Hamburg Ship Model Basin (HSVA)
SINTEF
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GROWTH Project GRD2-2000-30112 "ARCOP"

STATE OF THE ART REPORT ON OIL WEATHERING AND ON THE EFFECTIVENESS OF RESPONSE ALTERNATIVES

WP 4: Environmental Protection and Management System for the Arctic

WP 4.2.1.1: Oil Spill Weathering and Oil Spill Countermeasures

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PUBLIC **D 4.2.1.1 (a)**

DELIVERABLE D4.2.1.1 (a)

"OIL SPILL WEATHERING AND RESPONSE "

CONTRACT N°: GRD2/2000/30112-S07.16174

PROJECT N°: GRD2/2000/30112-S07.16174-ARCOP

ACRONYM: ARCOP

TITLE: Arctic Operational Platform

PROJECT CO-ORDINATOR: Kvaerner Masa-Yards Inc. (KMY)
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The Foundation of Scientific and Industrial Research at the Norwegian Institute of Technology (SINTEF)	NO
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Lloyds Register	UK
University of Lapland	FIN
The Norwegian College of Fishery Science	NO
Ministry of Trade and Industry	FIN

REPORTING PERIOD: FROM 01.12.2002
PROJECT START DATE: 01.12.2002 **DURATION:** 36 Months
DATE OF ISSUE OF THIS REPORT: July 2004

Project funded by the European Community under the 'Competitive and Sustainable Growth' Programme (1998-2002)

DELIVERABLE SUMMARY SHEET

Deliverable N°:	D 4.2.1.1 (a)
Due date:	September, 2003
Delivery Date:	13 February, 2004
Classification:	PUBLIC
Source:	ARCOP D4211a_Rev_C_040826_s.pdf

Short Description

Sea transportation of oil and gas products from the Pechora and Kara Sea region as well as oil/gas exploration in arctic waters will increase the risk of oil spills in this highly vulnerable environment. In this report the oil spill weathering, i.e. the fate and weathering of oil in arctic waters, is described and oil spill scenarios within the ARCOP shipping scenario are established. Reliable documentation of the oil weathering properties is of fundamental input for doing reliable Environmental Impact Assessment (EIA), Environmental Risk Assessment (ERA) and response analysis of oil spill scenarios.

The performance capability of various oil spill combating techniques is identified in this study. This documentation is essential both in connection to oil spill response analysis and in order to build up efficient and cost-effective oil spill response solutions for the area. Methods and devices for oil spill response with respect to mechanical recovery techniques, oil spill dispersants, in-situ burning and bio-remediation are investigated. This will form the basis for setting up a framework and guidelines / recommendations for preparing an oil spill contingency plan for the region.

This report is complemented with the report D4.2.1.1 (b), prepared by the Arctic and Antarctic Research Institute (AARI), St. Petersburg.

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Document History					
Revision	Date	Company	Initials	Revised pages	Short description of changes

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PREFACE

This report is prepared by Karl-Ulrich Evers, Hamburgische Schiffbau-Versuchsanstalt GmbH (HSVA), Hamburg, Germany, Hans V. Jensen, Svein Ramstad, Janne Resby and Ivar Singsaas, SINTEF Materials and Chemistry, Trondheim, Norway, Dr. Gerhard Dieckmann and Birte Gerdes, Alfred-Wegener- Institut für Polar- und Meeresforschung (AWI), Bremerhaven, Germany.

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1 INTRODUCTION

Sea transportation of oil and gas products from the Pechora and Kara Sea region as well as oil/gas exploration in arctic waters will increase the risk of oil spills in this highly vulnerable environment.

The general fate and weathering of oils spilled in open/ice-infested waters will be described in a ”state-of-the-art” study. This study will also reveal eventual needs to perform (at a later phase) a more specific oil weathering study according to standardized methodology on relevant types of oil in connection to the planned transportation from the Pechora Sea and Kara Sea region, (including both crude oils produced in the area and representative heavy bunker fuel oils (HFOs) used by the shipping industry). Reliable documentation of the oil weathering properties is of fundamental input for doing reliable Environmental Impact Assessment (EIA), Environmental risk Assessment (ERA) and response analysis of oil spill scenarios.

The performance capability of various oil spill combating techniques (both existing and eventual new concepts) will be identified in the ARCOP study. This documentation is essential both in connection to oil spill response analysis and in order to build up efficient and cost-effective oil spill response solutions for the area. The findings within ARCDEV showed a gap with respect to oil spill response methods and procedures. Methods and devices for oil spill response with respect to mechanical recovery techniques, oil spill dispersants, in-situ burning and bio-remediation are investigated to fill the existing gap. A scenario based response analysis will be carried out using modern numerical model tool systems. This will form the basis for setting up a framework and guidelines / recommendations for preparing an oil spill contingency plan for the area. This will also evaluate the potential for improvements and come up with recommendations / needs for further development and experimental research.

2 SCOPE OF WORK

Sub Task 4.2.1.1 is addressed to the oil spill weathering and response and gives an overview on general fate and weathering of oil types in arctic waters (state-of-the-art). Examples are given on weathering predictions by use of the SINTEF Oil Weathering Model on oils existing today in the Oil Weathering Model oil database.

This sub-task also gives a status on existing oil spill response alternatives for use in arctic and ice-infested waters. In particular this includes: mechanical recovery techniques, oil spill dispersants, in-situ burning and bio-remediation. The study evaluates the potential for improvements and come up with recommendations/needs for further development and experimental documentation of performance.

3 OIL SPILL WEATHERING

3.1 FATE AND WEATHERING OF OIL IN ARCTIC WATERS - STATE OF-THE-ART

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

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

Løset *et al*. (1994) presents status at the end of a research program on oil spill response in Northern and Arctic waters (ONA). The report that is produced for the Norwegian Clean Seas Association for Operating Companies (NOFO) is restricted and written in Norwegian. This report summarises the findings in the ONA program and includes information on physical environment, behaviour and properties of oil, oil spill response (biological, burning, dispersing, emulsion breaking and mechanical oil recovery). The program included both an extensive literature review and experimental work. The literature reviewed during this program is listed in Section 3.4, and in the bibliography at the end of the report.

3.1.1 Drift and spreading of oil spills

In cold and ice infested waters the partitioning of oil between water surface, water column and sea ice will have great influence on oil weathering and availability of oil in different oil spill response operations – especially if oil is spilled in ice.

Open water:

Spreading of oil spilled in open water is a result of the spill conditions and oil properties, as well as external factors such as surface wind, ocean currents and oceanic diffusion. Fay’s equations (Fay, 1971) have been used for two decades to describe spreading of oil on the sea surface. Mackay modified Fay’s approach and considered the oil spill divided into a thick and a thin part.

The distribution of oil in open water will be affected by advection of the oil - as determined by wind, waves and ocean currents. Wind and waves create a current in the water mass that, at the surface, is about 3% of the wind speed. In the absence of wind, the prevailing current governs the drift of spilled oil. *Figure 3.1* illustrates how wind and current influence the movement of the oil.

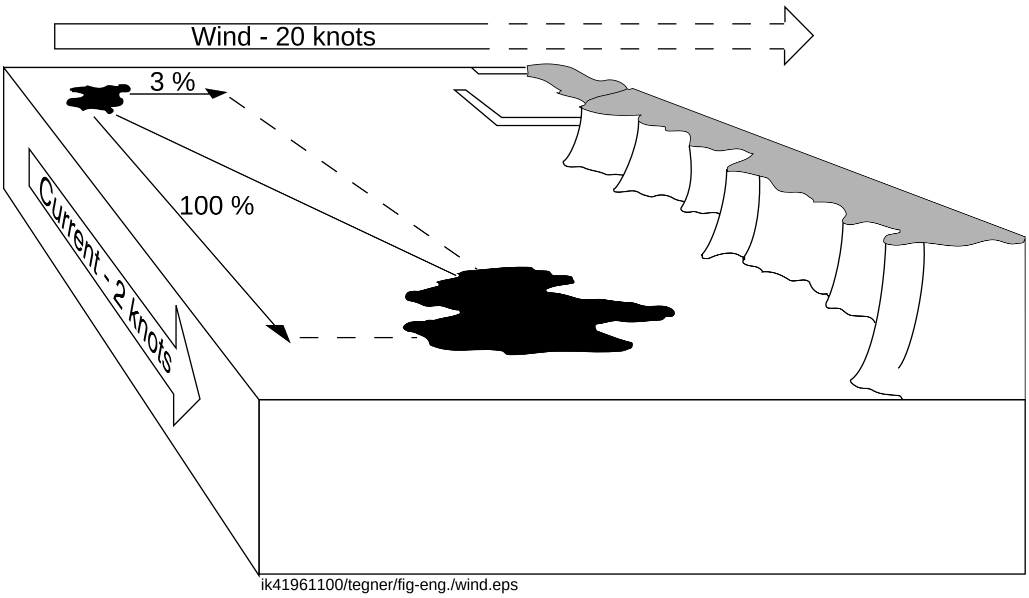

Figure 3.1. Illustration of wind and current induced drift of oil slicks.

Due to vertical current shear, oil that is mixed into the water by breaking waves (natural dispersion) will be subject to a different current compared to surface oil. Resurfacing of dispersed oil will thus cause an enhanced spreading of the surface slick (shear spreading), explaining the often observed elongation of oil slicks in the direction of the wind. In order to represent this effect of drift and spreading, Elliot (1986) and Johansen (1987) have used a particle presentation where oil particles can be mixed down into the water masses. Some of these theories and models have been calibrated against field trials.

Several field experiments have been carried out in Norwegian waters from 1978 to 2000 within the SINTEF Group. In addition, NOFO (Norwegian Clean Seas Association) has performed a number of full-scale field trials with oil on water in the period from 1980 up till today. These field trials, combined with numerical modelling, is one of the reasons why Norway today plays a leading role when it comes to the understanding and describing the drift and spread of oil on open sea.

After the initial stage, the oceanographic conditions (current, waves and wind) will be the dominating factor for the spreading of oil. Caused by wind and waves, the oil slick will be broken into "wind rows", which will align with the direction of the wind (*Figure 3.2*). The oil slick will spread mainly in the downwind direction, with large variations in the film thickness (by a factor of several thousands).

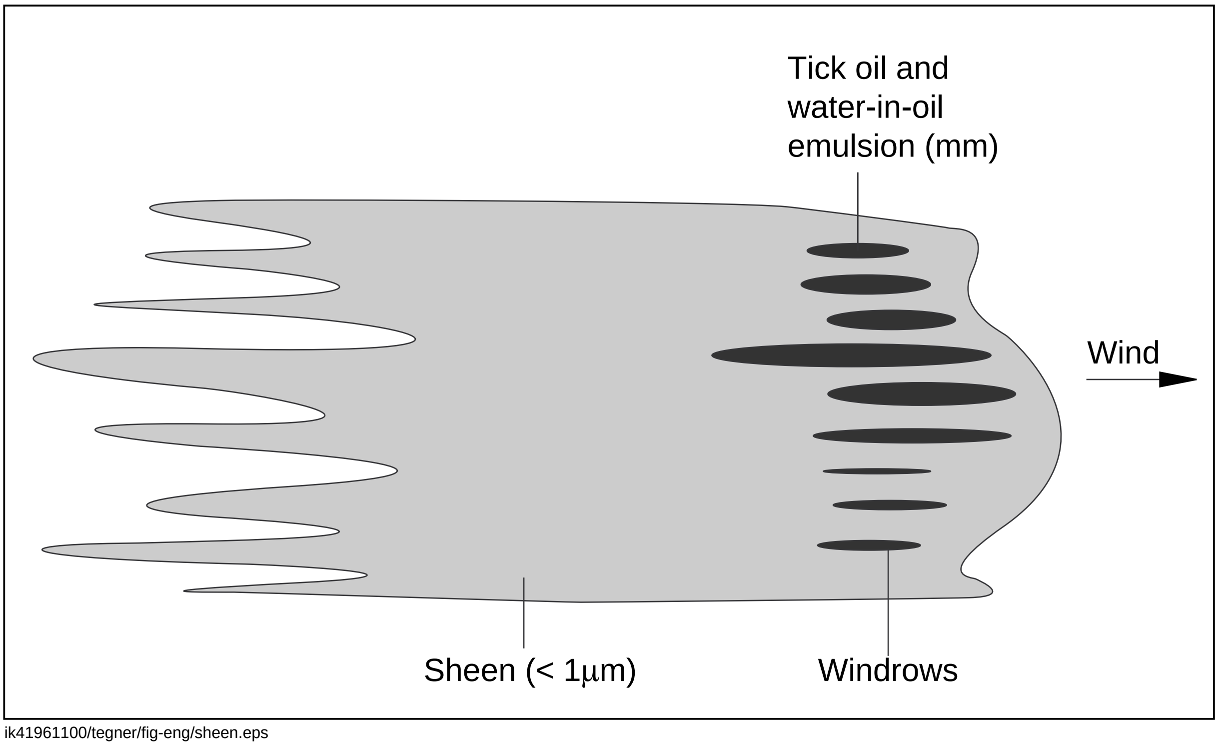

Figure 3.2. Illustration of surface slick with thick patches of oil (wind rows) embedded in a thin film (sheen).

Presence of ice:
Drift and spreading of oil in drifting ice is very complicated. In addition to the factors influencing drift and spreading in open water, the spill- and ice-conditions highly influence the spreading. The spreading in drifting ice could be distinguished between:

- broken ice
- level ice (sheet ice)

Field observations show that in broken ice there are nearly always free water surfaces in between the ice floes, or open water with slush ice. If this is the case, the lateral spreading of oil will be limited by the ice distribution around the spill.

The theories developed for spreading of oil in drifting ice are very empirical and somewhat insufficient (Hoult, 1972, Yapa and Chowdhury, 1990; Venkatesh et al., 1990; Yapa and Belaskas, 1993; Sayed and Løset, 1993; Sayed *et al*., 1994; Gjøstein, 2004). These theories and models are based on small-scale experiments and a few very limited field trials.

For level ice, based on the spill conditions, there may be spreading of oil both on the ice surface and under the ice. In case of a sub sea leakage, the oil is assumed to spread under the ice in a pattern that to a large extent will depend on the under ice topography. For spreading oil on the ice surface, it is necessary to know how oil interacts with snow (McMinn, 1972; Chen *et al*., 1974; Kawainura *et al*., 1986). Ovsienko (1999) has a promising model describing the different mechanisms for spreading of oil on ice with and without snow. Dickins (1992) gives a thorough summation of the western status on the area. His reflections show that there still is much to learn before sufficient knowledge on these mechanisms is achieved.

A rule of thumb is that about 90% of oil will cover approximately 10% of the spill area. The remaining 10% of the oil will cover about 90% of the spill area in the form of "sheen" (< 1 μm thick). The average spill thickness will be about 0.1 mm (100 μm).

Oil in dense drifting pack ice will drift with the ice, while oil in more open ice fields will drift more independently of the ice. An important, still unsolved question is whether the oil will drift faster or slower than the surrounding ice floes. Similar to spill in open water, spreading of oil with presence of ice will also depend on the spill conditions. Spreading of oil in between ice floes seems to give almost the same total oil infested area as in open waters, but the local concentration of oil increases with increasing ice coverage as ice reduces the available area. Spreading of oil on slush ice is considerably slower than in open water, and has a tendency to stop when a certain minimum thickness is reached. Oil deposited under ice in the freezing-season may be frozen into the ice (encapsulated), and will not be accessible until the ice melts. Oil found in relatively thick layers under ice will migrate to the surface through brine channels and cavities formed during thawing of the ice, while more dispersed oil (droplets) will only be released when the ice is melted down to the oil layer.

Sørstrøm et al. (1994) observed that in dense drifting ice (ice concentration > 75%) the secondary spreading of the oil is strongly determined by the dynamics in the ice field (wind and wave induced motions). The oil drifted with the ice and the spreading was highly reduced because of the barrier effect of the ice.

In total, oil spreading in broken sea ice is to a large extent determined by ice related factors – such as local ice coverage and the form of ice (separate ice floes surrounded by open water or slush ice), as well as the dynamics in the ice field (wind and wave induced motions). For oil spilled in continuous ice, the presence of snow on the ice surface, as well as the topography of the ice surface will be decisive factors. However, as long as present sea ice models in general do not represent such details, sophisticated models for predicting the spreading of oil in sea ice will be of limited value.

3.1.2 Evaporation

Open water conditions:

The rate of evaporation of given oil is mainly dependent on the surface to volume ratio, temperature and wind speed, but internal mixing (or lack of) in the oil film is also an important factor. Laboratory and meso-scale studies have shown lower evaporation rates at 0°C than at 13°C (Daling, 1990 and Singsaas, 1993). The observed evaporation rates in these measurements correlate to model calculations (Daling 1990). However, for some of the oil types tested (Statfjord and Ula crude) the evaporation were lower than expected (at 0°C) from the model calculations based on True Boiling Point (TBP) curves of the oils. The reduced evaporation rate was probably due to the high content of wax in these oils. Precipitated wax may build a matrix that limits internal mixing of the oil layer or acts as a diffusion barrier at the surface of the oil. The experiments also indicated that the evaporation rate of emulsions with a certain film thickness was almost similar or slightly lower than the evaporation rate of a water free oil film with the same thickness. Internal mixing in the oil film (caused by wind and waves) and film thickness are probably the most important factors determining the evaporation of oil at sea.

***Ice conditions*:**

When oil is spilled in broken ice, the ice floes will work as a barrier and prevent a free spreading of oil, resulting in an increased film thickness compared to open water. Meso-scale experiments carried out in a flume (Daling *et al*., 1990), show that there is no significant difference in the evaporation degree for oil in open water, and oil in slush ice if the film thickness is the same. In the referred experiments the film thickness was approximately 2 mm. However, when oil spreads in between ice floes, the area that the oil and ice together will cover is approximately the same area, as the oil will cover in open water. The film thickness of oil will therefore increase with increased ice coverage. Tests in a meso-scale flume with 70 % ice coverage showed a significantly slower evaporation compared to tests without ice present. The slower evaporation was due to higher film thickness as the oil covered only 1/3 of the area without ice present. Experiments conducted in a newer and modified meso-scale flume (Singsaas *et al.*, 1993) showed evaporation not significantly different with or without ice. This is probably due to higher energy in these experiments because of circulation of the oil / emulsion, leading to good wind and wave exposure. It is supposed that the earlier meso-scale experiments simulate low energy conditions as observed in a field experiment in the marginal ice zone (Sørstrøm *et al.,* 1994), while the experiments in the modified flume simulate a higher energy level to be found closer to the ice edge. Observations from the field experiment (Sørstrøm *et al*.,1994) showed that 20 – 25 % of the oil has evaporated after 3-4 days for *Sture blend* oil, while observations from an experimental oil spill at Haltenbanken with the same oil showed 35 – 40% evaporated after 3-4 days (Daling *et al.,*1989). The main explanation to the low evaporation is the high film thickness (1 – 65 mm, with an average of 9 mm), caused by the ice acting as a barrier against free spreading of the oil.

The general trend of evaporation is that it is rapid and high due to thin oil films in open waters, but in ice the film thickness will increase and reduce the rate and degree of evaporation due to increasing ice coverage. For oils with high wax content and pour point, the evaporation at low temperatures can be reduced due to a built up diffusion barrier of precipitated wax.

3.1.3 Natural dispersion

Depending on the sea state and the viscosity of the oil, wave action will split the oil slick into smaller or larger droplets (from 1 to 1000 µm) that disperse into the water masses.

Meso-scale experiments (Singsaas *et al*., 1993) show that the degree of natural dispersion is highest without presence of ice, and that it decreases significantly when ice is present. It seems that slush ice gives somewhat lower natural dispersion than ice floes, which may be due to a relatively more wave-damping effect from slush ice than from smaller ice floes. These meso-scale experiments probably simulate the more energetic conditions closer to the ice edge. However, it is important to emphasize that these experiments only give indications, and that further investigations both in meso-scale and in the field are necessary to be able to conclude on natural dispersion in ice.

In a field experiment carried out in the marginal ice zone, Sørstrøm *et al*. (1994) found that water samples taken at 0.5, 1, and 3 meters depth did not show traces of the oil used in the experiment (Sture blend). Therefore, the conclusion was that the wave energy during these field experiments was so low that natural dispersion did not take place.

3.1.4 Water uptake and formation of emulsions

Crude oils contain components with surface-active properties that enable them to emulsify water and form water-in-oil emulsions if the energy on the sea surface is sufficient. Formation of emulsions will mainly take place in the presence of breaking waves. In sea ice, ice-to-ice interactions like grinding, collisions and pumping between ice floes also contribute to emulsion formation. Water uptake is the most important weathering process that makes crude oils persistent on the water surface.

One of the sub-projects in ONA aimed at furnishing data on the properties of different crude oils at different weathering degrees, temperatures, and water salinities (Daling, 1990), especially emphasizing the emulsifying properties of the oils at low temperatures and at different sea water salinities. The results show that the rate of water uptake depends on the type of crude oil and that it slightly decreases with increasing weathering and with decreasing temperature, while there is no significant trend in the water uptake rate at varying salinities. The stability of emulsion is highly dependent on the chemical composition of the oil. It increases with increasing weathering, and with decreasing temperature. The salinity of the water is relatively insignificant for emulsion stability. The effect of emulsion breaker (Alcopol O 60%) decreases with increasing stability of emulsion. The efficiency of emulsion breaker decreases with increasing weathering and with decreasing temperature during low salinity conditions. The choice of correct emulsion breaker is therefore important.

Five experiments with weathering of oil in a meso-scale flume at different ice conditions were carried out as part of the ONA program (Daling *et al*., 1990). The presence of slush ice and/or small ice floes was important because of its damping effects on waves. Slush ice had a significant moderating effect especially on high frequency waves. Such effects were also observed for ice floes, but the shear force between oil and ice floes were more predominant than between oil and slush ice. The water uptakes in experiments with ice floes were higher than in experiments with slush ice due to ice-ice interactions. The conclusions from these experiments were that the water uptake rate for oil will be lower and the maximum water content will be lower than in open water due to the wave damping effect of ice.

The viscosity of given oil will increase with decreasing temperature, and the increase will, among other things, be dependent on oil type. The viscosity of oil/emulsion will also increase with weathering due to loss of volatile fractions (evaporation) and water uptake (emulsification). Because of reduced evaporation and water uptake in ice, the viscosity increase in ice will be lower than for the same oil in open water. This is reflected in the meso-scale and field experiments carried out. However, the viscosity during two meso-scale experiments with ice floes (Daling *et al*., 1990) were somewhat higher than expected based on water content and evaporation degree. This might be due to different emulsification mechanisms in ice and open water, producing emulsions with different properties (e.g. droplet size).

The conclusion is that for open waters studies of the water uptake and the emulsion properties have to be investigated for the specific oil types to be able to provide reliable predictions of weathering at sea.

Biodegradation
For biodegradation of oil we refer to Section 4.4.

3.1.5 Conclusions

The results show that oil **spreading** decreases with increasing ice coverage resulting in increased oil film thickness. Oil **drift** is governed by surface wind and ocean currents at low ice coverage (< 30%), while at high ice coverage (> 60-70%) the oil will drift with the ice.

The **evaporation rate** decreases with increased ice coverage due to increasing oil film thickness. Low temperatures also contribute to decreased evaporation due to wax structures building up a diffusion barrier on the surface of the oil.

The rate of natural dispersion of oil droplets into the water column decreases with increasing ice coverage and is relatively low in high ice coverage. The **emulsification rate** (water uptake) decreases with increasing ice coverage primarily due to wave damping.

Both emulsion stability and viscosity vary from oil type to oil type. Normally they both increase relatively fast with increased weathering time in open water. In ice infested waters the increase with time at sea is reduced. However, in emulsions created by collisions between ice floes, both emulsion stability and viscosity can increase as demonstrated in meso-scale flume experiments.

There are still several questions to be answered related to the fate and behaviour of oil in ice-infested waters. The weathering conditions, temperatures and ice conditions can vary considerably in the Arctic. As mentioned, the weathering degree is dependent on the original physical and chemical composition of the oil as well as the weather and ice conditions. The research need is to quantify the transport of different oils as a function of physical/chemical properties in porous media (ice and snow) under different environmental conditions, and to establish algorithms to describe these processes in numerical models.

If field experiments are to be conducted, the aim should be to perform physical and chemical measurements during the oil weathering process. The data can be used to validate and enhance oil-weathering algorithms to be used as parameters in oil weathering models. The objective is to collect basic research data on evaporation, dispersion, spreading, and other weathering parameters in the marginal ice zone. This data would then be used to improve and modify existing algorithms or develop new algorithms of oil weathering in the ice and on its surface. The work aims to provide an experimental basis for the enhancement or development of algorithms in analytical models.

Status on fate and weathering of oil in arctic conditions are summarised in *Table 3.1*.

Table 3.1 Status on fate and weathering of oil in arctic conditions

Parameter	**In open water**	**In ice with increasing ice coverage**	**Conclusion**
Spreading	Spreading due to diffusion, gravity, inertial force, and viscosity and interfacial tension. Spreading normally from thick to thin oil films, dependent of oil.	Spreading in ice decreases by increasing ice coverage resulting in increasing oil film thickness with increasing ice coverage.	Spreading of oil in sea ice is to a large extent depending on ice conditions. Reliable predictions are thus limited by the accuracy of sea ice models.
Drift	Oil drift due to wind and current	At ice coverage less than 30% the drifting of oil will be independent of the ice. At ice coverage larger than 60-70 % the oil will drift with the ice.	As above (predictions depend on the accuracy of sea ice models)
Evaporation	Evaporation is rapid and high due to thin oil films.	Increasing film thickness due to increasing ice coverage reduces the rate and degree of evaporation. Reduced evaporation at low temperatures due to a diffusion barrier of precipitated wax.	The knowledge of different weathering processes and properties of oil in open water are fairly good. To provide reliable predictions of weathering properties in open water the specific weathering properties of the spilled oil type have to be investigated. In ice the different weathering processes depend on the ice coverage and ice movement (wave damping effects). Reliable predictions are thus limited by the accuracy of sea ice models.
Natural dispersion	Natural dispersion dependent of oil type and sea states.	The rate of natural dispersion will decrease by increasing ice coverage and will be very low with high ice coverage.	
Emulsification	Emulsification will mainly take place in the presence of breaking waves.	Presence of ice will damp wave activity and the emulsification will decrease by increasing ice coverage.	
Water uptake rate	Rapid water uptake, dependent of oil type.	Water uptake rate decreases with increasing ice coverage due to wave damping effects and will be slow in dense sea ice.	
Maximum water uptake	High water maximum water content dependent on oil type.	Maximum water content decreases with increasing ice coverage and will be low with high ice coverage (wave damping).	
Stability of emulsion	Stability of emulsion dependent on oil type. Stability increases with increasing weathering degree.	Stability of emulsion dependent of oil type.	
Viscosity	Increasing viscosity due to increasing water uptake and evaporation.	The viscosity will increase with increasing water uptake and evaporation as in open sea, but the increase will be slower due to slower evaporation and water uptake.	

3.2 EXAMPLES OF WEATHERING PREDICTIONS

When oil is spilled at sea a number of processes take place such as spreading, drift, evaporation, emulsification, natural dispersion and biodegradation of oil. These processes will be highly dependent on the chemical composition and physical properties of the oil, weather conditions and ice coverage. Investigation of emulsion properties like viscosity, water uptake ability and rate of emulsion formation is therefore necessary to generate reliable predictions regarding weathering properties of a specific type of oil at sea. Based on the oil behavior at sea, SINTEF classify oils in four main categories: Paraffinic, asphaltenic, waxy and naphtenic crude oils. *Figure 3.3* shows a map of different oils analyzed at SINTEF.

