil hidden in snow and ice - Results from field training on Svalbard April 2008 |

| | | |
|---|---|---|
| 15 | P6 | Ice Regimes for Oil Spill Response Planning |
| 16 | P6 | Generic guide for oil spill response in ice |
| 17 | P8 | Full-scale experiment 2008 Field activity report |
| 18 | P8 | Full scale field experiment 2008. Summary of results. |
| 19 | P1/P2/P4 | Meso-scale weathering experiments performed with different ice conditions and five different oil types - Weathering, dispersability and ISB results |
| 20 | P2 | Laboratory testing of ignitability and burning efficiency. Establishing and testing of a laboratory burning cell. |
| 21 | P3 | Testing of oil skimmers via field experiment in the Barents Sea, May 2009 |
| 22 | P5 | Remote Sensing Technology Review and screening |
| 23 | P5 | Measurement of Methane Emissions from Oil Spills in ice |
| 24 | P5 | Airborne GPR to detect Oil Under Snow |
| 25 | P8 | Full-scale experiment 2009 Field activity report |
| 26 | P1/P2 | Experimental oil release in broken ice - a full-scale field verification of results fram laboratory studies of oil weathering and ignitability of weathered oil spills. |
| 27 | P2 | Test of fire-resistant boom in low concentrations of drift ice |
| 28 | P5 | Evaluation of Airborne Remote Sensing Systems |
| 29 | P5 | The utilisation of satellite images for the oil in ice experiment in the Barents Sea in May 2009 |
| 30 | P5 | Remote sensing summary report |
| 31 | P8 | Sjøfugler og sjøpattedyr i forsøksområdene 2009 (In Norwegian) |
| 32 | P1-9 | Summary report. Joint industry program on oil spill contingency for arctic and ice-covered waters. |

# JOINT INDUSTRY PROGRAM ON OIL SPILL CONTINGENCY FOR ARCTIC AND ICE-COVERED WATERS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