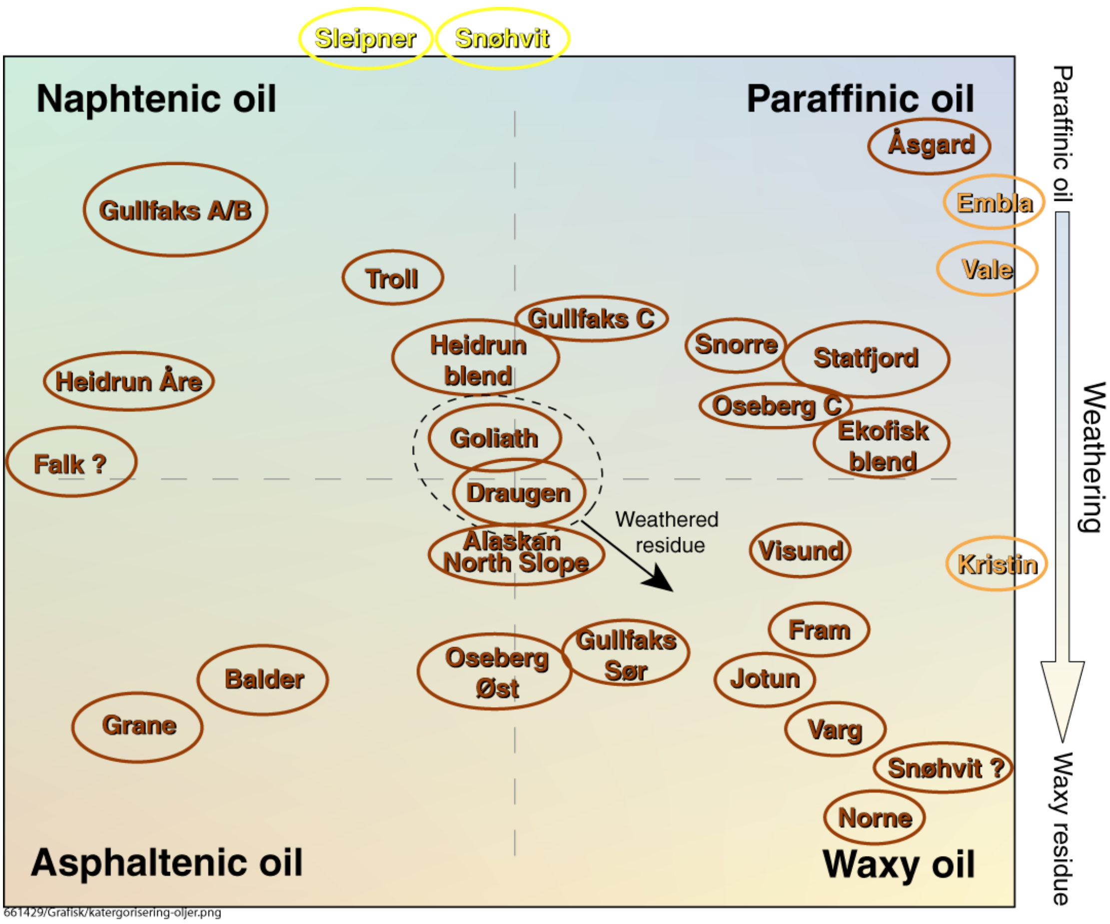

Figure 3.3 Categorization of oils tested at SINTEF

Different oils may have very different weathering properties at sea. Important properties in a spill response operation are the development of oil parameters like evaporation, pour point, flash point, viscosity of oil, water uptake, viscosity of emulsion, density of emulsion, and mass balance. The SINTEF Oil Weathering Model (*Figure 3.4*) predicts these properties based on input from a standardized step-wise weathering study performed at SINTEF. The model predicts weathering properties at selected temperatures, wind speeds and spill scenario.

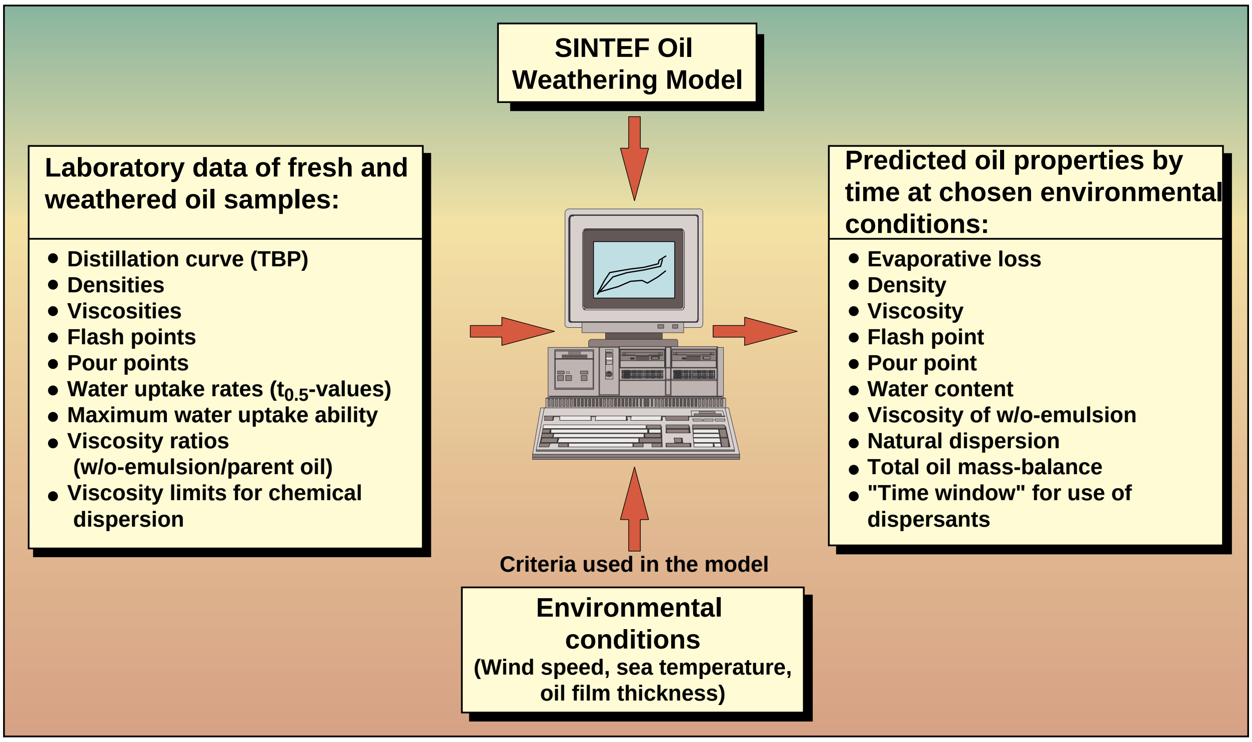

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Figure 3.4 SINTEF Oil Weathering Model.

Figures 3.5 – 3.9 show a comparison of predictions for five different oil types that have been analyzed for weathering properties at SINTEF. The environmental conditions are 10 m/s wind speed, 0°C air temperature and surface spill in open waters. The oil types are *Alaskan North slope, Norne, Grane, Sture Blend* and *Prestige*.

These four crude oils and one heavy fuel oil have been selected to show how different oil could behave when spilled at sea:

- *Alaskan North Slope* is a paraffinic crude oil that also has high asphaltene content and some wax.

- *Norne* is a waxy crude oil with a very high Pour Point. The oil will be able to solidify in a spill situation at a temperature of 0°C.

- *Grane* is asphaltenic oil that has been partly biodegraded in the reservoir. Emulsions formed from *Grane* are stable.

- *Sture blend* is a paraffinic crude oil with low asphaltene content.

- *Prestige* is a heavy fuel oil with an IFO degree of approximately 600 (viscosity of 600 Cst at 50°C). Refined products like heavy bunker fuels are high viscosity and high-density oils, made from crude oils in refinery processes, where residues are blended with a distillate fraction to achieve required physical properties. The properties of fuel oils with the same trade name (for instance IFO 580) from various refineries could vary considerably and thereby behave very differently if spilled at sea.

Example of how to use the prediction charts

If the *Grane* oil has drifted for a period of time on the sea surface the prediction charts can be used to determine the chemical, physical and emulsifying properties of the remaining oil. If you want to know the properties of *Grane* 24 hours after a spill at sea, you look at the predictions shown in Figure 3.5-Figure 3.9 and will find that the parameters are as listed in ***Table 3.2***:

Table 3.2 Weathering properties for Grane after 24 hours on the sea surface, obtained from the prediction charts. Wind speed is 10 m/s and sea temperature is 0 °C

Property	Winter temperature [0°C]
Evaporation	9 %
Viscosity of the water free oil	7200 cP
Water content	50 %
Viscosity of the emulsion	26000 cP

Predictions of weathering properties of 5 different oils

Predictions of weathering properties have been prepared for releases of oil at sea surface at a release rate of 1.33 metric tons/minute. The water temperature is 0°C and the wind speed is 10m/s.

Figure 3.5 shows that the evaporation of different oil types can be very different based on the chemical composition of the oils, but the evaporation not only depends on chemical composition, but also on the environmental conditions and film thickness. Good reliable True boiling point curves are fundamental for reliable predictions of evaporation but also for prediction of other weathering properties. In a spill situation the evaporation is important in the overall oil budget.

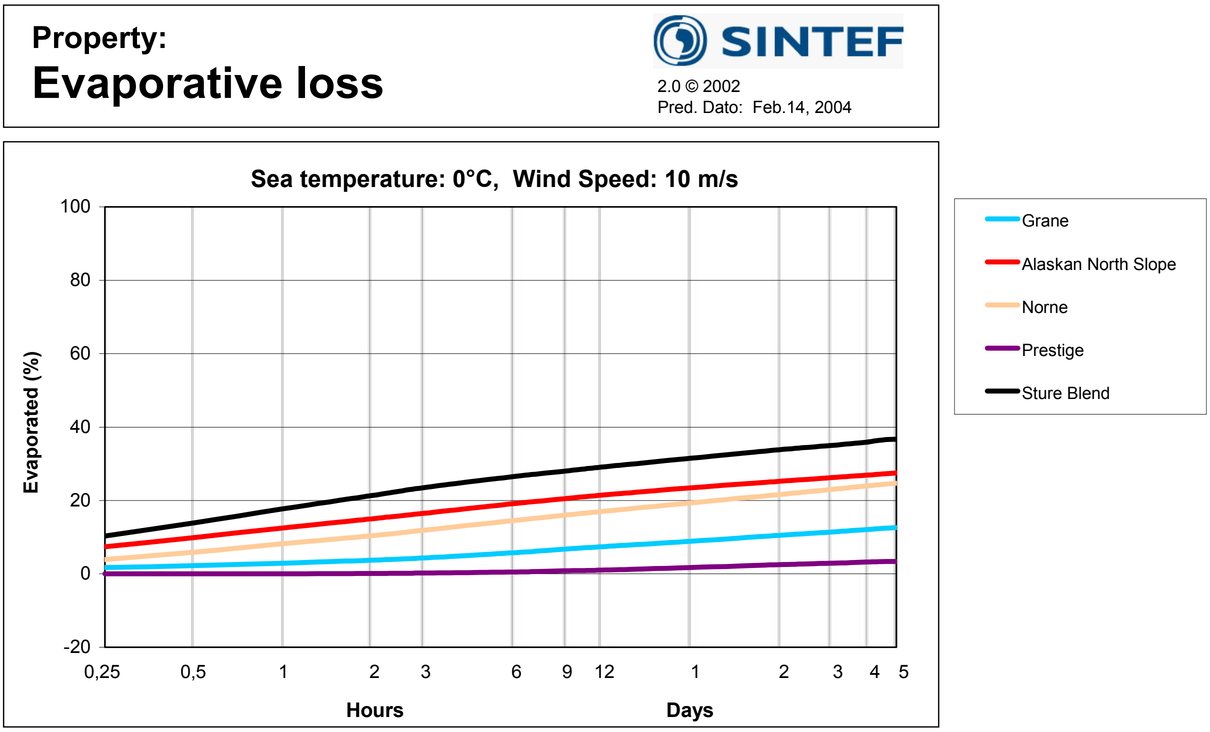

Figure 3.5 Evaporation of 5 different oils in open waters, at 0°C and a wind speed of 10m/s.

Figure 3.6 shows predictions of the pour point for five different oil types. The pour point can vary significantly and depends on the chemical composition. High wax content normally gives high pour points, but there is not a true correlation between wax content and pour point. The content of other compounds like asphaltenes and resins also contributes to the pour point. An oil with high asphaltene content contributes to low pour points. In a spill situation the pour point is important in the evaluation of the oil behavior. If the pour point is 10-15°C higher than the sea temperature and the weather is calm, the oil can solidify and a flow ability problem towards skimmers can occur. Specially designed skimmers like the HiWax skimmer has to be used in such cases. The pour point also defines a definite limit of use of chemical dispersants and has to be taken into consideration in cases where oil is removed from storage tanks of collected oil.

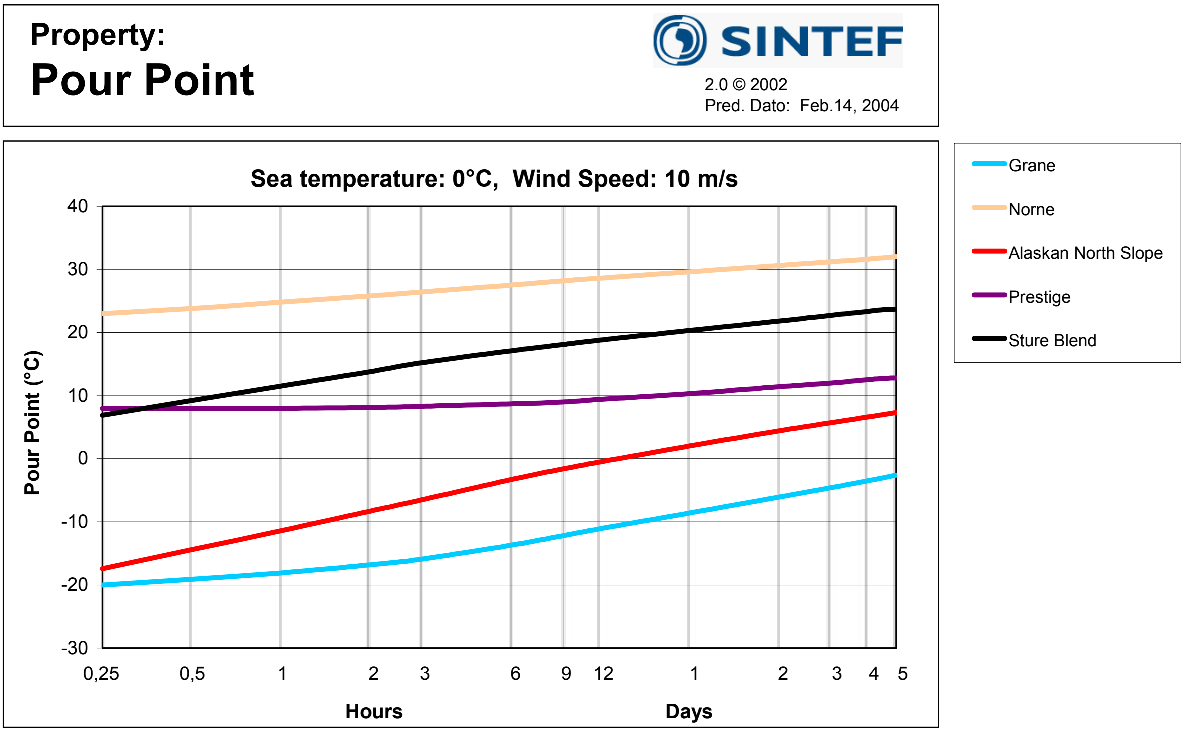

Figure 3.6 Pour point of 5 different oils in open waters, at 0°C and a wind speed of 10m/s.

Figure 3.7 show a prediction of the viscosity of water free oil for 5 different oil types. Viscosity of water free oil is an important parameter when water free oil is to be pumped or collected from sea surface. Measurements of viscosity of water free oil are an important input to predict the viscosity increase due to increasing water uptake.

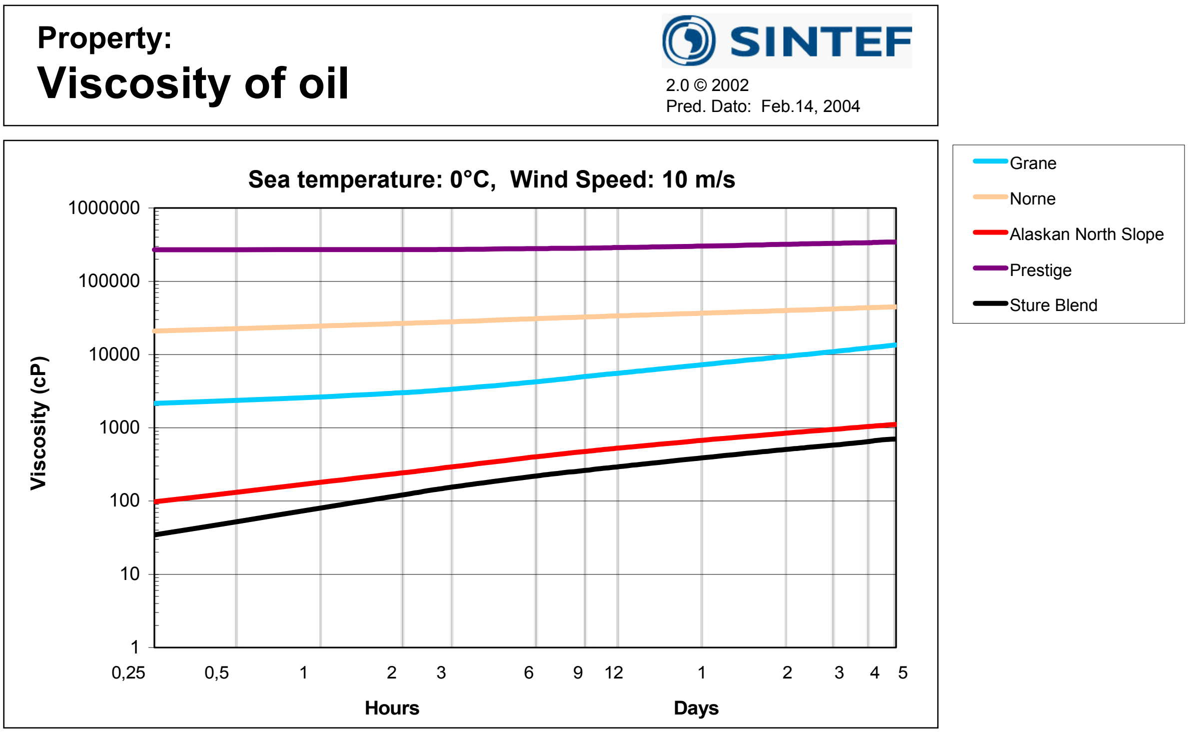

Figure 3.7 Viscosity of water free oil on 5 different oils in open waters, at 0°C and a wind speed of 10m/s.

Figure 3.8 shows the prediction of water uptake for 5 different oil types. But the water uptake rate and the maximum water uptake ability will differ from oil to oil. In this comparison *Sture blend* has the highest water uptake rate and the highest water uptake ability, while *Prestige* has much lower water uptake rate and water uptake ability. In a spill situation, the water uptake is important with respect to the mass balance and storage capacity in tanks. Emulsion breaker enabling water to be pumped out of the tank can break water-in-oil emulsions. Information on water uptake rate and maximum water uptake ability is important parameters to give reliable predictions of viscosity of emulsion.

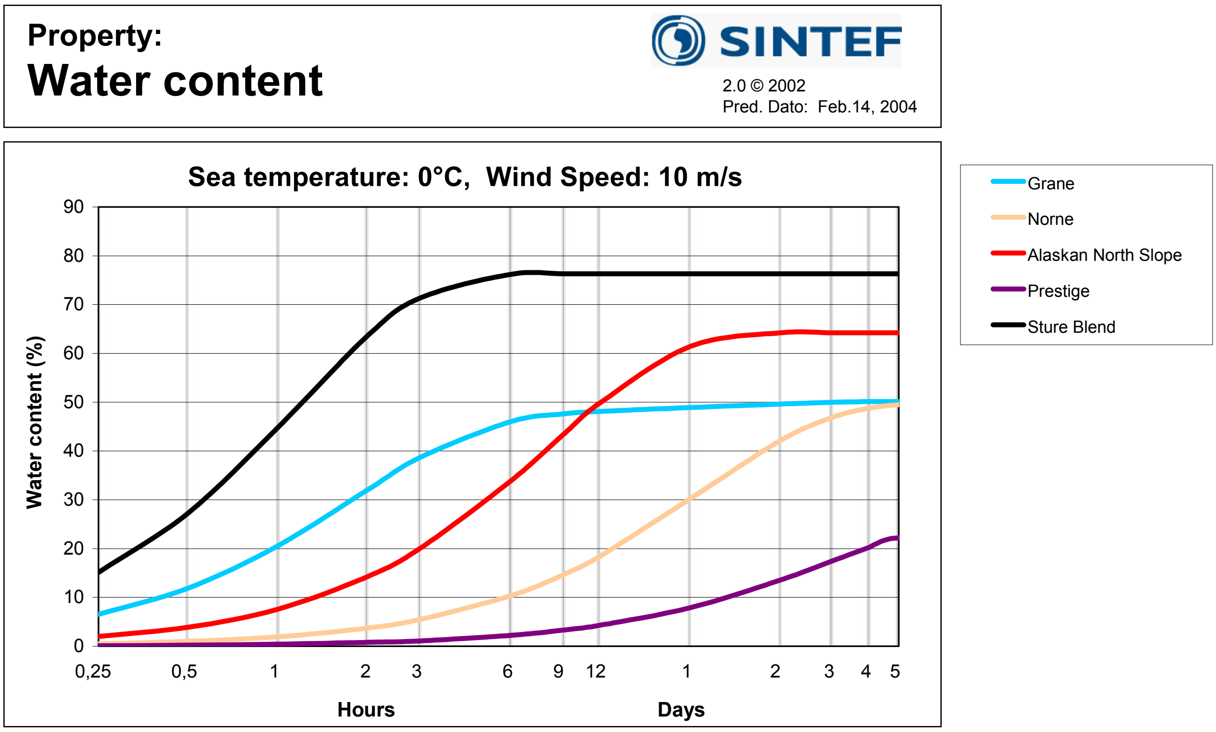

Figure 3.8 Water uptake of 5 different oils in open waters, at 0°C and a wind speed of 10m/s.

Figure 3.9 shows viscosity development by increasing water uptake and increasing evaporation. Viscosity of emulsion is the most important property to consider in choosing equipment or type of strategy in a spill situation. Viscosities higher than 15000-20000 cP ($10s^{-1}$) has shown to give reduced flow to for instance weir skimmers and reduction of pumping effectivity has also been observed. The dispersability of oil is also linked to the viscosity of emulsion and the window of opportunity for effective use of dispersants is defined by viscosity of emulsion. To be able to give good reliable predictions of viscosity, measurements of viscosity of emulsion with increasing evaporative loss and increasing water uptake have to be done. Such measurements are used as input to the SINTEF oil-weathering model to define the viscosity increase by increasing water uptake and evaporation. The viscosity increase is specific from oil to oil and can be very different. Other models of weathering of oil use a constant *Mackay curve* to predict the viscosity increase based on viscosity measurements of fresh oil. A good example of a situation where the laboratory measurements have been important is the *Norne* oil. While the viscosity of water free oil increases as normal and with increasing water uptake the viscosity of emulsion decrease. If a constant *Mackay curve* has been used the viscosity of emulsion would have been predicted to several hundred thousand cP after 5 days, while the viscosity is measured to be around ten thousand cP.

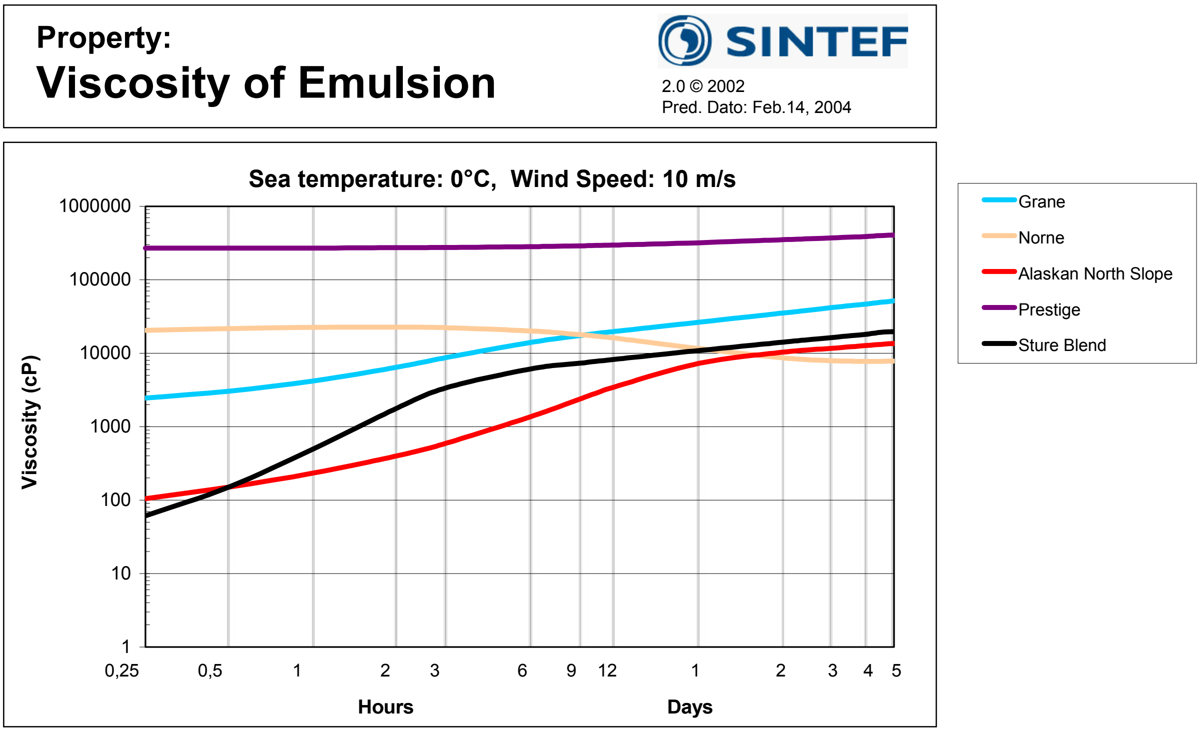

Figure 3.9 Viscosity of emulsion of 5 different oils in open waters, at 0°C and a wind speed of 10m/s

3.3 Oil spills within the ARCOP shipping scenario

3.3.1 Shipping scenario

The core issue in ARCOP is the transportation of oil from a terminal at Varanday to the European market. This could be done either by tankers going all the way from Varanday to the western Europe, or to some reloading terminal, for instance in the Murmansk area. We are talking about year round shipping, which means that the transport will go through areas with ice during the winter months. The ARCOP shipping scenario is characterized by the following parameters:

- Cargo: Crude oil from Varanday to Murmansk (year around)
- Tanker alternatives: 120 000 dwt, 90 000 dwt and 60 000 dwt tankers

- Size of the biggest crude oil tank is about 10 000 dwt (in 120 000 dwt tanker)

- Due to design of tankers, the defined ARCOP ice conditions for the shipping scenario are very detailed. Here we only refer some of the parameters:

o Ice thickness (average winter max)	1.1 m
o Rafted ice with a maximum ice thickness	2.4 m
o Average ice pressure intensity (0-3)	1
o Average ice drift speed	0.2 m/s
o Ice drift direction	irregular (wind driven)
o Maximum ice concentration	100 %
o Time of year	March
o Minimum air temperature in March	- 44° C
o Typical air temperature in March	-14.4°C

Based on hydrometeorological station data, average air temperature in the Varandey area in March is -14.4 deg. C (recorded minimum is –44°C, maximum is +3°C). Near Murmansk it is higher by about 4°C. However, this is applicable to coastal line. Air temperature in this part of the sea is 2°C to 5°C higher (depending on location: due to Gulf Stream influence; gradient of air temperature is very significant).

3.3.2 Potential oil spills

At a later stage two ARCOP oil spill scenarios will be defined. At this time we only consider some conditions that make it possible to discuss various spill combat techniques, to evaluate whether they are useful or not.

Type of oil
From the shipping scenario we already know that the cargo is crude oil to be loaded from a tank farm at Varandey. In the weathering section of this chapter, the properties of a few types of crude oil have been specified. The referred oil types are fairly light, and in the fresh state they have relatively low viscosity at the freezing point of water (between -1.5°C and –2°C).

The oil temperature in the tanks varies during the voyage. During on- and offloading the oil is typically heated to a certain point depending on the pump types and capacity. During the voyage the oil is not necessarily heated. This is a design question, which depend and/or effect on the loading facilities, tank materials, costs etc., and on oil spill characteristics.

Where and when

An oil spill associated with the ARCOP shipping scenario could be related to

- loading or unloading of tankers (in ice or open waters)
- with a tanker accident along the shipping route from Varandey to Murmansk, in ice or in open waters

Types of spill and amount of spilled oil

- The most frequent type of spill will occur during loading or unloading of oil, i.e. at the terminal in Varandey, or in Murmansk. Most of such spills will likely be from a few litres to some cubic meters, caused by all sorts of minor mishaps.

  - Slightly larger spills could happen during oil loading process due to a breaking hose or an open valve.

  - Spills happening during loading or unloading will be of moderate size. A leakage during transfer of oil will stop as soon as the pumping stops after detecting the leakage.

  - A tanker accident along the shipping route could create a major oil spill. The ARCOP shipping scenario indicates that a maximum damage will break four tanks (due to accident with another tanker, which hits to the tanker's side with high speed and cuts the tanker in two parts). Therefore the maximum amount of the crude oil that be spilled is 40,000 tonnes. This is actually the "standard" design value for oil spills with tankers.

Distance to open water

- The distance between the oil spill area and open water depends on where the damage occurs and current ice condition. An oil spill could happen in open water. The distance is largest if the spill happens near the Varanday oil terminal in severe ice conditions in March. In this case the distance is about 380 nautical miles (700 km). Therefore the distance can vary between 0 – 380n.m. (700 km).

3.3.3 Two examples of ice conditions in March

Two examples of ice conditions in March are considered and some of the ice conditions according the WMO "egg code" in the figures are explained. For both figures, the shipping route indicated, represents the shortest distance to open water. The ice conditions could however make it more effective to choose a longer route if the ice conditions are more favourable along this route. For both examples the maximum ice thickness in March is 70 cm according to the WMO "egg code" (see Fig. 3.10 and 3.11).

3.3.4 Example 1 – Light ice conditions in March

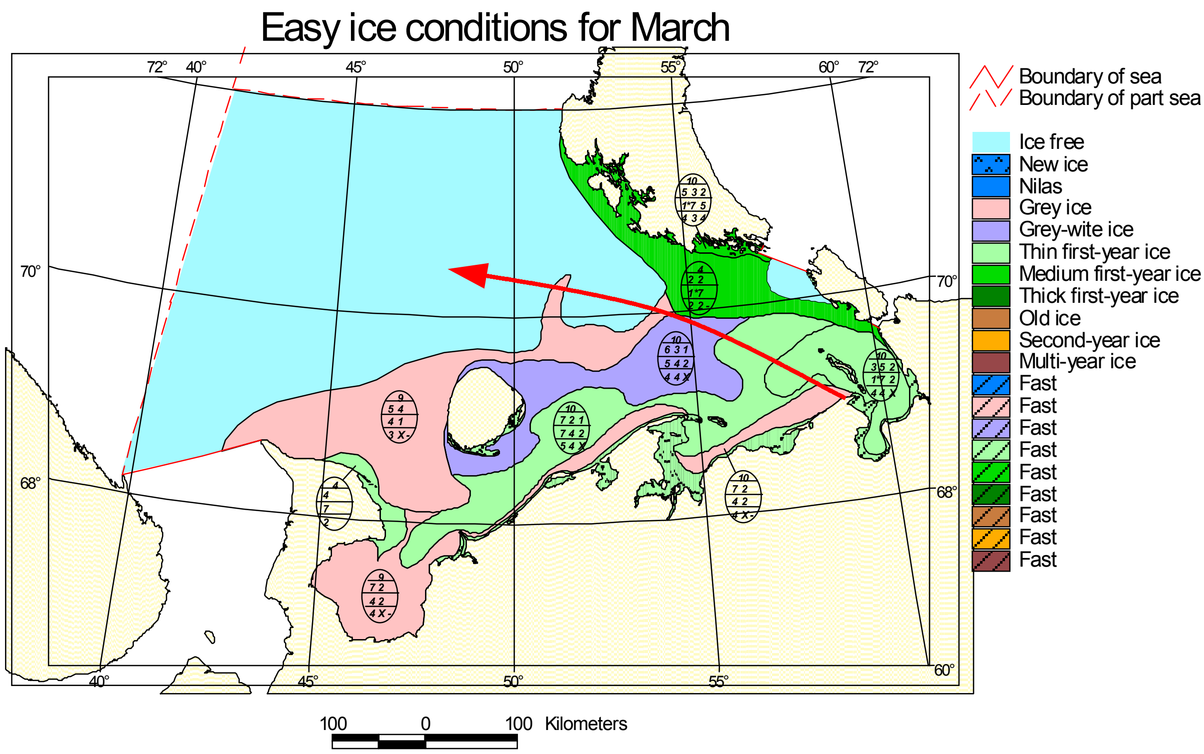

Figure 3.10 Light ice conditions for March.

Figure 3.10 indicates light ice conditions in March for the study area, and the shortest shipping route to open water from the Varandey terminal. From the terminal, a tanker has to pass through approximately 125 n.m. (230 km), with 100 % ice coverage. Close to the terminal, it is mostly ice of thickness 10-15 cm, and floe sizes 100 – 500 m across. Further offshore, approximately half the total distance to open water; 30-70 cm thick ice has more than 50% coverage, and ice floes is ranging from 100 m to 2 km across. The last third of the distance to open water has about 50% coverage of ice that is 15-30 cm thick, with floe sizes up to 500 m. The rest of the ice is less thick.

Although there is 100 % ice coverage more or less all the way through the ice field, there is also a huge amount of ice that is fairly thin. This should indicate that there is not much pressure in the ice, and relatively small workboats would be able to operate in the ice, once the ice is broken by an icebreaker or ice going vessel.

3.3.5 Example 2 - Severe ice conditions in March

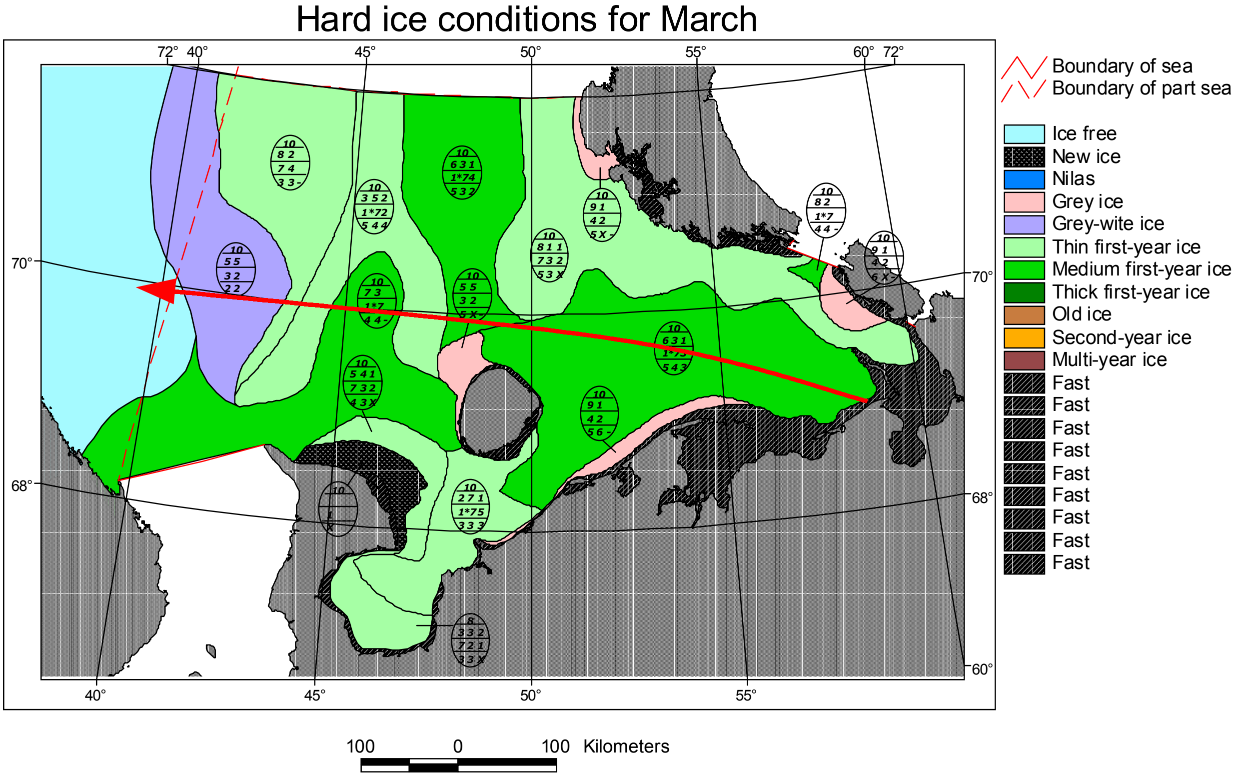

Figure 3.11 Severe ice conditions for March.

Figure 3.11 shows the severe ice conditions for March. At this time there is still some land fast ice at the Varandey terminal, ice thickness has not been indicated, but would probably be more than 70 cm thick. The total distance through the ice field is approximately 380 n.m. (700 km).

The total ice concentration is 100% all the way, but more than half of this distance from outside the land fast ice zone is covered with 0 - 10 cm thick ice of 60% concentration, while 30 cm – 70cm thick ice has a about 30% concentration. Further to the west there is about 80 n.m. (150 km) distance where 30 – 70 cm thick ice has more than 50% of the ice concentration, with the rest of the ice being thinner. By choosing a more southerly route, the distance of ice navigation would be longer, but with less ice thickness.

3.4 References fate and weathering

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4 OIL SPILL RESPONSE – PRESENT ALTERNATIVES FOR ICE COVERED WATERS

Oil spill response alternatives are described by category in the following sections of this chapter:

- Mechanical recovery
- In-situ burning
- Dispersants
- Bioremediation

4.1 MECHANICAL OIL RECOVERY

This section on mechanical oil recovery is based on a study of the literature as well as on experience from a number of field trials on ice data acquisition (sea ice and icebergs), experimental oil spills in the Barents Sea ice field, ice processing trials in the Alaskan Beaufort during freeze-up, and on planning and coordination of various field trials associated with oil spill countermeasures under temperate conditions (oil on water experiments in the North Sea, deepwater oil experiment in the Norwegian Sea).

4.1.1 Oil spill combating under arctic open water conditions

Figure 4.1 Arctic region, ice extent for July is indicated.

With no ice present during summer conditions, the technology developed for oil spill combating in the southern areas like the North Sea will have similar response capability for the Barents Sea and for the ARCOP study area. Longer distance to the mainland is more inconvenient and will make the oil spill preparedness more expensive compared to the North Sea, but will still be feasible.

For winter conditions in open waters and with non-icing conditions, use of existing mechanical equipment will be feasible in these waters. In ice-covered waters and under icing conditions, existing equipment has not been proven to be effective for oil recovery. The main problems are associated with accessibility of the oil, ice processing and manoeuvrability of a working platform. The opportunity to test and adapt techniques under real field conditions often has been lacking during development of recovery equipment.

4.1.2 Considerations and potential problems for oil-in-ice recovery

Oil recovery operations in ice-infested waters will be confronted with totally different problems than in open waters, refer Johannessen et al. (1996):

Limited flow of oil to the recovery device

Natural spreading by gravity forces and/or the relative velocity of the recovery device will, in open water, usually result in continuous renewal of oil encountered by the recovery device. Depending on the ice concentration and the viscosity/density of the oil, this effect is reduced or completely eliminated when oil is spilled in ice. This imposes special requirements on the recovery system since it will have to be able to move to the spilled oil or, alternatively, be able to deflect the ice and recover the oil. In ice concentrations up to 20-30%, oil is assumed to spread freely without any significant limitations due to the ice.

Limited access to the oil

Moving the recovery unit through the ice field to the spilled oil can be impossible, or very complicated due to the presence of ice. This depends on a series of parameters such as the ice concentration, floe sizes, ice thickness and the dynamics of the ice field. The ice conditions impose special requirements on the operational platform with respect to strength, manoeuvrability, crane working range etc. Depending on the temperature, wave conditions and weather since the spill occurred, the spill can be frozen into the ice or heavily mixed with brash and slush ice.

Deflection of oil together with ice

Ideally, the recovery of oil-in-ice should entail collecting the oil while leaving the ice behind. This usually implies that a form of ice processing or ice deflection is required. However, deflecting the ice without also deflecting the oil is difficult since oil often is trapped in clusters of ice and adheres to the edges of ice floes. A common problem when operating a skimmer from a ship is that the ship opens up the ice field and oil that initially was concentrated between floes spreads and forms a much thinner layer that is less recoverable.

Separation of oil from ice

Oil-in-ice recovery methods will collect varying amounts of small ice forms with the oil. In addition to the common oil/water separation problem, oil-in-ice recovery systems must address the problem of separating oil from ice and water onboard the recovery vessel. The complexity of this problem will vary depending on temperature, how well the oil is intermixed with the ice, the efficiency of the recovery equipment, oil properties etc. At low temperatures, storage of an oil/water/ice mixture could cause serious problems if no system to avoid further freezing is incorporated.

Contamination of ice /cleaning of ice

During the recovery process, some recovery principles are likely to increase the apparent oiling of ice. For example, in many cases, mop skimmers leave the ice apparently more contaminated after recovery. In addition to being a visual pollution problem, the oil may be more hazardous to wildlife when smeared over the top of the ice as opposed to being concentrated between the ice floes. Incorporation of an ice cleaning method into the oil-in-ice recovery system must be considered.

Increased oil viscosity

Generally, oil viscosity increases with decreasing temperature. The recovery device will have to be able to recover oils with very high viscosities, and the transfer of recovered product could also be difficult. Worst case, the temperature may be below the pour point of the oil, resulting in an almost solid product.

Icing /freezing of equipment
A variety of operational problems may be experienced due to low temperatures and ice. Examples are the freezing of hoses and moving parts as well as jamming of skimmers and pumps due to the accumulation of ice. Scrapers for adhesion skimmers may also work less effectively due to jamming by ice, stiffening of rubber compounds, etc. Hydraulics, fittings/adjustments can present various difficulties related to cold weather, as can gratings, screens and water spray systems.

Strength considerations
Both the operation platform and the recovery unit will have to be designed strong enough to withstand impact from ice. Exceptions are some amphibious type platforms that can operate on top of the ice.

Other problems
Winter oil recovery also involves problems for the personnel due to low temperatures. Cold conditions tend to lower the motivation, dedication and patience of people. All equipment should be designed with this in mind and be made robust and easy to operate with few delicate parts or adjustments.

Problems are also associated with the detection and monitoring of oil spills, in very poor light conditions as well as in ice.

4.1.3 Earlier R&D on oil-in-ice recovery

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

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

4.1.4 State-of-the-art review, Canada, 1992

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

1. Disc/drum skimmers

Comprehensive testing and use in spills had shown that both disc and drum systems allow small ice forms to pass the recovery mechanism as oil is being collected. Drawbacks include occasional ice jamming, underflow of oil at relative velocities exceeding 0.5 - 1.0 knot, and reduced recovery rate in very light and viscous oils, and in wave conditions. Vanes and discs are susceptible to damage.

Newer concepts like the Elastec, T-Disc and WP-1 skimmers (*Figure 4.2*) were recommended for study to further define operational limits. The first two comprise uncomplicated systems that should function optimally in medium viscosity oils. The WP-1, a porous drum concept designed to collect and transfer viscous oils, was assigned a high development potential. No need was foreseen to fabricate and assess small-scale models, since past results could be drawn upon, as appropriate. Evaluations were recommended which included utilization of a screw pump, and modifications to promote the movement of ice while not resulting in damage to the oil pickup components.

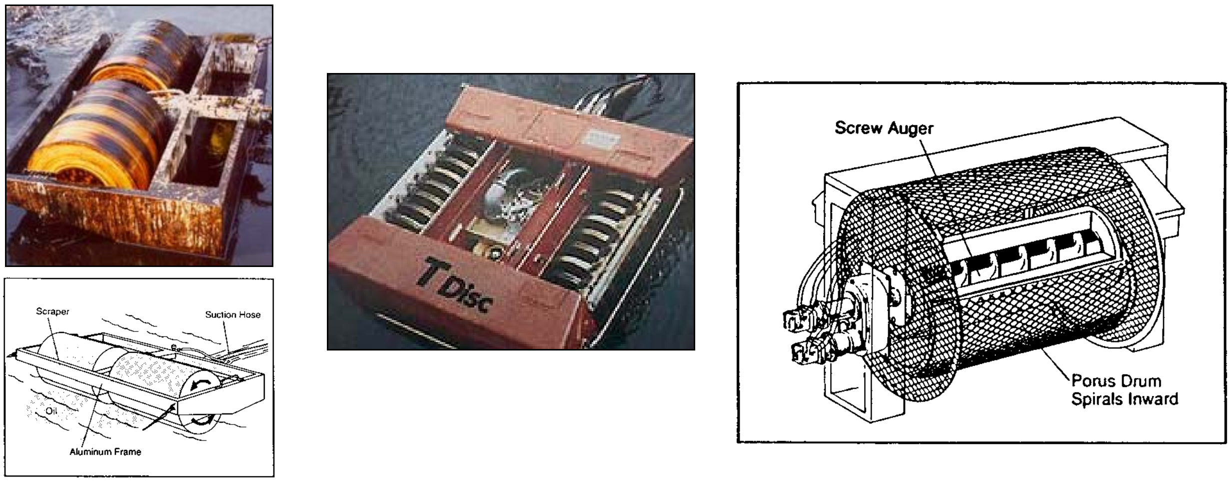


Figure 4.2 Drum skimmer (left), disc skimmer (middle), WP-1 porous drum skimmer (right).

2. Rope mop skimmers

Rope mop systems are adhesion skimmers that were reviewed extensively for application to oil-in-ice. The oleophilic rope principle had demonstrated its effectiveness in removing medium viscosity oils in low wave conditions, at relative velocities of up to several knots, and in debris (including ice). Various deployment modes had been developed, tested and used, including self-propelled vessels such as the ARCAT, Oil Mop Dynamic Skimmer and Shallow Water Access Mop Platform (SWAMP), see *Figure 4.3*.

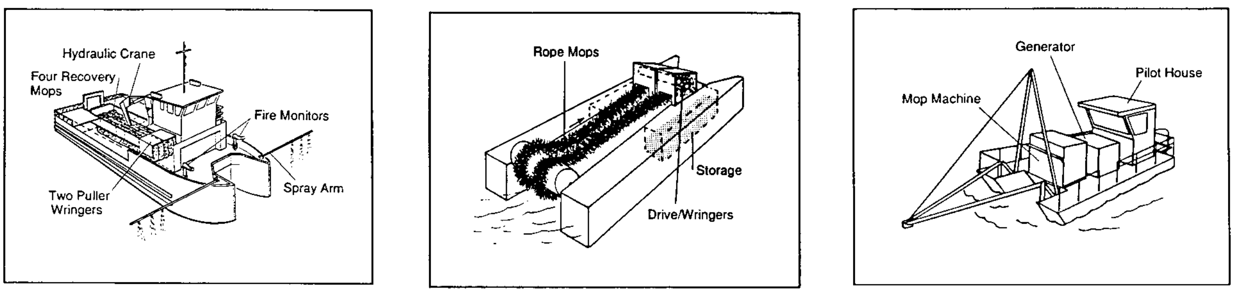
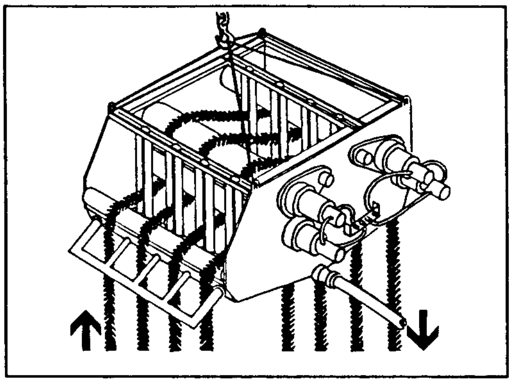


Figure 4.3 Rope mop skimmers in self propelled vessels. ARCAT (left), Oil Mop Dynamic Skimmer (middle), SWAMP (right).

Vertically oriented rope mops driven by a driver/wringer unit suspended from a crane, represented by the Foxtail and the Vertical Mop Wringer, were fairly new at the time (*Figure 4.4*). Overall, the vertical rope mop skimmers represented an appealing technology for removing oil-in-ice since selective positioning was possible and since there was no need any more to actively process all ice encountered by the recovery unit. Vertical mop machines were recommended for assessment, including the utilization of an internal pump in the wringer sump. Improved efficiencies were seen also to centre around reducing oil losses prior to entry of the rope mops into the wringer, separating matted rope mop strands, and by varying the mop configuration. Development potential was judged to be high.



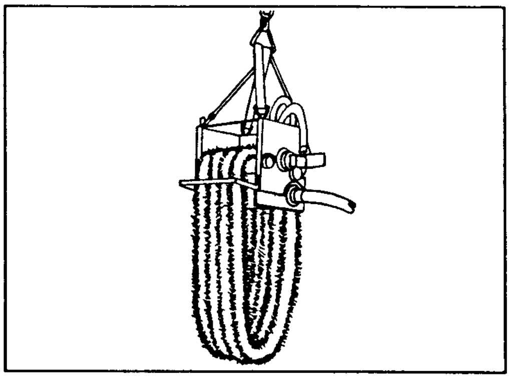


Figure 4.4 Vertical rope mop skimmers

3. Sorbent belt skimmers

Sorbent belts were commercially available, primarily as mobile skimmers and over-the-side systems. They had been successfully used on many spills and had been comprehensively researched for their application in ice conditions.

Testing had shown that performance of the Marco Class I Skimmer (*Figure 4.5*) in particular, improves through the addition of ice deflectors and passive and driven ice processors. Other modifications had centred around improvements to the scraper and transfer mechanisms. Development potential was judged to be low for sorbent belt systems in view of the extent of the research that had taken place, the proven capability of existing systems, and the relatively complex mechanism required to actually process ice. Other concerns related to the feasibility of deploying a skimming vessel that is not ice-strengthened and potential problems with the recovery mechanism and means of storage and transfer of oiled ice.

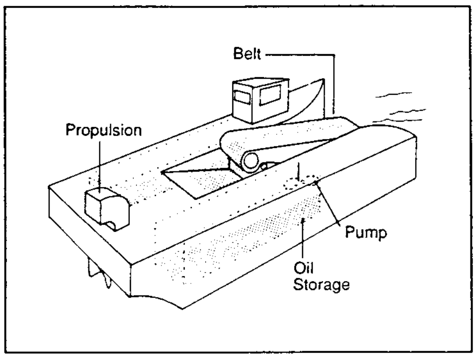
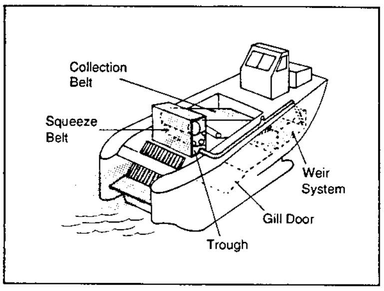


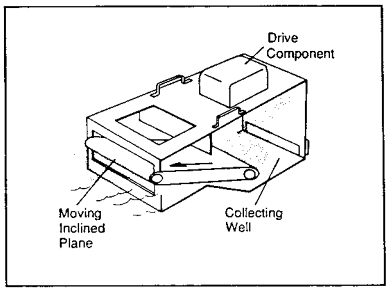
Figure 4.5 Marco Class I sorbent belt skimmer. A rotating porous belt entraps oil. A squeeze roller and scraper blade removes the oil from the belt, and the oil then drops into a sump. An induction pump behind the belt assists in drawing oil to the skimmer.

4. Submerging plane skimmers

Skimmers that submerge oil and ice to effect oil recovery use both sorbent and nonsorbent belt as well as porous planes. These included the Bennett/Versatech, JBF DIP and LPI Skimmers (*Figure 4.6*). Either ice accumulations and jamming or the deflection of both the oil and the ice away from the collection belt or well could affect performance of the belt systems. Development potential was therefore judged to be low.

Testing of a porous plane had shown that ice build-up could occur, thus preventing the intake of oil. As well, very viscous oils might not penetrate the porous plane. Submerging belt skimmers can encounter similar operational difficulties with oil viscosity as very viscous or very light oils bypass the belt. Development work was not seen to potentially result in improved recovery systems.





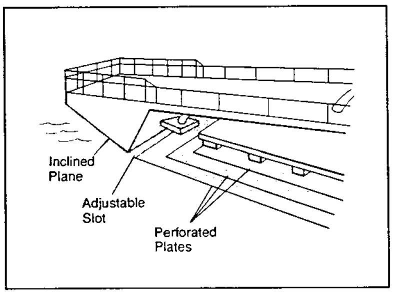


Figure 4.6 Submerging plane skimmers, Bennett (left), JBF DIP (middle), LPI (right).

5. Vacuum skimmers

A vacuum concept tested on a laboratory scale using a simulated ice cover (i.e., glass plate) resulted in high water uptake and indicated safety concerns as well as mechanical design complexities associated with the processing of flammable gases, assuming the spill originates from a sub sea blow-out. The small-scale investigation yielded limited test data. No development work was foreseen which would result in an improved system. Small-scale testing was judged to be of very limited value.

Conventional vacuum units (vacuum trucks, see *Figure 4.7*) and various skimming heads have been deployed in oil and ice with reasonable success, e.g. Buzzards Bay (Deslauriers, P.C., 1979). In addition to the amount of oil present, performance depends upon the efficiency of the skimming units, operator control, and common sense practices in ensuring the continued cold weather operation of pumps, hoses and prime movers (power packs). Although development potential was judged to be low, testing could be considered to characterize parameters, which optimise recovery rate and efficiency as well as to document procedures, which allow prolonged skimming at low temperatures.

Figure 4.7 Vacuum skimmers are often confused with air conveyors. The driving force for a vacuum unit is the pressure drop in the hose transferring the product, while the driving force for an air conveyor is the drag from air on the product to be transferred.

6. <u>Weir skimmers</u>

Generally, weir skimmers incorporate a simple or self-levelling edge over which oil and water flow. Of the many commercial devices available, the Destroil, Pharos Marine GT (*Figure 4.8*) and Foilex Skimmers utilize screw auger pumps that are capable of transferring viscous oil and ice. These units, along with the PEDCO self-adjusting weir, have therefore not been researched for their potential to incorporate hardware specifically developed for ice processing. Low development potential was assigned to this general class of skimmers in view of the limited research possibilities to improve performance.

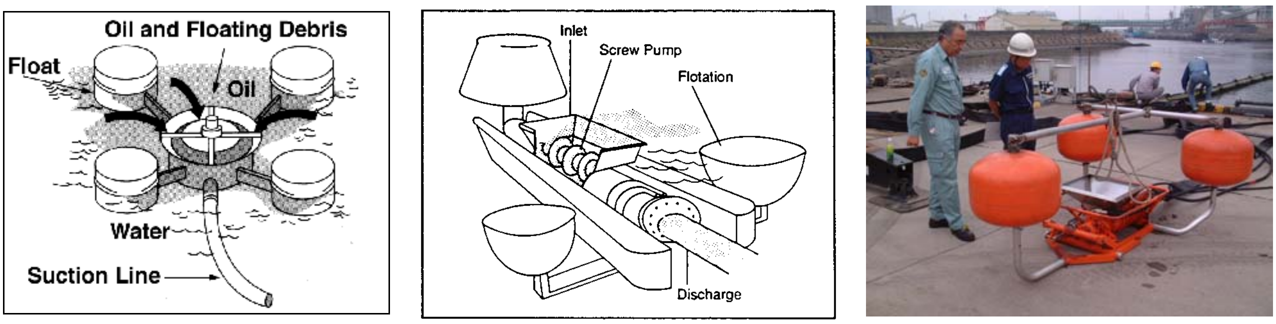


Figure 4.8 Weir skimmer principle (left). A hopper/weir collects oil, which is removed, from the sump by a pump, internal or external. Flotation chambers provide buoyancy. Destroil (middle), Pharos Marine GT 185 (right).

7. <u>Other concepts/combination skimmers</u>

A diverse number of other skimmers were considered for removing oil in ice. Of the systems noted in the literature, the Lori Brush Skimmer (Finland,

Figure 4.10 Other concepts. LORI brushpack (left), LORI Ice Cleaner (middle), Arcticskim (right).

) was found to offer the highest potential for recovering viscous oil in broken ice. Testing of the Lori Ice Cleaner, a two stage brush system developed for removing oil in ice, pointed to the difficulties of using brushes and water jets to process or clean ice and to low operational

efficiencies in light oil. However, the simple brush pack was seen to afford a high development potential as a viscous oil recovery approach for application to small ice forms, i.e. ice pieces that can underflow the skimmer.
An outrigger type of ice deflector called Arcticskim developed in Alaska was suggested for possible testing although it had potential limitations due to damage by ice floes, oil deflection, and the concentration and jamming of smaller ice forms which might prevent oil from reaching the skimming mechanism**.**

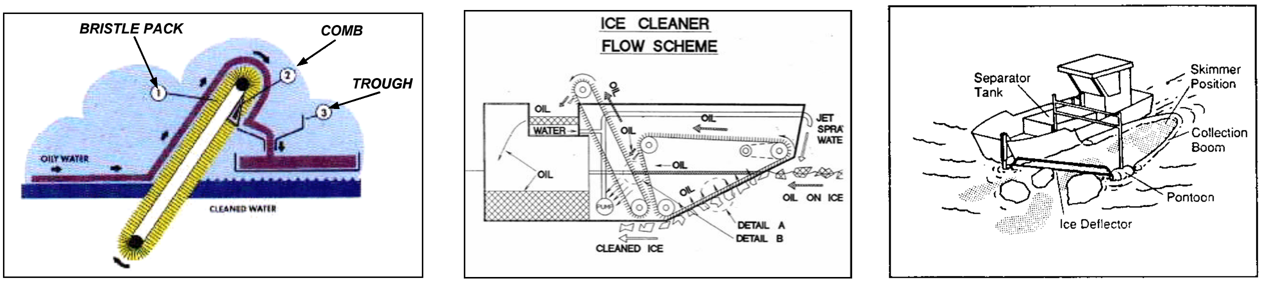


Figure 4.10 Other concepts. LORI brushpack (left), LORI Ice Cleaner (middle), Arcticskim (right).

4.1.5 MORICE

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

At the start of the MORICE, an extensive literature survey on mechanical recovery of oil in ice was carried out. A list of reports, papers and articles that were reviewed was prepared. This list of literature references from the MORICE is shown in table format in the bibliography chapter, and it includes classification of individual items.

The main objective for the MORICE was to develop new technology for ice-infested waters. An oil-in-ice spill can involve anything from very light ice conditions, where the presence of ice can be treated as a simple debris problem, similar to situations frequently encountered in open water, to heavy ice conditions where the oil is trapped between floes or is intermixed with small ice forms, which could make it virtually inaccessible for recovery. Before addressing the problems of oil-in-ice recovery on a technical level, it was essential to define one or more oil spill scenarios to focus the discussions on, since different environmental conditions or spill types may call for completely different approaches. Once the spill situation was defined, the various problems (see section 4.1.2) involved in oil recovery under such conditions could be addressed in a systematic manner.

The MORICE scenario included conditions that are fairly mild:

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

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

The main idea of the MORICE system (see *Figure 4.11*) is to open up some room between ice pieces so that oil and ice more easily can be separated: A grated belt is deflecting (lifting) the larger ice pieces out of the water. This ice is flushed with water to remove as much oil as possible, where after the ice is re-deployed behind the unit. Together with the small ice and oil going through the belt grating, the flushed off oil and small ice is guided into what is referred to as the recovery area. Here a recovery unit picks up the oil and maybe some small ice pieces. After recovery, the small ice pieces have to be separated from the recovered product, before the oil is stored, or maybe burned on site. The ice processing and oil recovery involved represents a fairly complex "production line", which also includes a relatively long processing time for the product (both ice and oil). This was a consequence of choices made by the participants: Ice should be cleaned as good as possible before it was redeployed.

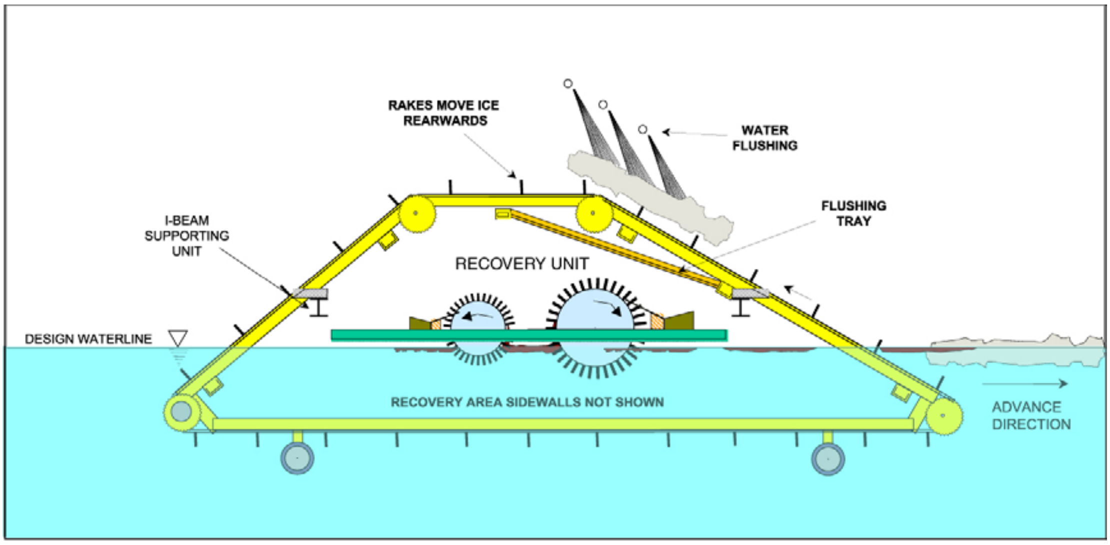


Figure 4.11 MORICE ice processing and recovery principle. Larger ice pieces have oil flushed off while lifted out of the water by the grated belt, where after the ice is redeployed behind the unit. Oil and small ice goes through the grating and enters the recovery area where the oil is recovered (together with some ice).

Nearly all the ice processing and recovery components were sheltered from exposure to wind by a lightweight enclosure (*Figure 4.12*) that could be kept at temperatures around 30^{o}C even at outdoor temperatures around -20°C. This proved to work very well, and solved the problems with icing and freezing.

Figure 4.12 Working platform with heated enclosure to avoid icing and freezing of equipment.

The concepts comprising the MORICE unit were brought to a stage where it is ready for industrialization. The unit that was built is referred to as a harbor sized unit to indicate the conditions in which this particular size and strength of unit could operate. The choices made regarding cleaning of ice before redeployment also very clearly limit the operating speed and hence the encounter rate. For these reasons the developed system would be suited for thorough cleaning of a small spill in ice in harbor conditions. To combat a larger spill in offshore conditions, the scale of the unit would have to be increased accordingly, both regarding size and strength. The ice processing speed would have to be increased dramatically, which would require a wider and more heavily constructed belt. At the same time the required cleaning of ice should be reduced. However, the basic idea behind the system, to ease the separation of oil from ice by opening up the space between ice pieces, represents a limitation since the amounts of ice to process could be enormous. Another limitation is the size of ice pieces that could be deflected (lifted) by the unit.

4.1.6 Alaska, North Slope - present status

The North Slope of Alaska contains the largest oil field discovered in North America, the Prudhoe Bay, together with many satellite fields. Oil production began in 1977 after the trans-Alaska oil pipeline was constructed. While initial production on the North Slope was from onshore areas, four fields produce at least some of their reserves from offshore areas. In 1987 the first offshore field, the Endicott/Duck Island, began production. Northstar is the second offshore field where production started in 2000 some 6 nautical miles from the shore. A buried sub sea pipeline is connecting the production facility to onshore infrastructure. During preparation for production at Northstar a task group was formed in 1997 by the Alaska oil industry and federal and state regulators. The objective of this task group was to develop a comprehensive oil spill response plan that could be used for all exploration and production operations on the Alaska North Slope. Such a plan was needed to assure adequate spill response capability as well as shared use of spill response equipment and expertise.

The task group considered oil spill cleanup methods well established for spills in open water and on land. The cleanup of oil spills in broken ice conditions on the other hand has been a concern in Alaska since oil exploration and production began to move into near-shore and offshore areas of the Alaskan North Slope. Ross & Dickins (1998) performed a study to evaluate the cleanup capabilities for large blowout spills in the Alaskan Beaufort Sea. The mechanical equipment in the evaluations included booms (Ro-boom) and key skimmers in the Alaska Clean Seas inventory at that time, weir skimmers (Transrec, Desmi, Walosep, Destroil) and oleophilic skimmers (LORI side collector brush-pack, Foxtail vertical rope mop, and T-disc skimmer). The evaluations for mechanical cleanup of spills from a surface blow-out in broken ice conditions during freeze-up came out with a very low efficiency.

In 1999 Alaska Clean Seas expanded its marine oil spill response tactics and assembled a marine task force at Prudhoe Bay. Both the oil industry and the government regulators agreed that the greatest response challenge was a potential oil well blow-out into the Beaufort Sea, particularly in pack ice conditions. The result was a barge-centred system for oil spill containment, recovery and intermediate storage, considered the best available technology for maximizing oil encounter rates under these conditions. To learn about the operational capabilities of the new system, the agencies and industry operated it as part of a fully deployed, barge-centred task force in a wide range of ice conditions in 2000. Bronson et al. (2002) summarize the results of the tests that took place during both spring break-up and autumn freeze-up. The tests involved targeted, replicated ice conditions and were not meant to subject the response equipment to ice distributions that it might typically encounter during a real spill situation. In addition, spilled oil was not part of the tests and therefore oil encounter rate, oil recovery rate and oil throughput rate were not estimated.

The barge-based oil containment and recovery system was installed on the ice-breaking barge Arctic Endeavor, a 63 m long double-hull deck/tank barge modified to support oil recovery and storage operations. For example, it deploys pontoon LORI-LFS brush skimmers and weir skimmers in the apex of its booms, see *Figure 4.13*. A “broken ice deflection system” (BIDS) grate was engineered and hung on each side of the barge hull to deflect larger ice from the LORI brush-pack skimmers. Up to 460 meters of ocean boom were deployed from barge deck storage reels, tied to each side of the vessel, and towed by 900-horsepower aluminium workboats. Other workboats and tugs pushed thick ice from the path of the containment booms in the spring break-up tests. During freeze-up, the Actic Endeavor conducted trials in newly formed ice. In new ice, each form of ice encountered by the containment boom was observed to isolate the skimmers quickly. The accumulations blocked surface water from entering the skimmers. As a result of the ice accumulations, the skimmers typically reached their operating limits less than 20 minutes after encountering ice. Ice in the containment boom areas and the LORI boom let areas did not move through the system during containment and recovery mode after the accumulations became large and thick. Observations showed no significant ice accumulation on LORI brushes, obstruction of discharge hoses and fittings, or interference with vessel transits and manoeuvring. LORI brushes and skimmer pumps and hoses did not freeze up. According to Bronson et al. (2002), the tests demonstrated that the response-operating limit of the specific barge-based system deployed in July and October 2000 was less than 1/10 ice coverage. Prior to testing, the operating limit was expected to be about 3/10 ice coverage.

Solsberg et al. (2002) describe evaluations performed regarding Best Available Technology (BAT) for mechanical response equipment for its application to oil spills in ice during break-up and freeze-up on the Alaska North Slope. The evaluations were based on a set of parameters like availability, transferability, effectiveness, cost, age and condition of equipment, compatibility with existing operations and technologies, engineering and operational feasibility of use, and environmental benefits. Using these BAT criteria, analyses were first of all conducted of commercially available spill technologies, then of some devices not yet generally available, and finally some additional devices and methods as requested by the Alaskan authorities. The analyses were performed for fall freeze-up and spring break-up, at water depths considered shallow (1-1.5m), and deeper (>6m). Equipment studied included vessels, barges, skimmers and vessel-skimmer-boom containment and recovery systems. All equipment was reviewed that could be used in ice near the Realistic Maximum Response Operating Limitations, usually in conjunction with ACS Spill Response Tactic R-19A (barge and boom combination).

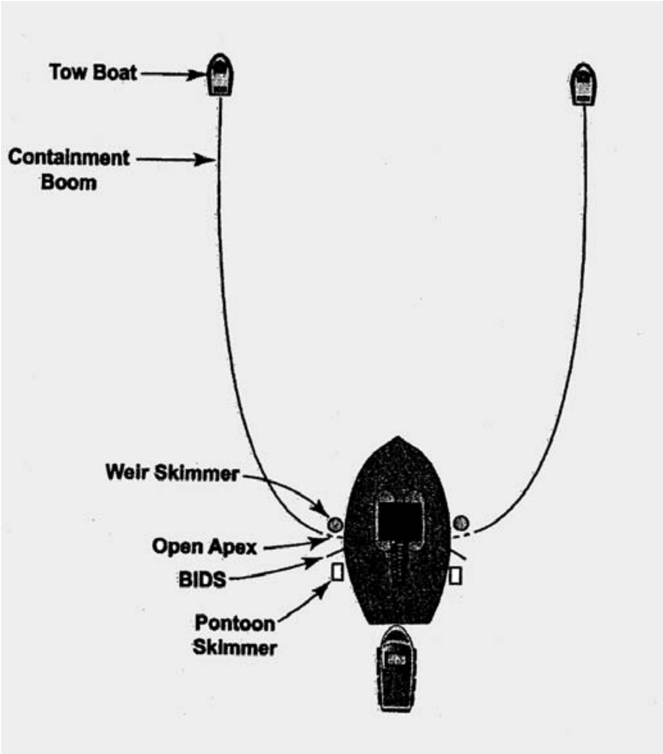


Figure 4.13 Prudhoe Bay barge-based containment and recovery system showing booms and alternative skimmers (left), on its way out from West Dock during freeze-up (right).

In some early stages of freeze-up the LORI brush-pack skimmer/boom combinations from the Alaska Clean Seas (ACS) inventory can deal with small ice forms that are sporadically distributed and move under the influence of wind. However, once ice concentrations generally reach 10% and/or start to form more continuous ice fields, booms used to concentrate oil from blowouts and batch releases for presentation to the brush pack also concentrate ice pieces. The brush pack was identified as the means to implement strategies defined in the Alaska Clean Seas Technical Manual. The main skimmer option identified in place of the brush pack was the brush drum, where similar models were made by Lamor and LORI (Finland). It was pointed out that their advantage over brush packs is that ice pieces are processed under the recovery device so that ice does not clog the system. The downside is that there is a loss of some oil as it passes under the device along with the ice. The more recently developed LORI Oil Recovery Bucket, a cylindrical brush attached to a scoop on a hydraulic arm, is briefly mentioned in the paper. Vertical rope mop skimmers are also mentioned, but were considered to have better potential application to batch spills than to blowouts, unless booms can be deployed to concentrate the oil. Several other types of recovery equipment like weir and belt skimmers are also mentioned. In short, for operation during freeze-up and break-up on the North Slope the Best Available Technology was considered to be LORI Brush Pack and brush drum skimmers, Archimedean screw pumps (Desmi DOP 160 and 250), and heavy offshore Ro-booms for containment.

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

The barge-based system for oil spill containment, recovery and intermediate storage prepared by ACS is a neat concept, although a drawback with the development in USA is the general lack of field testing with oil under real conditions, due to the rigid regulations regarding oil release permits. In other words, one of the most important elements in the development work has been missing. The system was intended for operation from break-up, through the open water season and until freeze-up when the ice conditions become too heavy for operation. If we compare with ARCOP conditions, the Alaskan freeze-up conditions will be present during most of the winter in the ARCOP study area, in the sense that the ice is not land fast. When people are using North Slope conditions in their studies and experiments, they easily tend to forget that ice conditions are often very different from one geographical area to another. Dickins and Buist (1999) give the reader the impression that their evaluations are valid for a wide range of geographical areas, including the Barents Sea. Although some of their descriptions and arguments are valid also for the Barents Sea ice regime, it is greatly misleading to think that their overall description is valid for the Barents Sea as well as for the ARCOP study area. It is also noticeable that most of the equipment that ACS considers as best available technology for marine oil combating operations at the North Slope has been developed and manufactured in the northern Europe (Denmark, Sweden, Finland, Norway).

4.1.7 Norway – present status

In addition to the MORICE project mentioned earlier, there has not been much focus in Norway on oil recovery under cold conditions and in ice during the last decade. Prior to this an R&D program on oil combating in northern and arctic waters (ONA, started 1989), was dealing mainly with fate and behavior of oil in cold water and ice. This program was motivated by exploratory drilling for hydrocarbons in the Barents Sea, and was funded by the Norwegian Clean Seas Association (NOFO). The program culminated in 1993 with experimental spills of crude oil (26 m^3) in the Barents Sea ice to study spread, weathering and fate of the oil. Due to lack of discoveries from the exploratory drilling in the Barents Sea, this R&D program came to a halt just as the focus was planned to be shifted towards improvement of combating techniques for oil in ice.

At present the interest in Norway for oil spill countermeasures in the northern areas is again increasing, partly due to new interest from the oil companies regarding exploratory drilling, partly due to the increasing tanker traffic outside the Norwegian coast from Russia to Europe and USA. To improve the preparedness against oil spills, Norway and Russia in 2003 have widened the scope of an existing bilateral agreement to cooperate in this area, and the first training course within this agreement took place in Murmansk in October 2003. Other actions have been taken by the Norwegian authorities to reduce the risk for oil spills associated with this tanker traffic, like frequent updating of positions of selected ships, tugboats on standby to assist tankers, and pre-identification of suitable harbors along the coast where tankers in distress could be guided or towed. More depots for oil spill equipment have also been established along the coast. Although these are precautions that point in the right direction, the equipment and preparedness to face a serious tanker accident are still far from good enough.

In a global perspective, Norwegian oil spill preparedness for temperate conditions in open waters is considered good or very good. For open water summer conditions in the ARCOP study area, the same combating techniques could be used. For open water winter conditions in the ARCOP study area, these techniques most likely could be adapted (winterized). Another important aspect is operation in darkness and during low visibility. The process to improve operations under such conditions has started, not due to the ARCOP transportation scenario, but as a preparation for exploration drilling in the north.

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

On behalf of the oil industry, NOFO is basing their oil spill contingency mainly on the Transrec system, where a high capacity weir skimmer with internal pump is the most common recovery unit. For more viscous oils a so-called Hiwax skimmer (*Figure 4.14*) could replace the weir skimmer. None of these skimmers have been designed to process ice, but both skimmers could be used under open ice conditions as long as ice is not obstructing the inflow of oil.

Figure 4.14 The Hiwax skimmer.

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

Another Transrec development underway for recovery of oil in ice covered waters is motivated by the preparation for oil production in ice in the Sakhalin area and for the Prirazlomnoye offshore oil field, which is close to the ARCOP loading terminal in Varandey. This design will be maneuvered like an ROV and will be able to operate under ice through the moon pool of a supply vessel. It is much too early to know whether this will be a useful tool, but it is appealing to have the possibility of operating in 100% ice coverage, even with pressure in the ice.

4.1.8 Developments in Finland

For a long time the Finnish Environmental Institute (FEI or SYKE) has encouraged manufacturers and designers to develop oil recovery devices for cold conditions, and the institute has also itself developed new technology for oil recovery. Several of the products developed over the years are now in operative use. In the following the more interesting technologies that are either finished or underway are mentioned.

For open water conditions, the stiff brush skimmer technology has proved to be a reliable oil cleanup method, especially at low temperatures and for heavy oil. With this method, oil-laden water runs through rotating brush units and oil is swept up by the brushes. Floating oil adheres to the brushes, which are scraped clean. The oil is then pumped into the vessel storage tanks. In addition to its high capacity for mechanical recovery, this method collects only small quantities of water. These recovery units are produced in various configurations, either permanently fitted into the vessel, or as over the side or bow units.

<u>The LORI Ice Cleaner</u>
The Ice Cleaner developed in the early 1990s was a result of this effort. This is a unit, which is operated and pushed by a vessel through broken ice. The displacement is about 25 tons, and the operating principle is a combination of a submerging inclined plane and brush skimmer in two stages to separate ice from oil and water prior to the final recovery, see
Figure 4.10 Other concepts. LORI brushpack (left), LORI Ice Cleaner (middle), Arcticskim (right).
from Solsberg and McGrath (1992).

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

<u>Air Plume</u>
The pneumatic air method to steer oil under ice into a pre-selected direction was tested in Finland in 1993. The air was pumped under the ice and released near the bottom of the ice sheet, and had a minor effect on the oil slick. In 2002 new experiments were conducted where the pneumatic air was released deeper under the ice, from 10 m to 30 m water depth (Rytkönen, 2003). This will cause a significant vertical water flow due to the rising bubble plume. When the vertical flow hits the ice cover, it changes direction and induces a horizontal eddying flow. As expected, the flow was strongest close to the plume centre, and decreased with distance. Higher air discharge and outlet depth both increased the velocities. The strongest measured flow was achieved with 4 m^3 air per minute at 30 m deep, creating a maximum average water velocity of about 40 cm/s. This could be enough to clean oil from the bottom of the ice, but will depend on the characteristics of the under ice surface. ExxonMobil has become interested in this technique, presumably for the production of oil under development in the Sakhalin area. The company is currently planning to perform more tests to investigate the possibility to develop an efficient oil deflection method for under ice slicks.

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

The Vibrating Unit

A novel *Ice Vibrating Unit* was designed for ice conditions by the FEI to be used in the presence of broken ice and brash ice in a typical shipping channel in Finnish waters. This is essentially a channel that is broken regularly through level, land fast ice for merchant vessels, including oil tankers.

The idea of the ice-vibrating unit is to submerge ice (and oil) by an inclined plane pushed through the ice field by a vessel. The inclined plane is a vibrating grid that forces the submerged rubble ice to move upside down and possibly to rotate by moving the grid. By increasing the relative movement between oil-covered ice blocks and the water, an objective of early model tests was to improve the overall flushing of ice blocks, which in turn would enhance the separation of oil from ice. The unit is designed to withstand the forces from the broken ice in the shipping lanes when moving at about 3 knots. The downside of this procedure is that the higher the speed, the less oil will be picked up. This probably is a matter of priority during the development of the unit.

The tests of the ice-vibrating unit were first conducted at a laboratory scale in 1997. The first full-scale test was with oil in rubble ice conditions in a shipping channel in 2001. Some heavy fuel oil was pumped into the sea. The main principle was confirmed here, and after some modifications, new tests were performed in the spring 2002. After further modifications the system was tested again in March 2003 in broken ice (without oil) where the system functioned satisfactorily, see *Figure 4.15*.

Figure 4.15 The Vibrating Unit attached to the side of the vessel Linja.

By changing the design, almost the total length of the grid now works as an oil separator, while the effective length on the prototype unit was approximately 50 - 70 % of the total grid length. Lampela (2003) referred that it has been decided to install vibrating units on a fairway service vessel and two Coast Guard patrol vessels. The length of the new units is 14.5 meters and the width is 2 m, compared to the dimensions of the prototype unit on board the MV Linja, which were 9.6 m and 1.0 m, respectively. Furthermore, a 4 m wide unit has been designed as an option for the asymmetric Finnish icebreaker – a design study by Kvaerner MasaYards.

The Finish authorities rely on the installations to be used on service and patrol vessels. However, the information from FEI indicates that there have been made no efforts to make the vibrating unit system suitable also in arctic conditions found in the Pechora and Kara Sea. Ice conditions in the ARCOP study area are characterized by drifting ice. This implies that unlike in the Baltic Sea, new shipping lanes may have to be broken all the time through fairly thick ice. The ice in such a shipping lane would be different from shipping lanes in the Baltic Sea filled with brash ice, and the typical size of ice pieces mixed with the oil would probably be larger.

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4.2 IN-SITU BURNING

4.2.1 Introduction

For removing oil spilled in ice-infested waters, in-situ burning is one of the practical options. With respect to countermeasures in any environment (open water and ice-covered water), the suitability of burning the oil depends on the oil characteristics and the behaviour of spilled oil in the ice environment. In-situ burning as a spill response technique is not new and has been used for a variety of oil spills. Since the late-1960s both laboratory, tank and field studies have been conducted in order to support drilling operations in arctic waters.

Ian Buist (2000) has made a comprehensive literature survey on in-situ burning of oil spills in ice for the International Oil and Ice Workshop 2000. The paper contains a concise description of the fundamental in-situ burning issues. Excerpts are given in the following chapters.

In general, in-situ burning techniques and methods have proved very effective for oil spills in ice and have been used successfully to remove spilled oil in ice-infested waters resulting from storage tank and ship accidents in Alaska, Canada and Scandinavia.

In-situ burning is particularly suited for use in ice conditions, sometimes offering the only option for removal of surface oil. In-situ burning of thick, fresh oil slicks can often be initiated very quickly by igniting the oil with simple devices such as an oil-soaked sorbent pad. Oil from the water surface can be removed by in-situ burning efficiently and at high rates. It is reported that removal efficiency for thick slicks can exceed 90%. Oil removal rates of 2000 m^3/hour can be achieved with a fire area of about 10 000 m^2. Mechanical recovery comprising transfer, storage, treatment and disposal is more complex compared to the use of towed fire containment boom to capture, thicken and isolate spilled oil, followed by ignition. However, there are limitations for application of the in-situ burning technique: when oil slicks emulsify and the water content of stable emulsions exceeds about 25%, most slicks are not ignitable. In this particular case further research is needed to overcome this limitation. In addition there are two other major concerns:

1. the fear of causing secondary fires that threaten human life, property and natural resources
2. the potential environmental and human-health effects of the by-products of burning (e.g. smoke, etc.)

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

4.2.2 Requirements for ignition

In order to burn the oil spilled on water, three elements must be present:

- fuel
- oxygen
- and a source of ignition

The oil must be heated to a temperature at which sufficient hydrocarbons are vaporized to support combustion in the air above the slick. It is the hydrocarbon vapours above the slick that burn, not the liquid itself. The temperature at which the slick produces vapours at a sufficient rate to ignite is called the *flash point*. The fire point is the temperature a few degrees above the flash point at which the oil is warm enough to supply vapours at a rate sufficient to support continuous burning.

4.2.3 Heat transfer back to slick

The rising column of combustion gases carries most heat from the burn away, but a small percentage (about 3%) radiates from the flame back to the surface of the slick. This heat is partially used to vaporize the liquid hydrocarbons, which rise to mix with the air above the slick and burn; a small amount transfers into the slick and eventually to the underlying water.
Once ignited, a burning thick oil slick reaches a steady state where the vaporization rate sustains the combustion reaction, which radiates the necessary heat back to the slick surface to continue the vaporization.

4.2.4 Flame temperature and total heat fluxes

Flame temperatures for crude oil burns on still water are about 900°C to 1200°C (Fingas et al., 1995). The temperature at the oil slick/water interface is never more than the boiling point of the water and is usually around ambient temperatures. There is a steep temperature gradient across the thickness of the slick; the slick surface is very hot (350°C to 500°C) but the oil just beneath it, is near ambient temperatures. Total heat fluxes generated by an oil pool fire are in the order of 100 to 250 kW/m^2 measured both inside and at the periphery of the fire (Ross, 1997; Walton et al., 1997). The higher heat flux values are associated with windy conditions that promote better combustion.

4.2.5 Importance of slick thickness

The key oil slick parameter that determines whether or not the oil will burn is slick thickness. If the oil is thick enough, it acts as insulation and keeps the burning slick surface at a high temperature by reducing heat loss to the underlying water. This layer of hot oil is called the "hot zone". As the slick thins, more heat is passed through it. Eventually enough heat is transferred through the slick to allow the temperature of the surface oil to drop below its fire point, at which time the burning stops.

4.2.6 Vigorous burning phase

At the final stages of burning, the “hot zone” approaches the water surface. No longer insulated by a thick slick, the temperature of the water directly beneath the slick increases. For slicks on calm water with no current, as may be the case in a drifting, broken ice cover, or in melt pools, the temperature of the underlying water can increase to the boiling point. When the water begins to boil, the steam vigorously mixes the remaining oil layer and ejects oil droplets into the flames. This results in increased burn rate, flame height, radiative output and foaming. This is called the "vigorous burning phase". This phenomenon has not been observed in burns using a towed boom, probably because the water beneath the slick does not stay there long enough to boil.

4.2.7 Effect of evaporation on slick ignition

Extensive experimentation on crude and fuel oils with a variety of igniters under various environmental conditions has confirmed the following “rules-of-thumb” for relatively calm, quiescent conditions:

- the minimum ignitable thickness for fresh, volatile crude oil on water is about 1 mm
- the minimum ignitable thickness for aged, un-emulsified crude oil and diesel fuels is about 3 to 5 mm
- the minimum ignitable thickness for residual fuel oils, such as Bunker C or No. 6 fuel oil, is about 10 mm

- once 1 m^2 of burning slick has been established, ignition can be considered accomplished.

4.2.8 Other factors affecting ignition

Aside from oil type, other factors that can affect the ignitability of oil slicks on water include wind speed, emulsification of the oil, and igniter strength. Secondary factors include ambient temperature and waves.

- The maximum wind speed for successful ignition of large burns has been determined to be 10 to 12 m/s
- For weathered crude that has formed a stable water-in-oil emulsion, the upper limit for successful ignition is about 25% water. Some crude oils form meso-stable emulsions that can be easily ignited at much higher water contents. Paraffinic crude oils appear to fall into this category (Fingas et al., 1997)
- If the ambient temperature is above the oil's flash point, the slick will ignite rapidly and easily and the flames will spread quickly over the slick surface. Flames spread more slowly over oil slicks at sub-flash temperatures.

4.2.9 Oil burning rates

The rate at which in-situ burning consumes oil is generally reported in units of thickness per unit time (mm/min is the most commonly used unit). The removal rate for in-situ oil fires is a function of fire size (or diameter), slick thickness, oil type and ambient environmental conditions. For most large (>3 m diameter) fires of unemulsified crude oil on water, the “rule of-thumb” is that the burning rate is 3.5 mm/min. Automotive diesel and jet fuel fires on water burn at a slightly higher rate of about 4 mm/min.

4.2.10 Residue amounts and burn efficiencies

Oil removal efficiency is a function of three main factors: the initial thickness of the slick, the thickness of the residue remaining after extinction, and the area coverage of the flame. The following rules-of-thumb apply for the residue thickness at burn extinction:

- for pools of un-emulsified crude oil up to 10 to 20 mm in thickness, the residue thickness is 1 mm
- for thicker crude slicks the residue is thicker; for example, 3 to 5 mm for a 50 mm oil slick
- for emulsified slicks the residue thickness can be much greater
- for light and middle-distillate fuels the residue thickness is 1 mm, regardless of slick thickness

Other, secondary factors include environmental effects such as wind and current herding of slicks against barriers and oil weathering. Wind and current can herd a slick against a barrier, such as a towed boom, thus thickening the oil for continued burning. As little as a 2 m/s wind is capable of herding oil to thickness that will sustain combustion. The phenomenon of “uncontained” in-situ burning in broken ice conditions is based on the requirement of a self-induced wind (drawn in by the combustion process and the rising column of hot gases), to "herd" and keep an uncontained slick at burnable thickness. Current can also dramatically increase burning efficiency (i.e., reduce the amount of burn residue) by herding burning oil against a barrier. The detrimental effects of current can include entrainment of residue beneath a floating barrier as the residue density and viscosity increase during the burn process, and over-washing of the burning slick, causing extinction of the flames. Excessive waves can also have a negative effect on the burning process.

The residue from a typical, efficient (>85%) in-situ burn of crude oil 10 to 20 mm thick is a semi-solid, tar-like layer. For thicker slicks, typical of what might be expected in a towed fire boom (about 150 to 300 mm), the residue can be a solid. The cooled residue from thick (>100 mm), efficient in-situ burns of heavier crude oils can sink in fresh and salt water (Ross, 1996).

4.2.11 Flame spreading

Flame spreading is a crucial aspect of effective in-situ burning. If the fire does not spread to cover a large part of the surface of a slick, the overall removal efficiency will be low. There are two ways in which flames spread across a pool of liquid fuel:

1. radiant heating of the adjacent liquid oil warms it to its fire point
2. hot liquid beneath the flame spreading out over the surrounding cold fuel.

As oil evaporation (or weathering) increases, flame spreading speed decreases. This is because the difference between ambient temperature and the oil's flash point increases, requiring additional heating of the slick to raise the temperature of the surface of the slick. Flame spreading speeds increase with increasing slick thickness due to the insulating effect of the oil layer. For a constant slick thickness and flash point, increasing viscosity reduces flame-spreading speed. Downwind flame spreading increases with increasing wind speed. This is likely due to the bending of the flame by the wind enhancing heating of the slick. Flames tend to spread straight downwind from the ignition point without significant crosswind spread. Flame spreading upwind is slow, although the presence of a barrier or edge that provides a windbreak can permit rapid upwind or crosswind spreading. The presence of current and regular waves (or swell) does not seem to affect flame spreading for un-emulsified oils, but choppy or steep waves have been noted to curtail flame spreading.

4.2.12 Flame heights

The thick black smoke that is produced, making it difficult to estimate flame heights, obscures flames from large oil fires. However, the best available data suggests the following rules-of-thumb:

- For small and medium fires having diameters less than 10m, fire heights are twice the fire diameter
- For larger fires the ratio declines, approaching a value of one for very large fires.

4.2.13 Effects of emulsification

Although the formation of water-in-oil emulsions is not as predominant a weathering process in spills in ice as it is for spills in open water, emulsions could be formed in some situations (i.e. a sub-sea blow-out in broken ice, grinding of ice-ice with oil in between). Emulsification of an oil spill negatively affects in-situ ignition and burning. This is because of the water in the emulsion. Water contents of emulsion could reach the 60% to 80% range with some up to 90%. The oil in the emulsion cannot reach a temperature higher than 100°C until the water is either boiled off or removed. The heat from the igniter or from the adjacent burning oil is consumed to boil the water rather than heat the oil to its fire point.

A two-step process is likely involved in emulsion burning: 1) "breaking" of the emulsion, or possibly boiling off the water, to form a layer of unemulsified oil floating on top of the emulsion slick, and 2) subsequent combustion of this oil layer.

High temperatures are known to break emulsions. Chemicals called "emulsion breakers", common in the oil industry, may also be used. For stable emulsions the burn rate declines significantly with increasing water content. The decrease in burning rate with increasing water content in the emulsion is decreased further by evaporation of the oil. The following rules-of-thumb can summarize the effect of water content on the removal efficiency of weathered crude emulsions:

- small effect on oil removal efficiency (i.e., residue thickness) for low water contents up to about 12.5% by volume
- a noticeable decrease in burn efficiency with water contents above 12.5%, the decrease being more pronounced with weathered oils
- no burn efficiency for emulsion slicks having water contents of 25% or more. Some crude oils form meso-stable emulsions that can be burned efficiently at much higher water contents. Paraffinic crude oils appear to fall into this category (Fingas et al., 1997).

Extinction of burning emulsions can be initiated by foaming action of the burning slick. The foaming is likely associated with boiling of water. Burning emulsion slicks may foam and extinguish over one area of their surface, but be re-ignited later by adjacent flames. This can result in sudden and rapid flare-ups of flame near the end of an emulsion burn. Compared to un-emulsified slicks, emulsions are much more difficult to ignite and, once ignited, they display reduced flame spreading and more sensitivity to wind and wave action.

4.2.14 Environmental and human health risks

The environmental and human risks must also be considered when applying in-situ burning techniques. This section describes the main risks associated with in-situ burning of oil spills and the safety measures used to overcome these risks. Humans and the environment may be put at risk by:

- flames and heat from the burn
- emissions generated by the fire
- residual material left on the surface after a burn

Flames and heat

Flames from in-situ burning pose a risk of severe injury or death to both responders and wildlife. The threat is obvious and needs no elaboration. Thus this section focuses on the problem of the heat radiated by the burn. Risks exist both in normal operations and abnormal conditions such as vessel breakdown and boom failure. The risk to oil spill responders at the spill site is the main concern because the risks to the general public must be eliminated through the use of an exclusion zone surrounding the spill site.

Effects of heat on spill responders

In-situ burning of oil produces large amounts of heat, which is transferred into the environment through convection and radiation. About 90% of the heat generated by in-situ combustion is convected into the atmosphere. The remainder is radiated from the fire in all directions, but there is most concern with heat radiated towards responders, causing heat exhaustion and burns to unprotected skin.

The potential for causing injury to exposed workers is a function of both the level of incident radiation and the duration of exposure. Wood will char if positioned about half a fire diameter from the edge of an oil burn. The "safe approach distance" to an in-situ oil fire is from 2 to 4 times the diameter of the fire depending on the duration of exposure, as shown in *Table 4.1*. Conservatively, it is assumed that the safe approach distance to the edge of an in-situ oil fire is approximately 4 fire diameters.

It is important to recognize that the oil contained in a towed boom is relatively thick in the early stages of a burn and that this thickness is maintained through towing. If the towing of boom stops or becomes too slow, or the boom breaks, this thick layer would spread quickly to cover an area several times larger than of the boomed oil. This will increase the fire diameter, the heat flux from the fire, and the need for workers to move further away from the fire to avoid discomfort or injury.

Table 4.1 Safe approach distances for in-situ oil fires (after Buist, I., 2000)

Exposure Time	Safe Approach Distance for Personnel
Infinite	4 x fire diameter
30 minutes	3 x fire diameter
5 minutes	2 x fire diameter

Environmental effects of heat

Heat from the flames is radiated downward as well as outward, and much of the heat that is radiated downward is absorbed by the oil slick. Most of this energy is used to vaporize the hydrocarbons for further burning, but a portion of the heat is passed to the underlying water. In a towed-boom burn or in a stationary boom situation in current, the water under the slick does not remain in contact with the slick long enough to be heated significantly. However, under *static conditions* (the slick does not move relative to the underlying water - for example in a melt pool) the upper few inches of the underlying water may be heated in the latter stages of the burn. In a prolonged static burn, the upper few millimetres of the water column may be heated to near boiling temperatures, but the water several cm below the slick has been proven to be unaffected by the fire.

Heating may eliminate the small life forms that exist in the surface layer of the water, but the areas involved are small and it seems that the lost biota will quickly be replaced, with negligible overall impact. The conclusion is that the environmental impact of the heat from an in-situ burn is less important.

Emissions generated by the fire

The components of the smoke from an in-situ burn and their approximate proportions are shown in *Table 4.2*. (N.B. the composition of burn emissions varies with the type of oil burned and the size of the burn). Smoke and particulate material is the main concern and is dealt in more detail:

Table 4.2 Airborne Emissions from In-Situ Petroleum Fire (after Buist,I., 2000)

Constituent	**Quantity Emitted** [b] **kg emission / kg oil burned**
Carbon dioxide (CO_2)	3
Particulate matter	0.05 – 0.20 [c,d]
Carbon monoxide (CO)	0.02 – 0.05
Nitrogen oxides (NO_x)	0.001
Volatile organic compounds (VOC)	0.005
Polynuclear aromatic hydrocarbons (PAH)	0.000004

[a] updated from ref. 1 based on Kuwait pool fire (Allen and Ferek, 1993) and NOBE data (Ross et al. 1996)
[b] Quantity will vary with burn efficiency and composition of parent oil
[c] for crude oils *soot yield* = 4 + 3 lg(*fire diameter*) ; *yield* in mass %, *fire diameter* in cm (Fraser et al., 1997)
[d] Estimates published by Environment Canada are considerably lower, ca. 0.2 to 3 % for crude oil (Fingas, 1998)

Smoke

Smoke is the main concern. Carbon smoke particles are responsible for providing the characteristic black colour of the plume rising from an in-situ burn. The smoke is unsightly, but more important the smoke particles can cause severe health problems if inhaled in high concentrations. Of particular concern are persons with special sensitivities, such as the very young, the very old, pregnant women, and persons with asthma, pulmonary and vascular diseases. In addition, carbon smoke particles serve to carry other adsorbed toxic materials (e.g., PAHs; PAH = polycyclic aromatic hydrocarbons) deep into the respiratory tract. Smoke particles are also of concern because they obstruct visibility and hence may pose a safety hazard to operators of ships, aircraft and motor vehicles in the immediate vicinity of the fire.

Particle size, PM-10

Smoke particles are formed as a result of the agglomeration of tiny specks of unburned carbon. The particles vary greatly in size. From a health perspective the focus is on those particles that are small enough to be inhaled into the lungs, i.e. particles smaller than 10 μm in diameter. Health scientists call these PM-10s (PM stands for "particulate matter"). PM-10s make up approximately 90 percent of the mass of particulate emitted from an in-situ burn. The average particle size of the soot is about 1 μm.

Health standard

One exposure standard that exists for PM-10s is the U.S. National Ambient Air Quality Standard (NAAQS) which states that PM-10 exposures of more than 150 μg /m^3, averaged over a 24-hour time period, can cause mild aggravation of symptoms in persons with existing respiratory or cardiac conditions, and irritation symptoms in the healthy population.

In the absence of any data, however, in-situ burn experts, health experts and regulators have agreed to adopt a more conservative standard for in-situ burning requiring that concentrations averaged over one hour should not exceed 150 μg /m^3.

Threat to and safeguards for workers

Exposure concentrations in the immediate vicinity of the fire will usually exceed public health standards both in-plume and at ground level, but are within acceptable levels according to industrial safety standards. In any case, safeguards are required to protect workers. These should include:

1. Screening process

It is important to screen potential workers in the burning operation for conditions such as asthma that would make them sensitive to elevated concentrations of particulate matter in the air.

2. Respiratory protection

Respiratory protection, eye protection and protective clothing should be available for all personnel involved in the burning operation.

3. Effects on Visibility

The precaution is to contact local authorities to notify them of the potential visibility problem and identify the area(s) potentially affected. Notify local air traffic control, vessel traffic control, police, and fire and transport authorities.

4.2.15 Residual material left on the surface after a burn

This section deals with the residue remaining following a burn. This residue will be much reduced in volume from the amount of oil at the beginning of the burn; and, it will be altered in terms of the chemical composition and physical properties and possibly the fate of the oil (i.e., the residue may sink rather than float). The environmental risks associated with burn residue will depend on its fate. Residue that floats may continue to pose a threat to wildlife and shorelines. Residue that submerges may pose a threat to benthic communities. Both may still pose some risk of toxicity or contamination to water column dwellers.

Chemical composition
Crude and refined oils contain a broad range of hydrocarbons. Crude oils contain the broadest range of compounds from the lightest alkane to the heaviest asphaltene, while refined products such as diesel fuel or residual fuel contain a narrower range of components. During an in-situ burn, both light and heavy components of the oil are combusted, but the lighter, lower-boiling-point (LBP) hydrocarbons are preferentially removed and the heavier, higher-boiling-point (HBP) components are concentrated in the residue. Therefore the residue remaining at extinction will differ in composition and properties from the parent oil. In laboratory test burns of thick slicks (50 to 150 mm) of crude oils, the residues remaining following natural extinction of the burn were completely stripped of lower boiling point compounds and were largely depleted of middle boiling range hydrocarbons. Thus, burn residues can be expected to be depleted of the more volatile, lower boiling point fraction which includes many of the more toxic and hazardous components of crude oils (benzene, naphthalene, benzopyrenes). Hence, burn residues should be less toxic than the parent oils and therefore less hazardous.
In general terms, the precise chemical composition of the residue will depend on the composition of the parent oil, the degree of weathering, and the efficiency of the burn. Several studies have shown that the levels of PAH's in residue from burns of relatively thin slicks are greater than in the parent oil, by as much as 40%. Considering the volume reduction accomplished by in-situ burning, the total amount of PAH's remaining in the residue is a fraction of what was in the slick before ignition.

Physical properties

The physical properties of burn residues are important from the perspectives of both their environmental fate and effects and their recoverability. Three properties are critical: state, density and stickiness.

1. State

The state of burn residue is important because it determines the possibility for collection and removal by mechanical means. Liquid residues could be removed by conventional methods used to recover spilled oil. Solid or semi-solid residues will require specially designed recovery methods, including manual methods.

2. Density

Density of burn residue is important because it determines whether residues will float or sink. Experience to date is that most residues are less dense than water when the fire extinguishes and float at the surface for a time, but residues of many oils may sink as they cool. The potential for sinking is important from both an environmental and a cleanup point of view. From an environmental point of view, the potential for sinking is regarded as a disadvantage, because of concern about potential effects of the sunken residue on the seabed community. It is for this reason that burning has been prohibited near coral reefs in some jurisdictions. The potential for residue sinking is a serious problem for responders if the residue must be collected, because it means that all residues must be collected soon after the fire extinguishes itself while the residue is still warm and buoyant.
The likelihood that the residue from an in-situ burn will sink is only poorly understood. Early in-situ burning studies with relatively thin slicks (i.e., 10 to 20 mm) suggested that the residues would have higher density than the parent oils, but would probably float, even in freshwater.
However, recent experience with real spills of heavy oils suggests that burn residues of these crude oils will sink, even in salt water. Preliminary laboratory tests suggest that residues from efficient burns of thick slicks of many heavier crude oils may sink in both salt and fresh waters.

3. Stickiness

Stickiness is important from an environmental point of view because of the potential for affecting marine wildlife. Liquid or sticky, semi-solid residues pose environmental risks that are similar to those posed by the parent oil, in that by adhering to birds' feathers they affect the birds either by disrupting the waterproofing of their plumage or through chemical toxicity if ingested while preening. Residues from crude oils are likely to be either sticky semi-solids or non-sticky solids, depending on factors such as the extent of weathering of the oil prior to the burn and the efficiency of the burn. Residues from light and middle distillate fuel oils are similar to the parent oil.

Environmental risks from burn residues

The chemical toxicity of burn residues appears to be low. In tests conducted at NOBE water taken from beneath the oil slick contained only low concentrations of hydrocarbons (<13 ppb total oil) and were not toxic to bivalve larvae or juvenile fin fish (EVS 1995). More recently, Environment Canada scientists developed methods for conducting toxicity tests on water-accommodated fractions from burn residues. Results showed that these water-accommodated fractions were not toxic to a variety of standard test organisms, including sea urchin gametes and three-spine sticklebacks (Blenkinsopp et al 1997).

Some of the environmental risks associated with sinking residues have been demonstrated in actual spills, the M/T Honan Jade (South Korea, February 1983) and the M/T Haven (Italy, April 1991). In the former case, sunken residues disrupted crab mariculture operations (Moller 1992). In the latter case, an area of the seabed of some 141 km^2 was measurably contaminated with sunken residue (Moller 1992), to the extent that most local trawl fishermen abandoned it for a period of two years (Martinelli et al. 1995).

Precautions and impact mitigation

Burn residues may or may not pose a significant environmental hazard depending on their composition and physical properties. Liquid or semi-solid residues should be collected because they may pose a threat to wildlife and property. Residues that show signs of sinking should be collected out of concern for the benthic environment, mariculture installations and demersal fisheries. Indeed, current thought is that all residues, regardless of properties should be collected. There is insufficient information on the potential effects of residues on sea bottom communities at the present time to suggest intentionally allowing residue to escape and sink.

4.2.16 Burning spills in ice and snow

In-situ burning has been considered as a primary arctic spill countermeasure, from the start of offshore drilling in the Beaufort Sea in the mid 1970s. Field trials at that time demonstrated that on-ice burning offered the potential to remove almost all of the oil present on the surface with only minimal residue volumes left for manual recovery (Norcor, 1975). Since then many studies and trials have been undertaken to investigate and document burning of large crude oil slicks (both fresh and emulsified) in open water, slush ice, and broken drift ice and test basins.

Oil on water among broken ice

In broken ice conditions the use of in-situ burning is controlled, to some degree, by the concentration and types of ice present. In general, the applicability of burning can be divided into three broad ice concentration ranges:

- open water to 3 tenths
- 3 to 6-7 tenths
- 6-7 to 9+ tenths

In the lowest range, the oil's spread and movement will not be greatly affected by the presence of the ice, and open water in-situ burning techniques can be applied. This would generally involve the collection of slicks with fire boom operated by tow vessels, and their subsequent ignition. The ice concentration range from 3 to 6-7 tenths is the most difficult from an in-situ burning perspective. The ice will reduce the spreading and movement of the slick, but not yet to the extent that it is containing the oil. The deployment and operation of booms in this ice concentration would be difficult, if not impossible. Unattended booms could be deployed into the ice by helicopter, but the amount of oil that could be collected by this technique is unknown. In the highest ice concentrations, the ice floes are touching and contain the oil; if slicks are thick enough they can be burned effectively in these ice concentrations (SL Ross and Dickins, 1987; Singsaas et al., 1994).
In-situ burning of oil spilled in broken ice during break-up will likely be easier than in the same ice concentration during freeze-up. In fall, the sea is constantly freezing, which generates significant amounts of slush ice which can severely hamper containment and thickening (naturally, or with booms) of slicks for burning; it is dark for much of the day, and it is cold, and only going to get colder with the onset of winter. During break-up, there is much less slush and brash ice present, the ice floes are deteriorating and melting, there is 24-hour daylight, and finally the temperatures are increasing.

Oil on solid ice
In-situ burning is the countermeasure of choice to remove oil pools (created in the spring by vertical migration from an encapsulated oil layer or by drilling into an encapsulated oil lens in the ice sheet) on ice. There is a high degree of knowledge on the ignition and burning of oil on melt pools. For large areas of melt pools, helicopters deploying igniters would be used to ignite individual pools of oil. For smaller areas, manual ignition techniques could be employed. Wind will generally blow oil on melt pools to the downwind ice edge, where it will be herded to thickness of approximately 10 mm. Individual melt pool burn efficiencies are thus on the order of 90%. The overall efficiency of in-situ burning techniques in removing oil from the ice surface ranges from 30 to 90%, with an average in the 60 to 70% range, depending on the circumstances of the spill (e.g., melt pool size distribution vs. igniter deployment accuracy, film thickness, degree of emulsification, timing of appearance vs. break-up, etc.). For areas where the oil surfaces early in the melt, it could be possible to manually flush and/or recover remaining burn residue. Winds and currents will herd oil in leads to the downwind edge, where it can be ignited and burned. In leads where a current herds the oil against an edge, very high removal efficiencies can be obtained.

Oil in snow
In the case of oil initially spilled on the ice surface and mixed with snow, burning of oiled snow piles can be successfully achieved even in mid-winter conditions. Oiled snow with up to 70% snow by weight can be burned in-situ. For higher snow content mixture (i.e. lower oil content) promoters, such as diesel fuel or fresh crude, can be used to initiate combustion. Also, for lower concentrations of oil in snow, the technique of ploughing oiled snow into concentrated piles may be the only way of achieving successful ignition and burning. In many cases, waiting for the snow to melt could result in thin oil films incapable of supporting combustion and spread over a large ice area. For this technique, the oiled snow is scraped into a volcano-shaped pile, with the center of the volcano scraped down to the ice surface. A small amount of promoter is ignited in the center of the pile. The heat from the flames melts the surrounding inside walls of the conical pile, releasing the oil from the snow, which runs down into the center and feeds the fire. This technique can generate considerable amounts of melt water, which needs to be managed.

4.2.17 Technologies for conducting in-situ burns

This section deals with the technologies available for in-situ burning. Specific pieces of equipment are documented in the categories of igniters and fire containment booms. Numerous variations of the above technologies have been researched, developed and tried on spills in the past, and most of these have had limited success or are no longer available for one reason or another. These obsolete systems are discussed in detail in the larger MSRC report (Buist et al., 1994). The following discusses only technologies that are presently available.

Igniters

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

Surface-deployed igniters

Both portable propane or butane torches, or weed burners, and rags or sorbent pads soaked in diesel have been used successfully many times to ignite oil slicks on water. Propane torches tend to blow thin oil slicks away from the flames and are best utilized on thick, contained slicks. Diesel is the best fuel to soak sorbents or rags for use as igniters; gasoline results in a less powerful flame and can be dangerous to handle.

A variation on this kind of sorbent igniter was used in experiments in the 1980s and involved sorbent wrapped around a short length of Ethafoam (a type of styrofoam) log, dipped in diesel or crude oil, and then sprayed with dimethyl ether (also known as starter fluid). This ignited easily and burned for a long time, even in choppy wave action.

At the Exxon Valdez spill a plastic bag containing gasoline gelled with "Surefire" gelling agent was used successfully to ignite oil during an in-situ test burn. The contents of the bag were mixed by hand, placed on the water surface, ignited and then allowed to drift from the towboat into the contained oil in the fire containment boom being towed behind. The manufacturer of the Heli-torch now offers a more sophisticated version of this approach, consisting of a plastic bottle with a marine flare attached to it with foam floatation collars (Thornborough, 1997). The manufacturer of the Heli-torch also produces a surface-deployable version called the Ground torch. The device consists of a storage drum and pump connected to a hand-held wand for application of the burning gelled gasoline.

Aerially deployed igniters

There are two aerially deployed igniter systems that are currently available for use on oil spills. These are the Dome igniter and the Heli-torch igniter.

1. Dome igniter

The igniter measures approximately 25 cm by 15 cm by 10 cm and weights about 500 g. The unit consists of a wire-mesh fuel basket with solid propellant and gelled kerosene slabs suspended between two metal floats. The Dome unit is intended as a hand-thrown device. The fuse wire is started with an electric ignition system consisting of a 12-volt, spill-proof battery with a gel electrolyte and a heater element. This provides sufficient heat to activate the igniter's fuse wire within two seconds of contact. Once started, the 25 cm long safety fuse allows 45 seconds of delay for throwing the igniter and allowing it to settle within the target oil slick. Once ignited the solid propellant burns intensely for about 10 seconds with temperatures in excess of 1200°C. During this initial burn, the gelled kerosene begins to burn, producing temperatures of 700° to 800°C. The total burn time for the igniter is about 10 minutes. The relatively long burn-time for the igniter helps get the slick lit even if winds temporarily separate the igniter from the heaviest concentrations of oil. Upon completion of the burn, all of the metal components of the igniter remain on the surface of the water and attached to the two floats.

2. Heli-torch

The Heli-torch is a field-proven, helicopter-deployable, gelled fuel igniter commonly used for burning forest slash and for setting backfires during forest fire-control operations. Three models are available with gelled-fuel capacities of 110, 210 and 1100 litres, respectively.
Of these, the 210-liter model has been most extensively tested for use on oil spills. The ignition system is a self-contained unit consisting of a gelled-fuel drum, pump, and motor assembly slung beneath a helicopter and controlled with an electrical connection from the Heli-torch to a panel in the cockpit. The fuel is pumped upon demand to a positive-control shut-off valve and ignition tip. The gelling mix used to thicken the gasoline (or diesel in some cases) is a fine powder that produces a smooth, viscous gel when mixed with liquid fuel. When ratios of 1.8 to 2.7 kg of product to 210 litres of fuel are used, adequate viscosities can normally be achieved within a matter of minutes at room temperature. At sub-freezing temperatures, twice the amount of product is needed. The gelling mix is normally poured through the entry port of the Heli-torch fuel storage drum, which is equipped with a hand crank for mixing. As it exits one or more nozzles, the gelled fuel mixture is lit with electrically fired propane jets. The burning gel falls as a highly viscous stream and quickly breaks up into individual globules before hitting the ground.
Experience has shown that the Heli-torch should be flown at altitudes of 7 to 23 m and with speeds of 40 to 50 km/h. The suggested altitude range is to provide accuracy during the release, to reduce the loss of gelled fuel while burning in the air, and to prevent the blow-out of smaller globules on the surface by down wash when the helicopter is flying at low speeds. The U.S. Federal Aviation Administration approves the Heli-torch ignition system. Recently, the Heli-torch was used in sea trials off the U.K.; part of this trial involved obtaining the appropriate approval to fly the Heli-torch from U.K. authorities.

Fire containment booms

The fire booms that are presently available are summarized below. The available booms are divided into three categories: 1) those constructed of steel, 2) those constructed from fire-resistant fabrics, and 3) those employing active water-cooling. It should be noted that many of the booms described below have been tested by the U.S.C.G. for oil containment (Bitting and Coyne, 1997) and fire resistance in waves, conducted in the fall of 1997 and the fall of 1998 by NIST, in Mobile, AL (Hiltebrand, 1997; Walz, 1999).

1. Steel fireproof booms

The first five steel booms are commercial products (Fireguard, FESTOP, Pocket Boom, Sandvik and Spilltain) and the next two (Dome and Merkalon) are not but their designs are available for construction.

Fireguard boom: This boom is made of short, rigid flotation units connected by flexible, fabric panels. The floats are made from 2 square tubes of AG-3 (a grade of galvanized steel) that is 2 mm thick. These are attached to either side of a 3 mm thick plate of AG-3 that serves as sail and skirt. To minimize heat transfer, the floats and vertical plate are separated by a 1 cm gap and the connections between the two are insulated with asbestos strips. The design draft and freeboard have been calculated so that there is sufficient heat transfer to the water at 1300°C to ensure that the boom does not melt. The connectors consist of stainless-steel mesh enclosed in a 3 ply asbestos fabric coated with a sacrificial PVC covering. Stainless steel cables at the top and bottom carry tension loads, not the flexible panels. Each unit (float + connector) is 5 m long. Each section is connected by means of 5 bolts. After exposure to fire the asbestos strips and flexible connections panels must be replaced.

FESTOP boom: This is a new stainless steel boom produced in France. Little detailed information is available at the present time (Fingas and Punt, 2000)

Pocket Boom: A large offshore stainless steel boom (the Dome boom, see below) was redesigned to serve as a high-strength, durable burn pocket inserted between two lengths of conventional fabric fire boom. The final design of the Pocket Boom has resulted in considerable reductions in cost, weight and size over the original design, and a commensurate increase in ease of handling. With a buoyancy-to-weight ratio of 3, a tensile strength in excess of 1.8 x 105 N (40,000 lbf) and an overall height of 100 cm (39 in.) the boom performs well in its intended operating environment (calm or protected environments with waves up to 1 m in conjunction with commercially-available fabric fire booms. Deployment, sea-keeping, towing and retrieval characteristics of the Pocket Boom are all good. Oil containment tests at Ohmsett showed that the boom will contain oil up to the normal limits (0.4 m/s = 0.75 knots) and can withstand catenary tow speeds up to 1.5 m/s (3 knots) without failure. Exposure to burning oil does not affect the oil containment characteristics of the boom. The boom was exposed to six hours of fire with full-scale heat fluxes: three hours of diesel fires in Mobile, AL (Walz, 1999) and three hours of enhanced propane fires at OHMSETT (SL Ross and AFTI, 1999). The boom survived this heat insult with only minor damage, none of which would have detracted significantly from its oil containment abilities. The final design of the connector section incorporates modifications to ensure that the boom's service life will be at least 1,000,000 wave cycles. This is equivalent to greater than 45 days at sea in Sea State 3.

Sandvik Steel Barrier: This product consists of sheets of cold-rolled stainless steel supported by pontoons of welded stainless steel cylinders. A bolt joint arranged so the boom, according to the manufacturer, can move freely and follow waves connects the boom sections. The manufacturer claims that the product has performed as a conventional containment boom for seven years without maintenance.

Spilltain boom: This product is a resurrection of an older design produced by Bennet Pollution Controls in the early 1980s. The present version consists of galvanized steel floats (foam filled) supporting sheets of galvanized steel connected with a piano-type hinge. The boom was fire and tow tested in the Seattle area in 1995 (McCarthy, 1996) and at OHMSETT in 1996 (Bitting and Coyne, 1997). More recently, it has been fire tested by NIST (Walz, 1999).

Dome stainless steel boom: This boom, developed by Dome Petroleum Ltd. from the late 1970s to the early 1980s, is large and heavy, in order to meet its design criteria of long-term deployment offshore and resistance to ice impacts. Each section (flotation unit plus connector unit) weighs 210 kg and is 2.7 m long, has a draft of 1.2 m and a freeboard of 0.6 m. The boom has been tested extensively for fire-resistance, oil-containment performance in wind and wave conditions, and durability in offshore waters. The boom's design consists of two units, the flotation and the connector. The flotation unit is constructed of Type 310 stainless steel with a steel sail and skirt attached. Each flotation unit incorporates a drain plug and wax-plugged vent pipe (for the release of over pressure air during burning and the ingestion of cold air during cooling). The connector units consist of a pleated, thin gauge 321 stainless steel sheets through which passes a universally jointed box beam. This design is necessary to avoid the self-abrasion problems associated with mineral-based fire resistant cloth when wetted as well as the stress cracking problems associated with simpler steel connector designs. The deployment and retrieval of this boom is a cumbersome process. A newer design, called the Pocket Boom, has been developed (see above).

2. Fire-resistant fabric booms

The following four fire containment booms constructed with fire-resistant fabrics are commercially available.

3M or American Marine Fire Boom: This boom is the most tested and advanced of the fabric booms. It consists of high temperature resistant flotation sections constructed of a 3M-patented ceramic foam. This material is stable at temperatures up to 1100°C. The float core sections are held together with stainless steel knitted wire mesh. These 2 m long flotation sections are laid end to end and surrounded by a continuous blanket of 3M NEXTEL fibres. These non-flammable, poly-crystalline, metal oxide fibres are designed for applications at temperatures up to 1400°C. The NEXTEL layer is wrapped with another layer of stainless steel mesh. This entire package is covered with a sacrificial layer of PVC, which extends below the flotation to form a skirt and double-layered pocket for a galvanized chain tension member. Short, stainless steel seaming bars riveted through the layers underneath the flotation are used to hold the package together. Individual flotation sections are contained in 7-foot long segments separated by a metal clamp fastened through the PVC/mesh/NEXTEL "sandwich". The connector for each 15 m section (consisting of 7 segments) is a stainless steel plate quick connector.
This product has evolved since the mid 1980s as a result of improvements made after a large number of tests. After several successful tests in quiescent waters in the late 1980s, the boom was put to real use during the response to the Exxon Valdez spill in March 1989. Subsequent experimental programs from July 1990 to May 1991 involving quiescent salt-water tank tests led to further design modifications to the boom. In the summer of 1993, 210 m of the 18" version was used to contain the burning oil in trials conducted 45 km offshore of St. John's, Newfoundland. Two discrete burns were conducted in 1 m waves and 2 to 3 m/s winds. The first involved 300 bbls of slightly weathered crude oil burned over a 1.5-hour period. At the end of the burn, the stainless steel in the boom showed signs of fatigue and some of the NEXTEL fabric was missing; however, the boom was considered fit enough for a second burn. One hour and 15 minutes into the second burn several flotation sections from the boom came loose, oil began to leak and the oil pumping was stopped.
After the fire had stopped (180 bbls had burned) the boom was again inspected. A prototype section of the boom that incorporated a middle tension member had lost 3 flotation sections and a number of other sections were completely missing NEXTEL fabric near the vertical stiffeners. It is presumed that the combined action of heat, saltwater and wave action were to blame for this self-abrasion problem.
In 1994, an earlier version of the Fire Boom was used to contain thick slicks of burning ANS (Alaska North Slope) oil and emulsions in a water-filled pit on the North Slope. In each of three burns the oil began to leak through the fabric after about 5 minutes exposure to flames. Similar leakage was reported at tests of the latest version of the boom near Seattle in 1995 (McCarthy 1996). No leakage was reported during test burns offshore England in the spring of 1996. At these tests the boom was reported to survive two short burns (of about 15 minutes each) in 1 to 1.5 m seas. The most recent tests by NIST, showed degradation of the boom during fire testing in a wave tank (Hiltabrand, 1997).

Sea Curtain Fireguard: This boom is designed to be reel-able and self-inflating. As the boom is drawn off the reel, a stainless steel coil springs from a flattened position to a helical position, thus providing flotation and freeboard. The flotation section consists of high temperature, closed cell foam protected by Thermoglas fabric. The coil supports a double layer of Thermotex coated with a sacrificial abrasion resistant coating; this coating will burn away at 300°C. The skirt is constructed of heavy-duty polyurethane coated polyester. Ballast and tensile strength are provided by a galvanized high strength chain in a pocket at the bottom of the skirt. Tow tests have shown that new boom has good towing and wave riding characteristics at speeds up to 0.5 m/s.
The boom has been burn-tested in quiescent, freshwater and saltwater conditions and containment testing has been conducted in a wave tank. After a one-hour exposure to maximum flame temperatures of 900°C the yellow sacrificial coating discolored to a pale green and were noticeably more brittle than the rest of the boom. However, even after 24 hours of exposure to

flames, and despite serious embrittlement of the Thermotex fabric and damage to the inner layer's sacrificial coating, the boom shape, freeboard and configuration were still satisfactory.
Design changes in 1992 proved unsatisfactory in test burns, and the manufacturer has returned to the original design with an enhanced thermal resistant coating on the covers and additional thermal protection for the internal float system. Recent tests in waves and diesel flames by NIST were curtailed after the first hour of a three-hour test protocol (Walz, 1999).

Pyroboom: This fence type boom consists of a sail constructed of Fibrefrax fabric, supported by Inconel wire mesh and coated with silicone rubber bonded to a PVC coated fabric skirt. A chain in a pocket at the bottom of the boom is provided for ballast and tension carrying (this replaces the lead ballast on earlier versions). Flotation is provided by a series of stainless steel hemispheres bolted together above and below the waterline. The floats are filled with a high temperature-resistant, closed cell foamed glass.
The boom has been the subject of both fire tests in quiescent conditions and towing and containment tests in a wave tank. The fire tests lasted 24 hours and peak recorded flame temperatures of 930°C were reached. After 6 hours exposure, the boom still contained oil and remained flexible, although the upper few centimeters of the sail were degraded, with several small holes where the internal Inconel wires were exposed. During the remainder of the 24-hour test the boom continued to contain the burning oil without loss of freeboard. At the end it was found that the baked silicone rubber and fabric in the upper area of the boom was very susceptible to abrasion, although from the waterline to a height of 10 to 12 cm the combination of silicone and burned oil residues had created a flexible and impermeable barrier protecting the boom. Although there were indications of some melting of the foam inside the floats, it was minimal and did not result in any loss of freeboard during the tests. Subsequent towing resulted in significant oil losses at tow speeds above 0.35 m/s; the design has later been modified to include a more flexible skirt, which is reported to have performed well during tests along with non-fire proof boom models of similar design. A revised design survived a three-hour diesel fire tests by NIST in 1998, but did suffer degradation above the water-line (Walz, 1999).

Auto boom - Fire Model: This is a single-point inflatable boom designed for storage and deployment from a reel. It is equipped with a fireproof cover that protects the individual flotation chambers. It is available in a range of sizes suitable for deployment in rivers to offshore. Little test information is currently available on this boom, although it has been exposed to fire at the U.S.C.G. Fire Training Facility in Mobile, Alabama. The boom is claimed to be designed to withstand temperatures in excess of 1093 °C.

3. Water-cooled booms
Three designs of actively water-cooled booms are available. These depend on ambient water pumped through a series of porous hoses to soak an external covering to protect the internal flotation and structural components from the heat of the fire. The available booms are: an Oil Stop model, one produced by Elastec/American Marine, and a third developed by Environmental Marine Technology Associates. All three have been fire tested in waves (Walz, 1999; Stahovec et al., 1999) with the first two passing all tests.

4.2.18 Operational aspects

This section summarizes the resources that are generally required to carry out a safe and effective controlled burn: trained personnel, vessels and aircraft, and fire containment boom and igniters. It is recognized that certain types of burning may not require all of these resources. For example, a situation involving an intentional program to burn a thick, uncontained spill in heavy ice concentrations would not involve fireproof boom. The requirements for trained personnel, and greater detail on the various planning aspects of a burning operation are given in the MSRC report (Buist et al., 1994) and in several in-situ burning manuals (e.g., Allen, 1993; Fingas and Punt, 2000).

Vessels and aircraft

It is important that all vessels used during offshore burning operations have sufficient power to pull the size and length of fire containment boom being considered. Vessels with twin variable pitch propellers are generally preferred; and powers in the 100 to 150 kW (150-200 hp) range are generally sufficient for boom towboats. Large vessels (e.g. 45 m to 60 m supply vessels) make ideal platforms for large containment booms and recovery systems, although such vessels are often over-powered for the needs of pulling boom. Experience has shown that small towing boats in the 8 m to 12 m range are usually much better for controlling a simple track-down and collection operation, particularly when towing speeds need to be maintained for extended periods at 0.4 m/s or less. This size of towing boat can often be transported to the burn area with a larger vessel and deployed and recovered from the larger vessel. Regardless of the size of vessel selected, it is important that its propulsion system permits the vessel to maintain steerage at speeds in the 0.4 m/s and lower range. All vessels should be equipped with explosimeters.

Vessels used for the towing of fire containment boom need to be equipped with properly positioned tow-posts or bitts and adequate lengths of tow line (typically 150 m to 250 m). The towlines need to be strong enough to accommodate the maximum drag forces that would likely be experienced during the towing of boom in open water conditions.

Vessels should also have space to carry fire containment booms to the burn site and space to deploy them. The size and weight of the boom must conform to the deck space and safe load-carrying capacity of each vessel. When the boom-towing boats are too small to carry the entire boom on deck, the fire containment booms may be pulled in a straight-line tow (typically at speeds of about 9 to 18 km/h), or the boom can be transported to the oil collection area with the aid of an additional vessel or barge. In some cases, helicopters may be used to transport boom from shore or from a vessel to the spill site.

With respect to aerial support operations, helicopters will provide an effective platform not only for the possible transport of boom and personnel, but also for the release of igniters onto the oil to be burned. Helicopters will also be of value for the spotting of oil slicks, the directing of vessels to the heaviest concentrations of the spill, and the monitoring of burn effectiveness and smoke plume transport and dispersion. Because of the diversity of tasks for which helicopters may be used and the distances that may have to be travelled offshore, it is important that the type and size of aircraft, the number of engines, and the need for pontoons be properly considered.

It should be recognized that while aircraft will usually play a key role during burning operations, there would be potential burn situations where controlled burning could be initiated without them. For example, as long as surface operations are located a safe distance from property and other vulnerable resources, boats could begin to concentrate and ignite oil with hand-held igniters released from one of the boom towing vessels.

Fire booms

From an operational standpoint, it is the specific location, nature of spillage to be contained and the prevailing ice conditions that will determine the type, size, length and mode of deployment of fire containment boom required. The location and nature of the spill, together with the boom deployment mode will then determine the best type of igniter and the most appropriate scheme for igniting the contained oil. It is important to remember that certain spill scenarios may not require the use of fire containment booms for the effective burning of large quantities of spilled oil, such as spills in higher ice concentrations. In such situations, extra safety precautions may be necessary to avoid unexpectedly large initial burn areas and harmful exposure levels.

When spilled oil has spread to thin layers covering large areas, fire containment boom will be required to concentrate the oil to thickness that will support combustion. If there is a chance that burning could spread to oil outside the towed boom configuration, the contained oil should be towed and ignited well away from the main slick.

U-configurations should be used with 150 m to 300 m of fire boom each. The larger fire containment booms would usually be used during open water conditions, while smaller fire containment booms could be utilized in calmer or ice conditions. Shorter lengths of fire boom may be employed in ice conditions to allow greater manoeuvrability. When wind and sea conditions require the use of large fire containment booms configurations, each U-configuration could be established with a short length of the large boom forming the apex, and with medium-sized boom serving as the deflection boom forward along each leading side of the “U”. In this situation care must be taken to ensure that the connection point between the two boom sizes can withstand the extra loads imposed by the differing wave response characteristics of each boom type. Where it is safe to do so (i.e., in situations where the oil is too thin to burn except where it is thickened within the apex), conventional boom could even be used to deflect oil directly into the fire containment boom portion of the U-configuration.

Some fire containment booms are heavy and difficult to handle. At the same time they are also durable and able to survive burning for long periods in an offshore marine environment. These are typically metal booms. Others are lighter and easier to handle and deploy, but are not designed for long-term deployment offshore or long-term exposure to fire. These usually employ fire-resistant, mineral-based fabric and ceramics. Water-cooled booms are initially relatively light, but become extremely heavy when soaked. As well, the additional complexity of water filtering and pumping must be accommodated with water-cooled booms. It is important for planners and field personnel to anticipate the full range of constraints that may be imposed on the burning operation because of a boom's particular weight and handling requirements. With proper training, experience has shown that fire containment booms can be deployed quickly and used in the same manner as most comparably sized conventional booms. If the fire containment boom is subsequently not used for the combustion of oil, it can be recovered, cleaned and stored for use again at a later time.

When fire containment booms are used to contain burning oil, there will almost always be some degree of thermal stress and material degradation with time. Some fire containment booms have been constructed of materials designed to strongly resist the effect of fire (e.g., steel). Other designs have outer coverings that protect the more fragile underlying material from abrasion during handling and storage, but are destroyed during the early phase of a burn. The underlying materials are refractory in nature and designed to withstand the effects of burning and to remain intact for subsequent burns over a period of several hours. Wave action or contact with ice may accelerate the degradation of these boom types. The actual number of times that a fire containment boom can be used will vary from one product to another and from one application to another. Repeated use will clearly depend on the intensity and duration of the burns, the sea conditions at the time of burning as well as the manner in which the boom is handled during and between each burn. As with some conventional booms, the extent of use and the degree of damage will likely make it cost-effective to discard the boom upon completion of use, rather than attempting to clean and restore it.

When using fire containment booms for multiple burns, the boom should be inspected (at least along segments exposed to the most thermal stress) for any significant breaks, tears, or deterioration, which could result in mechanical failure or loss of containment. Any damaged sections should be repaired or replaced as necessary. If it is necessary to tow used fire containment booms of the sacrificial-coating type to a new site for additional burns, care should be taken to avoid any excessive speeds (more than 2 to 4 knots) even in a straight-line tow. This is because exposed areas where the protective outer cover has burned away will experience more drag and be less resistant to abrasion. Even with metal boom, care should be used in transporting and reusing the boom due to the cumulative effects of mechanical and thermal stress upon its components.

Igniters

Several devices for igniting spilled oil have been described above. Of these, the Heli-torch is the most cost-effective, reliable and flexible system for the aerial application mode. Because of the quantity of gelled fuel that can be carried, it is possible to release ignition fuel as individual ignition points or in a continuous mode. With the Heli-torch operated from a hovering position, it is possible to create very large initial ignition areas for difficult-to-ignite weathered or partially emulsified oil layers.

In spill situations where a helicopter's staging area is distant from the proposed burn region, it may be advisable to locate nearby temporary landing sites where the helicopter could set down between ignitions. A single drum of gelled fuel within the Heli-torch would normally be large enough to support the ignition of numerous individual burns. During an extensive ongoing burn operation it may be helpful to move backup Heli-torches, fuel, mixing facilities and gelling agent to forward landing sites in order to avoid delays because of long transit distances to the primary staging location. Ships with appropriate heli-decks may also be used, if the transport and mixing of the gasoline-based Heli-torch fuel is allowed onboard.

When in-situ burning is relied upon as a cleanup technique in ice covered waters, questions should be addressed before starting activities regarding in-situ burning of oil spills in ice (Smith, N.K. and Diaz, A., 1985):

- What is the likely condition of the oil slick in broken ice fields, i.e. what degree of emulsification should be anticipated in broken ice conditions?
- What degree of containment is afforded by the broken ice fields?
- What slick thickness can be anticipated?
- What burn efficiencies can be expected in a given slick thickness?
- What are the best methods of igniter deployment?
- Under what environmental and oil spill conditions are igniters reliable?
- What is the effect of fallout from the fire on the surrounding environment

4.2.19 References – In-situ Burning

A bibliography of in-situ burning is found at the end of the report.

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4.3 Use of dispersants

A dispersant consists of a mixture of surfactants (surface active agents) in a carrier. When applied to an oil slick the dispersant will be oriented towards the oil-water interface and contributes to formation of small oil droplets that easily will be mixed into the water column and rapidly diluted and biodegraded (*Figure 4.16*).

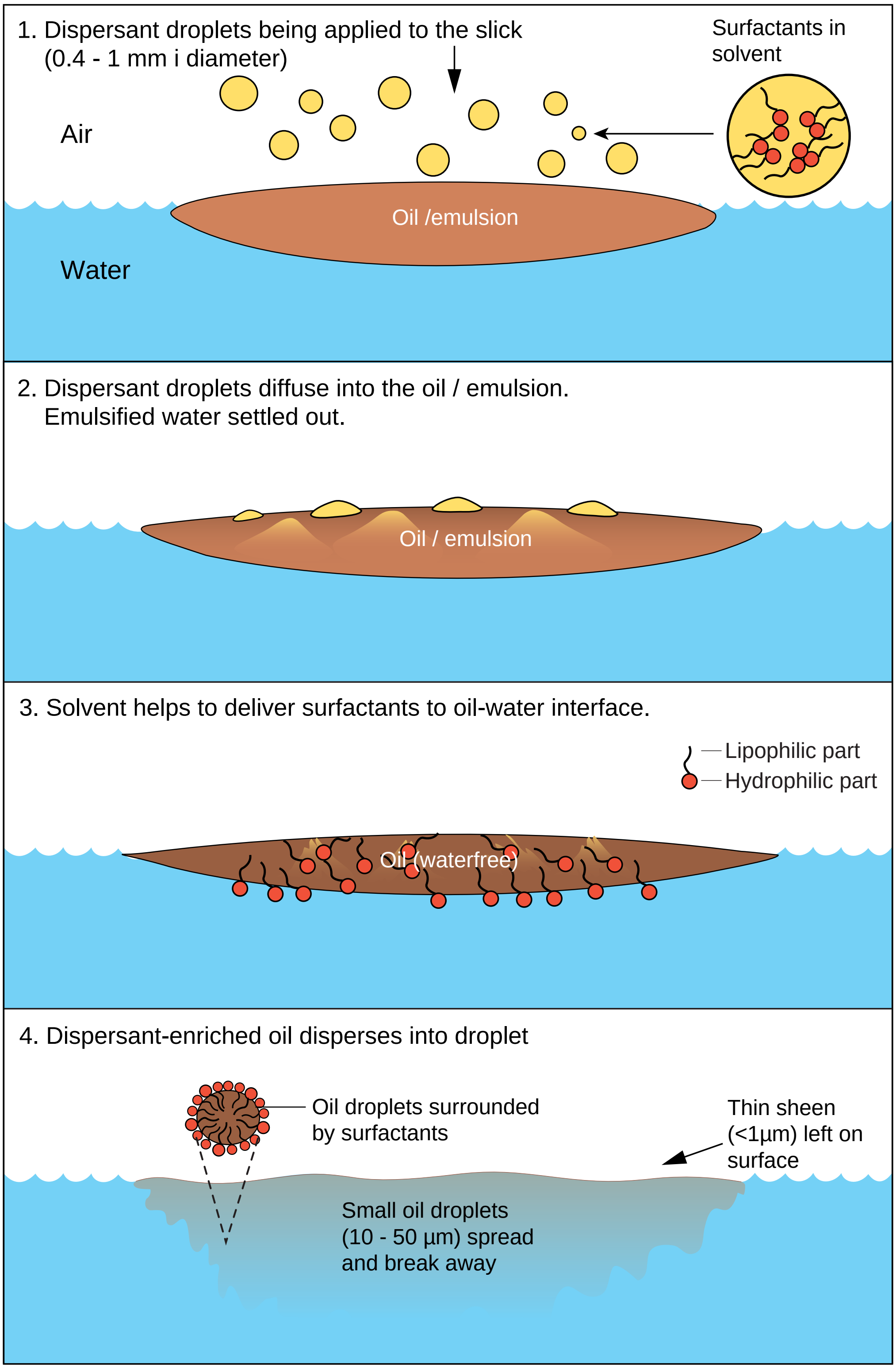

Figure 4.16 Simplified mechanism for dispersant action.

Very little fieldwork has been performed with dispersants and oil in ice. Most of the studies with dispersants under "arctic" conditions have been performed through the ONA-program (Daling et al., 1990) and the DIWO-program (Brandvik et al., 1993). "Arctic" conditions are in this context defined as low temperatures (0 to -20°C) both in the presence of ice and without ice. The effectiveness of dispersants is dependent on temperature and seawater salinity. Dispersants that earlier have shown high effectiveness at high salinity (3.5%) can give very low effectiveness at low salinity (0.5%) (Brandvik et. al., 1993). This is an important aspect under "arctic" conditions as the salinity of the surface water can vary e.g. during melting periods. The effect of low temperature on the effectiveness of a dispersant will vary for different dispersants (Daling et al., 1990). Some products are not very sensitive to temperature reductions, and even positive effects have been registered. Changes in physical/ chemical properties of the oil (pour point etc.) as a result of low temperature can be more significant. The physical/chemical properties of the dispersant itself can also be important for the effectiveness. Especially the viscosity of the dispersant at low temperatures will be important, for instance during application by a helicopter bucket at low temperatures.

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

Experiments with leaching of dispersants from the oil phase to water (Daling et al., 1991), have shown that dispersants can remain in the oil phase for a longer period than previously suggested. It is important to study this effect more in detail, as it is important for defining the potential for use of dispersants under different low energy "arctic" conditions.

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

Earlier calculations and field experiences (Sørstrøm et al., 1994) show that the oil weathering will be slower than in open waters, and considerably slower with high ice concentration and low wave energy. Evaporation, water uptake and viscosity increase will take place at a lower rate in ice. Therefore, the window of opportunity for use of dispersants can be wider under "arctic" conditions than in the North Sea. In addition, increased oil film thickness due to reduced spreading can have a positive influence on the effectiveness of dispersants. Dispersibility testing on specific oil types in accordance with e.g. the Norwegian regulations for use of dispersants is also strongly recommended because the effect of dispersants and the time window of opportunity for effective use of dispersants will be different for different oil types.

4.3.1 Application technology

An important aspect for an effective chemical combat of an oil spill is that the dispersants hit the oil and that the amount of dispersant applied is in correspondence with the amount of oil on the sea surface.

Today three main application methods exist: from boat, helicopter and fixed-wing aircraft. Two main systems for boat application exist, spray booms and spraying guns. In Norway spray booms have been tested in experimental field trials several times, and were successfully used during a field trial in the North Sea in August 1995 (Brandvik et al., 1995). The advantage with boat application is that it gives the possibility for a long-term continuous application due to large storage capacity. The major disadvantage is the relatively long response time compared to helicopter and fixed-wing aircraft. In ice-infested waters boat application can be an advantage under low energy conditions. It is important that the spray booms are installed in the bow to secure that the oil is treated before the bow-wave makes turbulence in the ice/water.

Helicopter application has been tested several times during experimental field trials in the North Sea. During last year field trial a large bucket (3 m^3) was successfully used (Brandvik et al., 1995) (*Figure 4.17*). A new helicopter bucket has been developed in Norway. Due to limited capacity (maximum 3 m^3) helicopter-based systems are recognized to be adequate for relatively small spills in near-shore areas or in ice. The response time can be improved if the helicopter is operating from a platform or a supply ship. The excellent maneuverability of a helicopter makes it a good response tool for application of dispersant in ice-covered waters. Even with an ice concentration up to 50% it should be possible to maneuver the helicopter in that way that most of the dispersant will hit the oil between the ice floes.

The most relevant fixed-wing aircraft system for use in Norway would be a Hercules C-130 equipped with ADDS (Aerial Dispersant Delivery System). The major advantages would be quick response, short application time and good overview of the dispersant distribution within the oil slick. Larger oil slicks can be treated within a relatively short time. However, due to reduced maneuverability compared to a helicopter, fixed-wing aircraft are not so relevant for oil spills in ice-infested waters. The system will probably have the largest potential for larger spills outside the ice edge, i.e. in open waters.

Figure 4.17 Testing of the Norwegian Response 3000 D helicopter bucket.

4.3.2 Scenario-based approach for the use of dispersants in cold and ice-covered waters

In the following section the usefulness of dispersants is evaluated in relation to 3 chosen scenarios.

Dispersant Scenario 1: Open water under winter conditions

The oil is spilled in open water but is drifting towards the ice edge, and after two days the slick has partly migrated into the ice field. After 1-2 weeks the remaining oil/emulsion has drifted together with the ice in the direction of the ice edge again and is released into open water.

The weathering and behavior of the oil during this scenario will be similar to that of oil spill situation in the North Sea or other open waters. This means that use of dispersants has a high potential as an alternative combat method for small to medium oil spills, and in combination with mechanical recovery for larger oil spills. The weathering degree can highly reduce the time window-of-opportunity for use of dispersants. Due to low water temperatures, oils with high wax content and high pour point can solidify, preventing use of dispersants. It is also important that the dispersant supply is close to the spill site, avoiding too long transport time for refilling of dispersant. During winter time there are only few hours of daylight in this area (or no daylight at all) and remote sensing equipment like e.g. FLIR camera is recommended for optimal operation.

Dispersant Scenario 2: Late winter spill in dense drifting ice

The oil is spilled in 70-80% ice coverage from a vessel drifting in the ice field. During the first week the distance to the ice edge is slowly reducing and most of the oil is found in bigger and smaller continuous areas between floes with a thickness up to 2-3 cm.

The oil weathering will normally be slow in this scenario increasing the time window for use of dispersants. Helicopter application is probably the only viable option in this scenario. However, it will be difficult to hit the oil with dispersant in an optimal way. At the same time the energy conditions in such a scenario will probably be low, so the most realistic use of dispersants in such a scenario is to have a positive influence on the break down of the oil when it reaches more open waters.

Dispersant Scenario 3: Early summer spill in open drifting ice

The oil is released during a whole day, creating an initial spreading about 1 by 1 nautical mile. The oil is prevented from further spreading by patches of ice acting as barriers. The ice field is fairly open and is comprised of floes and brash ice in the melting stage.

The relatively large areas of open water expected to be found in this scenario make the oil more accessible for application of dispersant. The weathering will be slow compared to open water conditions and due to reduced spreading, dispersants can be applied to a relatively thick oil film, e.g. 0.5-2 mm. Application by helicopter as well as vessel can be successfully used in this scenario. Even if the waves are considerably dampened, the remaining wave activity combined with wind in more open areas can support the system with sufficient energy to start the dispersing process after application of dispersant.

4.3.3 Conclusions

Only dispersants type 3 (concentrates) are of interest for arctic conditions. Strict requirements concerning physical properties have to be applied in order to fulfill the requirements of viscosity, precipitation, cloud-point and pour point at low air temperatures. Many dispersants show quite low effectiveness at low temperatures and salinity compared to North Sea conditions, and only products tested and approved for "arctic" conditions should be used. Laboratory and meso-scale flume experiments show that oils can disperse even with ice floes and slush ice present, provided that the level of energy is sufficient. Dispersibility testing on specific oil types in accordance with for instance Norwegian regulations for use of dispersants is also strongly recommended because the effect of dispersants and the time window of opportunity for effective use of dispersants will be different for different oil types.

There is reason to believe that the major challenges for the future will be on the operational side. Factors like low temperature, visibility, darkness and variable ice conditions will be very important for the success of an eventual dispersant action in arctic conditions.

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4.4 BIOREMEDIATION OF HYDROCARBON UNDER ARCTIC CONDITIONS

4.4.1 Introduction

After the first reports on microbial degradation of hydrocarbons, many studies have been performed to stimulate this process so it could be used as a cleanup response technique of oil contaminated shoreline sediment. The shoreline clean up after Exxon Valdez incident in 1989 was the first operation were bioremediation was used in large-scale. The rate of success for this response operation has been a matter of discussion in scientific and operation fora since then. Today bioremediation is still a "new and promising" secondary response technique, which still is under development. However, the possibilities and limitation of the bioremediation is now far better understood, which will make use of this technique more predictable.

During the last years US Environmental Protection Agency, International Tankers Organisation and EU/University of Cadiz have published at least three different guidelines for use of bioremediation in marine environment, respectively. SINTEF has been involved in the development of the two later guidelines.

In this chapter the main fundamental topics related to use of bioremediation in Arctic environment will be discussed; biodegradation of hydrocarbons at low temperatures, the limiting factors of bioremediation will be discussed and the different bioremediation strategies that could be utilized.

4.4.2 Biodegradation - Fate of arctic marine oil spills

The use of bioremediation in cold climate is one of the more challenging topics of bioremediation from an operational point of view, mainly due to the low temperatures in these environments. However, the basis for bioremediation is biodegradation of hydrocarbons at low temperatures, which has been reported in a large number of papers.

After release to the arctic marine environment, petroleum hydrocarbons will gradually weather due to natural physical and chemical processes including spreading, evaporation, dispersion, emulsification, solubilisation and chemical modification by oxidative processes. From earlier studies it is known that this weathering process is influenced by both chemical composition and physical properties of the oil, environmental parameters like temperature, water quality, and the solar radiation, and the biota. Several studies have shown that natural biodegradation in the Arctic is a significant process for removal of the spilled oil. These variables have to be considered to ensure that the study is environmentally relevant.

The immediate impact of oil spills has been studied and is fairly well understood, but the long-term effects of such pollutants are less investigated. In this project we want to focus on the following important processes: weathering of the bulk oil phase (evaporation, w/o-emulsification and dispersion), dissolution of water-soluble components, photo-oxidation and biodegradation processes.

In the Arctic, discharged oil will be more affected by different environmental conditions than in temperate regions, particularly lower temperatures, possible presence of ice and different light conditions. For this reason the fate of discharged hydrocarbons (HC) in the Arctic differs from those in temperate regions. For instance wax and asphalthene content in combination with temperature-dependent oil viscosity and weathering processes will be important for the fate of oil in the Arctic during cold-water conditions. At low temperatures surface evaporation of small HC (< C10) is retarded, thus increasing their toxicity. If the marginal ice zone is infested with oil, a secondary discharge situation will occur in the summer season. In the spring and summer seasons, chemical photo-oxidation of oil may become an important HC degradation process.

Natural biodegradation is a major process determining the fate of the oil in the marine water column. It was found that the transformation half-lives (t_{50}) of the water-accommodated fractions (WAF) was 2-3 days, and 10-60 days for various groups of C_{10}-C_{36} alkanes of mechanically dispersed oil or thin oil films. However, the mineralisation rate of the oil compounds is considerably longer, and very little is known about the metabolites and the effects of these on the marine biota. Thus, biodegraded compounds may have significant impact on the marine biota since the degradation process increases the bioavailability of the compounds. Early studies showed that biodegradation of oil hydrocarbons in seawater at 0-1°C were slower, but more extensive than at 10-12°C. Degradation of HC in arctic areas is caused mainly by indigenous psychrophilic ("cold-loving") or psychrotrophic ("cold-tolerant") petroleum-degrading and heterotrophic microbes. Psychrophilic bacteria are found in a variety of biotopes. Significant amounts of such microbes have been found in Arctic or Antarctic ice, showing high metabolic activity in the ice down to temperatures of 0.3°C. This indicates no biological activities in the ice during winter periods, but considerable activities during the summer, since ice temperatures rise above the freezing temperatures seawater.

During the PROFO pre-project a system was developed at SINTEF for simultaneous determination of natural depletion (dissolution and biodegradation) of hydrocarbons on the oil-seawater interface in cold seawater and ice slurries, using bacterial cultures enriched at 5 or 0.5°C. The system was based on immobilisation of thin oil films (< 10 µm) on hydrophobic fabrics and enabled studies both in static and flow-through systems. Initial results from the project showed that transformation of C_{10}-C_{36} alkanes in a paraffinic model oil were >90% at 5°C after 30 days, but considerably reduced at 0-0.5°C (35 % transformation after 60 days). The results indicated that oil characteristics were the limiting factor on biodegradation at low seawater temperatures rather than reductions in microbial metabolism.

One significant feature of the marine environment in the Arctic is the enormous seasonal variation in solar energy. From early November to early March the Arctic hardly experiences any solar radiation, whilst from late April to late August the sun is continuously above the horizon. In the latter period ozone, clouds, and the elevation of the sun significantly influence the solar radiation. Consequently, hardly any light-induced degradation should be observed in the Arctic during the winter, whereas a more or less continuous light-induced degradation should take place during the Arctic summer. This clearly suggests that oil weathering under natural conditions in the Arctic is considerably influenced by the variation in global radiation.

Detailed studies of the photo-oxidation of selected oil samples and oil components have shown that the reaction is facilitated by the presence of aromatic hydrocarbons, asphaltenes, and resins, and that several reaction pathways may operate at the same time. Several reactions may operate at the same time, but irrespective of the reaction involved, hydroperoxide formation takes place. However, the conversion of petroleum hydrocarbons to toxic hydroperoxides and other oxidised products is sensitive to the wavelength of the incident light. In order to study this sensitivity properly it is therefore necessary to expose oil in the marine environment to natural radiation (field experiments). When laboratory experiments are performed it is important to control the wavelength distribution of the light from the lamps to secure that the oil is irradiated under environmentally relevant conditions.

On the basis of these observations we want to study the interactions between carefully selected oils and the marine environment with focus on important weathering processes (bulk oil properties, generation of water soluble components, photolysis and natural biodegradation) under real and simulated arctic conditions.

4.4.3 Major factors affecting bioremediation of hydrocarbons

For a successful use of bioremediation from an operational point of view, a large number of factors will affect the rate of success, but will be of variable importance. Several publications have summarized these factors with supplement even from other sources, and are listed below:

a) *Microbial*
Growth until critical biomass is reached
Mutation and horizontal gene transfer
Enzyme induction
Enrichment of the capable microbial populations
Production of toxic metabolites

b) *Environmental*
Depletion of preferential substrates
Lack of nutrients
Solubility of contaminants
Temperature
Shoreline/sediment type (porosity)
Water content
Light

c) *Substrate*
Too low concentration of contaminants
Chemical structure of contaminants
Toxicity of contaminants
Solubility of contaminants
Contaminant/water interface
Composition of contaminant(s)
Physical properties of contaminants

d) *Biological aerobic vs. anaerobic process*
Oxidation/reduction potential
Availability of electron acceptors
Microbial population present at site (indigenous micro-organisms)

e) *Growth substrate vs. co-metabolism*
Type of contaminants
Concentration
Alternate carbon source present
Microbial interaction (competition, succession, and predation)

f) *Physical-chemical bio availability of pollutant*
Equilibrium sorption
Irreversible sorption
Incorporation into humic matters

g) *Mass transfer limitation*
Oxygen diffusion and solubility
Diffusion of nutrients
Solubility/miscibility in/with water

h) *Weathering processes (interaction with other)*
   Clay-oil flocculation
   Dispersion
   Oxydation processes (photo-/auto-)

4.4.4 Pros and cons of bioremediation

The experience from use of bioremediation over the years has generated knowledge on advantages and disadvantages of this technique. These are summarized in the table below (from IMO guideline).

Pros	Cons
Oil degrading micro-organisms are ubiquitous (present everywhere) and therefore it can be used on a range of shoreline types	Will not work in open water due to the dilution
Relatively non-intrusive method for final polishing	Cannot be used on heavily contaminated beaches unless free contaminant has been removed.
Is a natural process	Dependant on prevailing environmental conditions and the nature of the oil (i.e. limitations on heavy fuel oils)
Does not generate waste products	Takes longer than other physical/chemical techniques
Is generally not labour intensive and can be cost effective	Requires thorough planning and detailed monitoring
Has received a positive public response	Concerns exist regarding potentially adverse health effects associated with release of bioremediation agents particularly bio-augmentation products, and those resulting from the metabolic by-products of biodegradation.

4.4.5 Factors affecting biodegradation/bioremediation

Bioremediation as a response technique is largely influenced by the nature of the physical and chemical properties of the contaminants, the contaminated environment and the interactions between microorganisms. As a biological process, factors that impact microorganism growth such as temperature, dissolved oxygen (DO), and nutrient concentrations can also limit bioremediation. Such factors should be taken into account in any decision making process regarding the use of bioremediation. (Most of this information is copied from the IMO bioremediation guideline!).

Temperature

Sea surface temperature range from about -2^{o}C in polar region to about 35^{o}C in tropical areas. Biodegradation rates are significantly lower at lower temperatures. Low temperature also increases oil viscosity, thereby reducing bioavailability and volatilisation of the toxic short chain alkanes thus retarding the onset of biodegradation. Temperature has often been shown to be a limiting factor to bioremediation in cold climates.

Dissolved Oxygen

Appropriate dissolved oxygen (DO) concentrations are vitally important for bioremediation to occur. The surface layers in beach environments are generally sufficiently oxygenated, with DO concentrations usually higher in coastal areas where wave action enhances oxygen supply/transport. However, reduced oxygen availability is of greater concern for beaches with fine-grained sediments, such as salt marshes or mudflats. Here, mass transfer of oxygen may not be sufficient to replenish oxygen consumed by microbial metabolism.

Nutrient limitation

Bioremediation can only be sustained as long as there are sufficient concentrations of nutrients available. With the hydrocarbons supplying carbon, the remaining nutrients must come from the environment for successful degradation to occur. The typical concentration of nitrogen in seawater is 0.5-0.6 mg/l, which even allowing for efficient water exchange means that nitrogen may be a limiting factor. Nutrient concentrations may also be limited in pristine areas. In polluted or sediment rich inland waterways, estuaries and coastal waters nutrient concentrations may be sufficient.

Pollutant accessibility and toxicity

The pollutant accessibility or bio availability and its potential toxicity are crucial to the success of bioremediation. Bio availability is influenced by the solubility of the contaminant and its sorption onto organic matter or sediment particles. Research has shown that the longer contamination remains in the sediment (or soil), the less bio available it tends to be. Thus, for "weathered" contamination an assessment of the bio availability of the pollutants is advisable prior to treatment. Moreover, weathering of oil on shorelines will increase viscosity in the longer term rendering it less amenable to biodegradation.

Under certain circumstances (if the hydrocarbons concentrations are very high), biodegradation may also be inhibited by the presence of toxic organic molecules such as low molecular weight alkanes (heptane, hexane and pentane, etc.), high levels of BTEX and substituted mono-aromatics. This is rarely a problem after an oil spill at sea as these toxic components tend to evaporate rapidly.

4.4.6 Main bioremediation strategies

The choice of bioremediation strategy and its potential success are dependent on the nature of the contaminated shore as well as on whether or not there is a chance that contamination may reach un-oiled area and/or impact a sensitive resource. Those bioremediation strategies that can be used directly on the polluted site (the beach, the beachhead and the back of the beach) are presented below. This includes *in-situ* and *ex-situ* techniques.

Biostimulation

Biostimulation means providing the micro biota sufficient amounts of elements needed to biodegrade the oil, oxygen and nutrients. Biodegradation requires oxygen (2,6 times the amount of hydrocarbon to be actually degraded), nitrogen (nitrogen/hydrocarbon = 0.07) and phosphorus, (phosphorus/hydrocarbon= 0.007).

As most porous shorelines (sandy, gravel, pebble and cobble) are carbon limited, where the appropriate biodegrading microorganisms are present they will respond rapidly to the presence of hydrocarbon contamination by proliferation. At low oil concentrations (probably <1 g/kg), the hydrocarbon toxicity will be reduced and the oxygen availability as well as the nitrogen and phosphorus ambient concentrations should be sufficient for rapid oil degradation. In such circumstances, bioremediation should consist of monitoring the natural processes. However, at high oil concentration (probably >5 g/kg) the microbes will eventually become oxygen or nutrient limited, biostimulation may be an appropriate choice of clean-up strategy.

In general, bioremediation through biostimulation (addition of oxygen or nutrient) takes time, and is used as a polishing technique, (i.e. when the bulk of the oil is already cleaned).

Oxygen stimulation

Oxygen limitation occurs when the sediment is not sufficient permeable to allow the oxygen to diffuse to the microorganisms themselves. This lack of permeability can be caused by the presence of oil in the sediment, which clogs the interstitial spaces. In this case, oxygen can be supplied by aerating the sediment through periodic raking, tilling or harrowing in order to restore the sediment permeability, and to allow the oxygen in the air enter into it; However, when moving the sediment, care should be taken not to bury the oil deeper in the sediment.

As microbial oil degradation rates within sediments are very low under oxygen limited conditions, increasing the concentration and depth of oxygen availability by mechanical treatment has been shown to improve either the rate of the natural biodegradation or the efficacy of bioremediation treatments. If field surveys indicate oxygen limitation within the oiled sediment, agricultural procedures (e.g. raking, tilling and disking rotavator) can be used to increase the permeability of the sediment. Precaution must be taken to contain the oil which might be released from the sediment by the mechanical means (use of floating booms, sorbent) and/or to avoid transfer of oil to deeper layers of the sediment, particularly when those remain anaerobic.
Such mechanical means will not likely be suitable to sensitive habitats with vegetation such as marsh or wetland as their use would result in destroying the vegetation. The use of chemical oxidants may also be considered for improving oxygen availability. However, care should be taken to use non-toxic and/or pre-approved products. When potential sites for these treatment strategies include mudflats, wetland or salt marshes, monitoring programs must be included to ensure minimal damage from physical disturbance and chemical toxicity.

Nutrient stimulation

Nutrient, mainly nitrogen, can be added in order to maintain enough nutrient concentration; ideally to ensure having no limitation, the ratio between hydrocarbon and nutrient should be up to C:N:P = 100:10:1. A wide variety of nutrient products are available for use as biostimulants. Appropriate inorganic and/or organic nutrient sources may be used as briquettes, granules or liquid fertilizers. Accumulation of nutrients (e.g. ammonia) must be avoided as it could lead to eutrophication and toxic algal blooms.

The potential capability of indigenous micro flora to degrade oil is a function of the physical and chemical properties of the seawater and oil, the environmental conditions, and the biota themselves. It is generally accepted that nutrient availability is one of the limiting factors that is possible to correct. Fertilizing with nitrogen and phosphorus offers great potential as a countermeasure against marine spills. The ratios of carbon, nitrogen, and phosphorus to support optimum oil degradation rates have been identified (C:N:P = 100:10:1). Controlled studies suggest that optimum rates of degradation could be sustained by retaining high, non-toxic, renewable concentrations of nutrients within the interstitial pore water.

Field and laboratory beach microcosmic studies point to interstitial concentrations of nitrogen at approximately 2 mg/l for optimum bio-stimulation. Liquid inorganic fertilisers have proven effective, but they require frequent applications and are comparatively labour intensive and expensive. Field trials have demonstrated the feasibility of applying commercial agricultural fertilisers on a periodic basis as a cost-effective bioremediation treatment. Other advantages of this protocol include product availability and ease of application.

Slow-release briquettes tend to decompose through hydrolysis and tidal action. Because briquettes are moved independent of the oil by tidal action and waves, it is important that the briquettes be of sufficient density and appropriately secured for maximum benefit. Slow-release granules are easily applied, releasing the nutrient when contacted by seawater or rain. However, in high-energy tides, small granules may be washed away before dissolving, and hence be ineffective. It may be prudent to secure the nutrients to the beach in meshed containers. Slow-release products may decrease the cost of fertilisation. The use of agricultural slow release fertilisers decreases the cost of fertilisation procedures.

Proprietary oleophilic nutrient formulations including other organic products have also been developed. These compounds partition preferentially with the oil to promote growth of local microbial hydrocarbons degraders at the oil-water interface.

Product availability and environmental conditions must be considered during selection and application of bioremediation agents. For example, low temperatures (<10°C) were shown to reduce the permeability of the coating of a slow-release fertiliser formulation, effectively suppressing nutrient release.

Other clean-up procedures

Procedures that increase the surface area of the oil (surf washing or the use of surfactants), and hence increase the rate of oil degradation, could be classified as a bio-stimulation strategy for bioremediation: when oil is spilled in the marine environment, microbial attack occurs mainly at the oil-water interface. Thus, facilitating an increase in the oil-water interface through the addition of chemical dispersant, surface agents or bio-surfactants may enhance the rate and extent of biodegradation. However, precaution must be taken prior to such an operation as the use of surfactants (e.g. dispersant) at the shoreline can lead to adverse effects like ecological impact or driving the oil deeper into the sediments.

Microbial attack of oil spilled in the marine environment mainly occurs at the oil-water interface. Thus, facilitating an increase in the oil-water interface may enhance the rate and extent of biodegradation, as the oil becomes more accessible to nutrients, oxygen and bacteria. Increases in microbial activity and oil biodegradation have been correlated with the addition of chemical dispersants, surface agents, bio-surfactants, and the facilitation of oil mineral aggregate formation. Only pre-approved products should be used. Treatment should be made following the manufacturer's recommendations. Application of the product should disperse oil stranded within coastal sediments into the water column at concentrations below the threshold, which will otherwise cause significant toxic effects. Controlled feasibility studies (i.e. plot studies) should be conducted prior to full-scale response operations, to ensure that the chosen procedure will not transport oil deeper into the sediment. For surf-washing operations, where oil dispersion is facilitated by mechanical procedures to accelerate the interaction between oil and mineral fines, consideration must be given to the ecological impacts associated with physical disturbance of the site to be cleaned. For protection of near shore habitat, a biological monitoring program must be implemented with the use of remedial operations based on enhanced dispersion.

Bio-augmentation
If competent degraders are not indigenous to the contaminated site, then their addition may be helpful provided they can survive in their new environment (a process termed bio-augmentation). However, a shoreline environment in which there is no recorded hydrocarbon degrading microorganisms is yet to be found. Bio-augmentation has not been used with success on any contaminated shorelines, except when added with nutrients. It should be noted that where indigenous degraders are present, competition generally results in the failure of bio-augmentation.

There is a perception that marine oil spills may be effectively treated by the addition of oil degrading bacteria. In fact, there is little or no need to add microorganisms to oil contaminated ecosystems. Microbial ecologists have conclusively demonstrated that oil-degrading bacteria within the environment increase in numbers following exposure to oil. Furthermore, field trials have shown that the addition of commercial mixtures or enriched cultures of indigenous oil-degrading bacteria do not significantly enhance the rates of oil biodegradation over that achieved by nutrient enrichment alone.

Phytoremediation
Freshwater wetlands and salt marshes are among the most sensitive ecosystems and the most difficult to clean. Application of traditional oil spill cleanup techniques within this habitat may cause more damage than the oil itself. Consideration is now being given to the inherent capacity of wetland plant species to aerate the rhizosphere as a means of stimulating aerobic biodegradation. This process of utilizing plant growth to accelerate the rate of oil biodegradation and/or habitat recovery is called phytoremediation. Furthermore, there is now evidence that some wetland plant species may effectively stimulate aerobic oil biodegradation by aeration of the rhizosphere and the release exudates and enzymes that stimulate microbial activity. Phytoremediation, contaminant degradation associated with plant growth shows promise as an oil spill countermeasure for coastal environment. The procedure is based on the growth stimulation of existing tolerant plants (e.g. fertilisation) or re-planting with plants from the impacted region (preferably those with phytoremediation attributes) when residual oil concentrations have diminished to levels to which the plants are tolerant. Conduct of phytoremediation operations should include the advice of biologists with experience in wetland ecology.

Ex-situ techniques
Ex-situ techniques can be conducted on site, close to the contamination. The main *ex-situ* techniques include land farming, composting, and bio piling. These processes are probably most appropriate for dealing with oily waste arising during oil spill treatment, and this approach was used extensively after the *Sea Empress* incident in 1996.

Land farming is long standing and well understood. Composting involves the formation of large windrows of contaminated material and the addition of biodegradable additives (*e.g.* nutrients).

The windrow can be turned periodically for aeration and homogenization. In essence, this is a slightly more intensive version of land farming capable of treating more material per unit area.

Engineered bio piling is a more intensive version of composting, where a greater effort is made to optimize the biodegradation processes. Air is either sucked or blown through the pile, either continuously or periodically, to ensure that the biopile is completely aerated. Suction of air through the bio piles has the advantage of concentrating any volatiles in a fixed volume of air such that they may be treated using other equipment, whereas blowing can lead to the dispersal of volatiles and odors in the atmosphere and cause a nuisance. The bio pile may be covered and heated in periods of low temperature, thereby maintaining an optimum temperature for biodegradation (20-30ºC). The leach ate can be collected and sprayed back onto the pile to keep the soil moist.

4.4.7 Monitoring

Monitoring programs are needed to verify ongoing treatment success without detrimental effects on the environment. Treatment success can be assessed by chemical analysis to illustrate the reduction in residual oil concentrations or changes in composition. Biological studies can be used to show a reduction in oil-induced effects. Detrimental effects include any changes to ecosystem structure and function as a result of bioremediation treatment.

Monitoring programs are also needed to identify operational endpoints for the remediation operation. Since traces of hydrocarbons will be found at all spill impacted sites, regardless of the treatment process used, operational endpoints for bioremediation should be based on evidence of attaining an acceptable level of residual oil and/or habitat recovery. Monitoring programs should document the net benefit of bioremediation over natural attenuation (i.e. leaving the site alone to recover naturally).

Heterogeneity within the natural environment is the major obstacle to overcome when designing programs to monitor bioremediation success. To ensure that the resultant data accurately reflect reality, it is paramount that all survey/sampling plans are based on standard statistical procedures. Efforts should be made to ensure that an adequate number of samples are taken to resolve significant differences, if any, to illustrate treatment success. A comprehensive monitoring program will cover changes in environmental factors that can influence bioremediation rates, the efficacy of treatments, evidence of oil biodegradation, toxicity reduction, and habitat recovery. For operational guidance, the monitoring program must be capable of identifying detrimental treatment effects (e.g. toxicity of the bioremediation agent or oil degradation by-products). Ecological significance of the bio tests is improved by the use of a multi-trophic level test battery approach (e.g. integration of bio test results with bacteria, plants, invertebrates and vertebrates).

Analysis of nitrogen can be done either on or off site. For off site analysis, sediment samples should be kept frozen (-20°C) until analysis. In this case, total nitrogen will be measured e.g. using Kjeldahl – nitrogen. For analysis of organic nitrogen, samples of interstitial water should be taken using nutrient wells. On site measurements can be done using colorimetric kits or electronic probes, following manufacturer guidelines. Nutrients should be monitored weekly to determine the time required for nitrogen depletion. The sampling strategy can be modified dependent on results.

Oxygen is measured on-site following the same procedures as for nitrogen. The requirement for oxygen analysis will depend on the treatment. Where oxygen is the limiting factor and aeration is part of bioremediation strategy, levels of dissolved oxygen should be measured to determine effectiveness of aeration (oxygen may also be used as an indicator of microbial activity).

Total Petroleum Hydrocarbon (TPH) can be measured using gravimetry, spectrometry or chromatography to determine oil loss. The progress of degradation can be monitored by detailed chemical analysis (GC-MS) on selected sediment samples according to TPH levels. To measure the benefit of the treatments the results should be compared to similar untreated areas. Samples should be taken before treatment and than every 2 months. The samples should be stored frozen until analysis.

In addition to the demonstration of the reduction of contaminant concentrations, it is necessary to demonstrate that bioremediation does not induce significant biological effects that may suppress the rates of natural habitat recovery. Environmental assessments should be conducted to govern the application of the bioremediation strategy chosen. In such assessments, ecosystem structure and function must be considered.
Two separate, yet complimentary, approaches have evolved for environmental assessment: bio-assessment and bioassays. Consultation with the appropriate regulating bodies and experts is recommended.

For bio-assessment, changes in benthic community structure can be used as a means of assessing ecosystem response to contaminated sediments in aquatic ecosystems. Of particular importance are the macrobenthic invertebrates because of their basic longevity, sedentary lifestyles, proximity to sediments, influence on sedimentary processes, and trophic importance. The bio-assessment process can readily include potential impacts on vegetation.
If the aim of oil spill bioremediation is to restore a site to its pre-spill condition, recolonization of impacted areas should be a primary process to monitor in bio assessment.

Bioassays are toxicity tests that measure organism response on exposure to a sample matrix. A single species bio test cannot represent the range of sensitivity of all biota within an ecosystem. To improve ecological relevance, a test battery approach with species from different trophic levels is required. While any living organisms can be used, toxicity tests with fish and macro invertebrates have been standardised by environmental agencies to assess the hazards of industrial wastes to aquatic systems. Major criteria to consider in the selection of species for sediment toxicity testing include: behaviour in sediment, sensitivity to test material, ecological and/or economic relevance, availability and geographical distribution, taxonomic relation to indigenous animals, acceptability for use in toxicity measurement (e.g., standardised test method) and tolerance to natural sediment characteristics such as grain size. In general, assays using whole sediment samples and larval or juvenile life stages are the most sensitive and therefore recommended.

4.4.8 Operational endpoints for bioremediation

Bioremediation treatment should be terminated when it is deemed that the contaminant concentrations are reduced to acceptable levels (according to the usage and environmental specificity of the site) or if detrimental effects from the treatment strategy are identified. Cost-benefit analysis should be considered in the decision of the acceptable level. Like most oil spill countermeasures, it is futile to expect bioremediation techniques to remove all traces of residual hydrocarbons. In terms of ecological relevance, clear evidence of habitat recovery such as toxicity limits within regulatory guidelines and return of original community structure should suffice. For methods see section above.

4.4.9 Summary of the literature survey on bioremediation

As shown in this document and in numerous scientific and operational papers, bioremediation is still a technique for cleanup of oil-contaminated shoreline under development. However, it is clear that this response technique is not a general method that is universal, but has strict limitations. It will be of great importance to define the "window of opportunity" for bioremediation with respect to the quantitative and qualitative information on the contaminants and the environment. In addition, important subjects will be operational and logistics matters, as compared to other possible response techniques.

From the textbooks it is established that microbial activity, and thereby microbial degradation of hydrocarbons, is dependent on the ambient temperature. The microbial activity is also dependent on presence of free water. The time to fulfil these requirements is normally significantly shorter in an arctic environment, giving a shorter active season for microbial activity. However, microorganisms that are present are adapted to this environment (psycrophilic and/or psycotrophic) and will have a high microbial activity. In general the potential of these microorganisms as a source for degradation and removal of contaminants has, however, not been studied under correct and relevant conditions.

All of the discussed strategies for enhanced bioremediation can be used in cold climate (nutrient, oxygen, availability etc), but it is of great importance to consider other aspects as the properties of chemicals, availability, as well as logistics and infrastructure, and compare these to other potential response techniques.

4.5 ARCOP BIOREMEDIATION EXPERIMENTS CONDUCTED BY AWI

Bioremediation of oil is the acceleration of the degradation process through the addition of exogenous microbes and through the stimulation of the indigenous microbial population by the addition of fertilizers. Nutrients are required to expedite growth of microorganisms. Former studies show that the addition of fertilizers increased the degradation process significantly. In the arctic seas, nitrogen and phosphorus are, however, often limiting factors.
Inipol, an oleophilic fertilizer is well proved under various conditions for the use of oil spill clean up. It has to be proven, if Inipol is a useful fertilizer under arctic sea ice conditions as well.
Important factors for biodegradation are temperature, pH, nutrient and oxygen availability as well as the availability of iron and the physical composition of the contaminants (size of oil droplets, viscosity of oil).

4.5.1 Laboratory experiments

Ice cores from arctic sea ice were taken on the cruise ARK-XIX/1 in April 2003 with the German ice breaking supply vessel IB “Polarstern”.
Bioremediation experiments were set up in glass tanks in the home laboratory at the Alfred-Wegener Institute in Bremerhaven. The tanks were filled with 12 litres of sterile, pre-filtered arctic seawater. The ice cores were crushed into smaller pieces of about 3 to 5 cm diameter, then homogenised and afterwards added to the tanks. The experimental set up is shown in *Figure 4.18*. Each tank was then inoculated with 10 ml crude oil from the Southern Barents Sea. The dispensation of the oil on the sea ice is shown in *Figure 4.19*.

As low temperature is an important limiting factor of bioremediation, the experiments were/are incubated at two different temperatures. Some batches are incubated at -2°C others at 4°C. At -2°C there is equilibrium between sea ice and liquid water.

For the aerobic degradation of hydrocarbons by microorganisms, molecular oxygen is required as an electron acceptor, hence aeration of the tanks is supplied by pumping.

Sub samples of the bioremediation approaches were taken and filtered. To determine the bacterial diversity of the bioremediation experiments and to follow alterations in the composition of the bacterial communities, the samples were analyzed with the culture-independent finger print method DGGE (denaturing gradients gel electrophoresis) and the FISH method (fluorescence in-situ hybridization). For DGGE the bacterial DNA was extracted from the sub samples and about 500 base pairs of the 16S DNA were amplified by PCR (Polymerase Chain Reaction).
Cold adapted bacteria were isolated from oil-bioremediation experiments on specific media with crude oil as sole carbon source.

Figure 4.18 Experimental set up

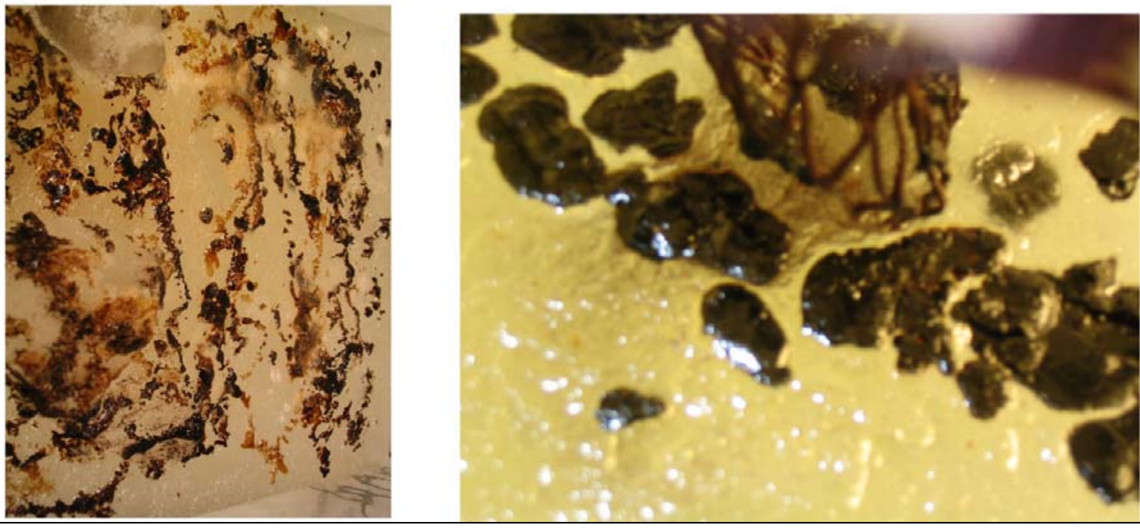

Figure 4.19 Dispensation of the oil on the sea ice

4.5.2 Preliminary results

One of the dominating genera in the oil-contaminated samples was *Marinobacter*, which is ubiquitous and found worldwide, at oil-polluted locations. The sea ice isolates proved to be well adapted to the cold arctic conditions.

FISH analysis with oligonucleotide probes for Bacteria, alpha-proteobacteria, beta-proteobacteria, gamma-proteobacteria and Cytophaga-Flavobacteria indicated a shift towards the gamma-proteobacteria.

DGGE confirmed the reduction of diversity with a shift towards the gamma-proteobacteria group.

Bacteria of sub samples from the oil-contaminated experiments were stained with 4', 6-Diamidino-2-phenylindole (DAPI), a DNS binding dye, and visualized under a fluorescent microscope. The microscopic image (*Figure 4.20*) shows that many of the sea ice bacteria (blue) were closely associated with the oil droplets (yellow-green).

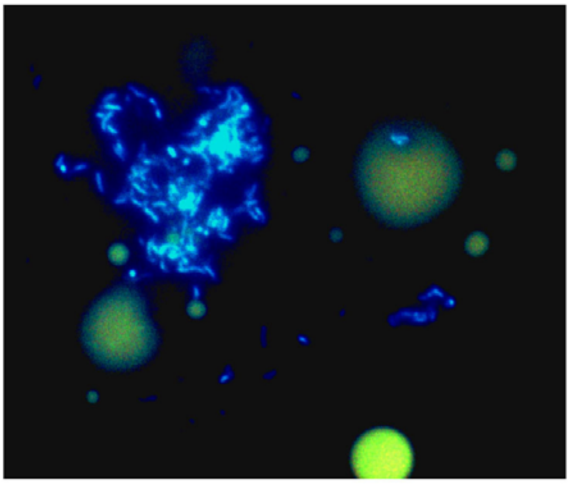

Figure 4.20 Sea ice bacteria (blue) closely associated with the oil droplets (yellow-green).

4.5.3 Further planned laboratory experiments

Monitoring oil degradation with infrared spectroscopy: In aerobic conditions bacteria oxidise a part of the carbon from the contaminant to carbon dioxide (CO_2) the other part of the carbon is

used to produce new cell mass and water. To assess oil degradation in the course of time (mass balance) and to obtain information on the time taken before degradation in oil contaminated samples begins under cold conditions the CO_2 production will be monitored by infrared spectroscopy in a closed system.
Simultaneously GC analysis will show the change of the hydrocarbon composition of the oil. The analysis should provide information on the initial composition of hydrocarbons in the oil and about the compounds that are degraded during bioremediation. Sterile approaches (controls) will reveal whether components of the oil will disappear in the absence of microbial activity (i.e. evaporate, photo oxidation, or dilution into the water column).

Isolates of cold adapted bacteria capable of degrading hydrocarbons will be tested for the existence of specific hydrocarbon degrading genes.

4.5.4 Planned field experiments in 2004

Bioremediation field experiments with crude oil in arctic sea ice have been organized and are scheduled to take place in the van Mijenfjord on Svalbard in spring 2004. Cooperation with SINTEF and UNIS (Longyearbyen). The studies will be co-ordinated with the project *"Weathering process of marine oil spills under arctic conditions"* supervised by Per Johan Brandvik from UNIS, Longyearbyen. Duration of the study is expected to be from several weeks up to a few months. The study will begin in February 2004 and the final sampling and clean up will be done in May 2004, depending on the ice conditions at the study site (as bioremediation at low temperatures is a slow process, the execution of the experiments should be carried on as long as possible).

5 POTENTIAL IMPROVEMENTS FOR OIL SPILL RESPONSE ALTERNATIVES

When studying the literature on state of the art technology for oil spill response in arctic and ice covered waters, the general opinion seems to be that in-situ burning would be the preferred countermeasure for most oil spills. It is easy to understand this attitude when considering that igniting the oil in a spill area is the only activity to remove most of the spilled oil. The logistical problems and costs involved with in-situ burning are very modest compared to combating the same spill with for instance mechanical methods.

We agree that in-situ burning is probably the most important countermeasure for oil spill response in ice. At the same time we should remind ourselves that an oil spill in ice in general is far more complicated to combat compared to spills in open water, although there are also some advantages like reduced rate of weathering, less wave action and sometimes more time is available before the oil is too widespread for any kind of countermeasures. Considering all the situations and conditions where burning cannot be started, or will not be allowed for safety reasons, we believe that the proper attitude is that a variety of countermeasures is needed in our response toolbox.

For most of the ARCOP shipping route from the loading terminal at Varandey to Murmansk, the distance to land requires that the spill response technology can be used offshore, mainly from larger vessels like icebreaking and ice going tugboats and supply vessels, and with assistance from helicopters and fixed-wing aircraft for surveillance/monitoring, dispersant application and ignition of in-situ burning. Smaller workboats will mainly be restricted to those that could operate from the larger vessels.

Within the ARCOP geographical area (and in the Norwegian part of the Barents Sea) there are various activities related to exploration, development, production and transportation of hydrocarbons, and the level of activity is expected to increase significantly during the next years. All of these activities represent a larger or smaller risk for oil spills, whether on land, in open water or in ice. Similar to other geographical areas, an oil spill could have very negative consequences for the entire environment, not only locally. When preparing spill response plans it is therefore useful to plan and prepare a coordinated assistance between companies, regions and nations. The development of the offshore oil field Prirazlomnoye presumably makes it logical to coordinate spill response capabilities between this activity and the ARCOP transportation.

In the following we describe potential improvements and needed developments, partly revealed through this study, partly selected from various sources like Vefsnmo et al. (1996), Dickins (2003), Reed et al. (2001) and Lampela (2001). In this context we are keeping the ARCOP shipping scenario in mind, which means that the most likely oil spills will be associated with a tanker accident (maximum 40.000 tons of oil), and smaller spills that typically could happen at the loading terminal. Both types of spills could occur either in ice or in open water.

5.1 WEATHERING, FATE AND BEHAVIOR

Transport and spreading of oil in ice

After an accidental oil spill under arctic conditions with snow and ice, the interaction between the oil and the frozen porous media (ice and snow) will depend on a large number of parameters including the oil type and weathering degree, the physical properties of the porous media and the environmental factors. Information on these processes will be important in a decision making process to choose the best response strategy, both within a short- and long-time window. The research need is to quantify the transport of different oils as a function of physical/chemical properties in porous media (ice and snow) under different environmental conditions, and to establish algorithms for these processes for numerical models.

Oil weathering, validation, and enhancement of weathering algorithms

The aim is to perform physical and chemical measurements of oil weathering to validate and enhance oil-weathering algorithms for oil weathering models. The objective is also to collect basic research data on evaporation, dispersion, spreading, and other weathering parameters in the marginal ice zone. This data would then be used to enhance and modify or develop new algorithms of oil weathering in and on ice. The work aims to provide an experimental basis for the enhancement or development of algorithms in analytical models.

5.2 Training exercises combined with testing of equipment

For any kind of response methods that might be chosen for potential ARCOP oil spill scenario, there is a general need for training of all types of personnel that would be involved in oil spill response in these areas. Even though there are gaps to fill for any oil spill response technology, the most essential single element to focus on for oil spill response in ice, is training and exercises in the field with real oil under realistic conditions. Some of the training could be conducted as meso-scale and full-scale testing of equipment and methods in laboratories.

5.3 Mechanical oil recovery

Mechanical methods dealing with spills in moving broken ice in general have serious limitations, especially for large oil spills, and recovery values will be highly variable depending on a variety of natural conditions and logistics constraints. However, the present developments underway give hope for considerable improvements for mechanical methods in cold water and in ice.

Winterizing

Most mechanical methods at hand are technology developed for open water conditions, and many types of recovery units will not be suitable for recovery in ice at all, while others could probably be improved considerably with relatively simple means. In general we recommend going through various designs of recovery units in a systematic manner to address problems associated with operation in ice and cold conditions, like freezing, ice accretion and ice processing.

Avoid exposure to cold air, supplying heat

Since the ARCOP transportation route includes transportation through open water, mechanical recovery methods for open water conditions will be required, also during operation at freezing temperatures. Such operation could end up in icing of equipment and finally in ice, whether it is slush or more solid types of ice. Even when testing oil recovery equipment in a room without wind at low temperatures, the problems that occur due to heat loss are very evident: freezing of pumps and hoses during stops, and the accretion of ice that for instance could cause a malfunction of a scraper mechanism. It is quite important to protect the recovery equipment from the heat losses that occur during operations in sub-freezing temperatures combined with wind. We have also mentioned the development underway, which will include high capacity heating systems for processing the recovered product. To include the heating system at the early design stage when designing the recovery vessel makes it much easier to remove a serious of bottlenecks for more or less any mechanical system under cold conditions. The positive effects from sheltering ice processing and recovery units as well as using air heating were clearly demonstrated during the MORICE project. Similar protection could be provided also for much smaller equipment since air heaters are produced in very compact units.

Mechanical recovery to respond to large oil spills in broken ice

There is a need to develop mechanical response technologies that will make it possible to recover large quantities of oil in dynamic broken ice of various floe sizes (not just small ice). All current technologies are limited by ice size and/or lower recovery efficiencies in cold environment and in ice. Techniques that overcome these limitations are desired. The Finnish Vibrating Unit mentioned earlier is an attempt to develop such technology. So far it has not been tested with ice during a real spill, and it is not clear whether this technique would work under ARCOP conditions.

Separation of oil from ice and water

During recovery of oil in ice-infested waters, considerable amounts of ice (and water) could be recovered together with the oil. Prior to storing recovered product, as much ice and water as possible has to be separated to reduce the necessary storage capacity and to avoid creating massive ice in the storage. This is one of the most important problems to solve, or at least to reduce, and the technology can be developed in laboratories without field trials.

Further develop of MORICE unit, Vibrating unit

In the following ARCOP activity we plan to look into how to develop the MORICE system for ARCOP conditions. This will probably be discussed in cooperation with potential use of the Vibrating Unit for ARCOP conditions.

5.4 In-situ burning

Operational in-situ burning in broken ice conditions

The technology and techniques to conduct in-situ burns (ISB) have matured in the past few years. New types of fire resistant booms (actively cooled) have been developed and tested in the past few years; none have been tested in arctic conditions. Most ISB projects have been conducted in small-medium test tanks. At the same time there are certain tactics and techniques that can only be accomplished through an in-the-field exercise. Testing both inside and outside the ice edge could be included. Information from such experiments will be used to make justifiable, scientific-based decisions on the suitability of in-situ burn packages for the intended operating environment.

Identify "window of opportunity" for ignition and efficient burning of oil spills in arctic waters

Improvement of the ignition techniques and of fireproof booms will increase the window of opportunity for in-situ burning. As demonstrated through several larger programs in North America and Norway, in-situ burning has the potential to be an effective oil spill response technique in arctic and remote spill scenarios. However, operational feasibility may be difficult to determine without actually trying to burn. It is proposed to establish a standard methodology to predict the "window of opportunity" for in-situ burning. The essential element is the development of a laboratory ignitability assessment test. Results from laboratory experiments should be compared with results from meso-scale systems and verified through field experiments. The data from these tests and experiments should be used with existing oil weathering models to predict the window of opportunity for the use of in-situ burning for a variety of oil types. The objective is to establish how the physical/chemical properties of oil, the oil weathering/emulsification and environmental factors will affect the ignitability and burning efficiency of both crude oils and refined petroleum products for in-situ burning in arctic spill scenarios.

5.5 Dispersants

The potential usefulness of dispersants in arctic conditions has not been demonstrated by earlier limited laboratory or field trials. An objective would be to establish a better understanding of the potential for operational use of dispersants in various spill scenarios under arctic conditions, to define the limiting cases for applicability of dispersants in cold and/or ice covered waters, and to explore the capabilities of dispersants to effectively disperse various oils in (1) cold water, (2) in the presence of brash and slush ice, and (3) with different levels of mixing energy.

Under marine conditions with low wave heights, clean up of oil spill by use of dispersants is difficult due to the lack of wave energy to mix the dispersant with the oil and facilitate dispersion of droplets into the water column. Modern icebreakers and ice classed oil field support vessels are being designed with Azimuthal Stern Drive (ASD) as the propulsion mechanism. With the ability to rotate the propeller pods, a large area behind the vessels may be exposed to turbulent mixing resulting from the propeller wash. ExxonMobil is currently planning a series of laboratory experiments to test the feasibility of using an ASD vessel to apply dispersant onto an oil spill in ice and use the propellers to provide the mixing energy required for dispersion. Considering that ExxonMobil is both an oil company and a producer of dispersants, we assume that the results of these tests will be communicated to the research community in case the experiments indicate a potential for this technique.

5.6 Bioremediation

Presently, no specific recommendations have been prepared for bioremediation. The bioremediation experiments conducted by AWI are still in progress and results are not yet available.

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6.2 BIBLIOGRAPHY - MECHANICAL OIL RECOVERY

The following table on mechanical oil recovery was worked out during the MORICE project in 1996.

No.	Title	Author	Source	Year	Ref. Type	TOPICS: Mechanical recovery of oil in ice: Field Exp.	Real Spill	Lab Test	Theor. Assess.	Plat-form	Hist. Oil Spill	Inform. on Specific areas: Env. cond	Oil activity	Oil behaviour	Spill scenar.	Misc	MORICE relevance
3	A field evaluation of oil skimmers	Abdelnour, R., Roberts, B., Purves, W.F. Wallace, W.	AMOP 1980, pp 253-280	1980	CP	X*											L
4	Workshop on Alaska Arctic Offshore Oil Spill Response Technology		Alaska Arctic Offshore Oil Spill Response Technology, Proceedings (AAOOSRT)	1988	CP											X	H
5	Containment and recovery techniques for cold weather, inland oil spills	Allen, A.A.	Oil Spill Conference 1981, Atlanta, Georgia	1981	CP				X								L
6	Oil spill demonstrations in broken ice Prudhoe Bay, Alaska - 1983	Allen, A.A.	AMOP 1984, pp 342-354	1984	CP	X											L
7	SOCK- an oil skimming kit for vessels of convenience	Ayers, R.R., Barnett, A.V.	Oil Spill Conference 1977, New Orleans	1977	CP												N/A
8	Oil spilled with ice: some qualitative aspects	Barber, F.G.	Oil Spill Conference 1973, pp 133-137	1973	CP				X	X				X	X		L
9	Oil spill recovery in brash ice		Black Sea Cen-tral Plann-ing and Design-ing Bureau, Odessa	1977	TR		X				X						H
10	The BIOS project-frontier oil spill countermeasures research	Blackall, P.J., Sergy, G.A.	Oil Spill Conference 1981, Atlanta, Georgia	1981	CP											X	L
11	Evaluation of the LIC Lori ice cleaner	Bowen, S.J.	Alaska Clean Seas	1991	TR	X											L
12	Heavy oil skimmer tests	Brown, H.	Esso Wave Basin, Calgary	1990				X									L
13	Heavy oil skimmer trials in Scandinavia	Brown, H.		1991	TR	X											L

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14	Arctic field testing of the Lockheed Clean Sweep and VEP Arctic Skimmer	Buist, I.A., Potter, S.G., Swiss, J.J.	AMOP 1983, pp 85-96	1983	CP	X*											L
15	Tank testing of skimmers with waxy and viscous oils	Buist, I.A., Potter, S.G.	AMOP 1989, pp 193-225	1989	CP			X*									M
16	Cleanup and containment of a diesel fuel spill to a sensitive water body at a remote site under extreme winter conditions	Burns, R.C.	AMOP 1988, pp 209-220	1988	CP		X				X						L-M
17	Proceedings of a brainstorming workshop on recovery of oil in an ice environment, project report	Canadian Off-shore Oil Spill Research Asso-ciat. (COOSRA)	Prepared by S.L. Ross Environment Res. Ltd.	1982	TR				X								H
18	Oil recovery from under river ice	Canadian Petro-leum Associat.		1978	TR	X											L
19	An oilspill in pack ice	Centre for Cold Ocean Res. Eng	Prepared for Environment Canada, date unavailable		TR		X				X						L
21	Field manual for cold-climate spills	Deslauriers, P.C., Morson, B.J., Sobey, E.J.C.	Pre-pared for U.S. Environmental Protection Agency, EPA-3-05-009-8, data unavailable		TR				X								
23	Testing of an oil recovery concept for use in brash and mulched ice	S.L. Ross Environmental Research	Environmental Studies Revolv-ing Funds Report No. 018	1986	TR			X									H
24	A winter evaluation of oil skimmers and booms	Environment Canada	EPS 4EP-84-1	1984	TR	X											H
26	Tests of oil recovery devices in a broken ice field, Phase 1	Shultz, L.A.	Prepared for U.S. Department of Transportation, United States Coast Guard, Report No. CG-D-130-75	1975	TR			X									H

No.	Title	Author	Source	Year	Ref. Type	TOPICS: Mechanical recovery of oil in ice: Field Exp.	Real Spill	Lab Test	Theor. Assess.	Plat-form	Hist. Oil Spill	Inform. on Specific areas: Env. cond	Oil activity	Oil behaviour	Spill scenar.	Misc	MORICE relevance
27	Oil removal techniques in an arctic environment	Golden, P.C.	MTS Journal v.8n.8		TR	X											L
28	Cold weather testing at OHMSETT	Griffiths, R.A., Desiauriers, P.C.	AMOP 1981, p 287-305	1981	CP											X	L
29	USNS Potomac oil spill	Grose, P.L. et al.	Joint NOAA and USCG report	1979	TR						X						
30	ABSORB: A three year update in arctic spill response	Hillman, S., Shafer, R.V.	Oil Spill Conference 1983, San Antonio, Texas	1983	CP											X	L
31	"Arctic Skimmer"	Huston, D.A.C.	AMOP 1979, pp 130-135	1979	CP/MI			X									L-M
32	Testing of the Navy's Cold Oil Modi-fi-cations to the Marco Class V Skimmer	Kilpatrick, R.D., Saecker, A.J.	AMOP 1981, pp 219-242	1981	CP			X*									M
33	Oil skimming vehicle for ice-infested waters	Kivisild, H.R., Milne, W.J., Jackson, P.	AMOP 1978, pp 131-135	1978	CP				X	X							M
34	Lake Champlain: A case history of the cleanup of #6 fuel through five feet of solid ice at near-zero temperatures	Lamp'l, H.J.	Applied Control Technology, pp 579-582	1975	CP						X						
35	Oil spill 1978 west coast of Sweden	Maare, M.		1978	TR						X						
36	Cold regions spill response	March, G.D., Schultz, L.A., DeBord, F.W.	Oil Spill Conference 1979, Los Angeles, California	1979	CP				X							X	M
37	Development of Morris skimmers for arctic use	Morris, D.	AMOP 1979, pp 125-129	1979	CP			X									L
38	Oil-spill-response measures for Alaskan offshore oil and gas operations	Murrell, T., Levine, J.R., Regg, J.G., Tennyson, E.	OSC Report MSS 86-0000	1986	TR				X								L
39	An investigation of techniques for the pumping of oil from under solid ice cover	Norcor Engineer-ing and Research Limited	Prepared for Panarctic Oils Limited	1975	TR	X											L

No.	Title	Author	Source	Year	Ref. Type	TOPICS: Mechanical recovery of oil in ice: Field Exp.	Real Spill	Lab Test	Theor. Assess.	Plat-form	Hist. Oil Spill	Inform. on Specific areas: Env. cond	Oil activity	Oil behaviour	Spill scenar.	Misc	MORICE relevance
40	Oil spill response in the Arctic, Part 2, field demonstrations in broken ice	Industry Task Group		1983	TR	X				X							H
41	Oil spill response in the Arctic, Part 3, technical documentation	Industry Task Group		1984	TR				X	X							H
42	Dome Petroleum's oil spill research and development program for the Arctic	Pistruzak, W.M.	Oil Spill Conference 1981, Atlanta, Georgia	1981	CP											X	L
43	Ice exercise North Saskatchewan River		Prairie Region Oil Spill Con-tain-ment and Re-co-ve-ry Advisory Com-mittee	1976	TR	X											L
44	A background to countermeasures for a Beaufort Sea well blowout	Purves, W.F.	Prepared for Environment Canada Countermeasures Innovation Session	1977	TR				X								L
45	Spill experiences in the St. Lawrence River	Rivet, C.	AMOP 1985, pp 400-401	1985	CP											X	L
46	Design & development of an oil re-covery vehicle (skimmer) to operate in ice-infested water	Roberts, D.	AMOP 1978, p. 128	1978	CP/MI				X								M
48	Oil recovery systems in ice	Ross, S.L.	Prepared for COOSRA	1984	TR				X								
49	Development of an oil spill recovery system for arctic operations	Scharfenstein, C.F., Hoard, M.G.	Oil Spill Conference 1977, New Orleans, Louisiana	1977	CP/MI			X									M
50	Cleanup efficiency of a fuel oil spill in cold weather	Schrier, E., Eidam, C.	Oil Spill Conference 1979, Los Angeles, California	1979	CP		X				X	X					H
51	Tests of oil recovery devices in broken ice fields, Phase II	Schultz, L.A.	Prepared for U.S. Department of Transportation, United States Coast Guard, Report No. CG-D-76	1976	TR			X						X			H

No.	Title	Author	Source	Year	Ref. Type	TOPICS: Mechanical recovery of oil in ice: Field Exp.	Real Spill	Lab Test	Theor. Assess.	Plat-form	Hist. Oil Spill	Inform. on Specific areas: Env. cond	Oil activity	Oil behaviour	Spill scenar.	Misc	MORICE relevance
53	Systems for arctic spill response, Volume II - appendices	Schultz, L.A., Deslauriers, P.C., DeBord, F.W., Voelker, R.P.	Prepared for U.S. Department of Transportation, United States Coast Guard, Report No. CG-D-44-78	1978	TR			X						X			H
54	Tests of the arctic boat configuration of the Lockheed Clean Sweep oil recovery system in a broken ice field	Schultz, L.A.	Prepared for U.S. Department of Transportation, United States Coast Guard, Report No. CG-D-108-76	1976	TR			X									H
55	Oil spill response scenarios for remote arctic environments	Schulze, R.H., Grosskopf, W.G., Cox, J.C., Schultz, L.A.	EPA 600/2-82-036	1982	TR				X								L
56	An oil spill response system for an offshore ice environment	Schulze, R.H., Zahn, P.	AMOP 1982, pp 151-176	1982	CP				X	X				X	X		H
57	Performance tests of four selected skimmers	Schwartz, S.H.	Oil Spill Conference 1979, Los Angeles, California	1979	CP			X*									L
58	Shallow water access platform (SWAMP)	Shafer, R.V., Glenn, D.	AMOP 1988, pp 201-203	1988	CP				X			X					N/A
59	ARCTICSKIM: An oilspill skimming system for broken ice and shallow waters	Shafer, R.V., Bown, S.J.	AMOP 1988, pp 205-208	1988	CP	X			X								M
60	Test of a skimmer in ice-infested waters at OHMSETT	Shum, J.S.	Draft report prepared for US EPA	1984	TR			X									H
61	Summary of U.S. Environmental Protection Agency's OHMSETT testing, 1974-1979	Smith, G.F., Lichte, H.W.	EPA-600/9-81-007, pp 141-142	1981	TR			X									L
62	A catalogue of oil skimmers	Solsberg, L.B.	Environment Canada	1983	TR				X								H
63	Design and development of oil recovery devices for ice-infested waters - oil mop arctic	Stewart, P.	AMOP 1978, pp 129-130	1978	CP/MI				X								L

No.	Title	Author	Source	Year	Ref. Type	TOPICS: Mechanical recovery of oil in ice: Field Exp.	Real Spill	Lab Test	Theor. Assess.	Plat-form	Hist. Oil Spill	Inform. on Specific areas: Env. cond	Oil activity	Oil behaviour	Spill scenar.	Misc	MORICE relevance
	skimmer																
64	Construction of a prototype arctic off-shore oil mop skimmer	Steward, P.	AMOP 1979, pp. 159-165	1979	CP/MI			X									L
65	Testing of oil skimmers developed in Japan for use in cold climates	Suzuki, I., Miki, K.	AMOP 1984, pp 96-118	1984	CP			X*									L
66	Research and development of oil spill control devices for use in cold climates in Japan	Suzuki, I., Miki, K.	Oil Spill Conference 1987, Baltimore, Maryland, pp 349-352	1987	CP			X									L
67	Recent results from oil spill response research	Tennyson, E.	Oil Spill Conference 1991, San Diego, California, p 674	1991	CP				X								L
68	Field evaluation of oil mop and preheat unit	Tidmarsh, G.D., Solsberg, L.B.	Fisheries and Environment Canada, EPS-4-EC-77-12	1977	TR	X											M
69	Field trials of the ARCAT II in Prudhoe Bay	Williams, R.E., Bowen, S.J., Glenn, D.H.	AMOP 1984, pp 119-126	1984	CP	X				X							L
70	Study of viscosity and emulsion effects on skimmer performance	Lorenzo, T., Therrien, R., Johannessen, B.O.	AMOP 1995, pp 705-729	1995	CP			X*									L
71	Adhesion of oils to plastics, stainless steel and ice	Liukkonen, S., Koskivaara, R., Lampela, K.	AMOP 1995, pp 69-90	1995	CP			X									L
72	Sea ice over-flooding: A challenge to oil spill countermeasure planners in the outer MacKenzie Delta, NWT	Webb, R.	AMOP 1995, pp 243-256	1995	CP												N/A
73	Analysis of the Kominefť pipeline oil	Lambert, P. et al.	AMOP 1995, pp 1187-1231	1995	CP						X						N/A

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74	Fate of oil determinations under arctic conditions: the Komi pipeline oil spill experience	Nadeau, R.J., Hansen, O.	AMOP 1995, pp 1163-1174	1995	CP						X			X			L
75	Behaviour of spilled oil at sea (BOSS): Oil-in-ice fate and behaviour	DF Dickins Associates Ltd, Fleet Techn. Ltd		1992	CP TR									X			M
76	Experimental oil spills in the Barents Sea marginal ice zone	Johannessen, B.O., Jensen, H.	Alaska Conf. on Oil Spill Response in Dynamic Broken Ice	1994	X	X											L
77	Experimental spills of crude oil in pack ice	Buist, I.A., Dickins, D.F.	Alaska Conf. on Oil Spill Response in Dynamic Broken Ice	1994	CP									X			L
78	Behaviour of oil spills in cold and ice-infested waters - analysis of experimen-tal data on oil spreading	El-Tahan, H., Venkatesh, S.	AMOP 1995, pp 337-354	1995	CP									X			L
79	Fate and behaviour of oil spilled in the presence of ice - a comparison of the results form recent laboratory, meso-scale flume and field tests	Singsaas, I., Brandvik, P.J., Daling, P.S., Reed, M., Lewis, A.	AMOP 1994, pp 355-370	1994	CP									X			L
80	Testing of the Lori “Stiff Brush” skimmer sweep system	Guenette, C.C., Buist, I.A.	AMOP 1993, pp 451-476	1993	CP	X*		X*									L
81	New test basin for experimental studies on oil spill in ice	Wessels, E.	AMOP 1992, pp 271-279	1992	CP												N/A
82	State of the art review: Oil in ice recovery	Solsberg, L.B., McGrath, M.	Canadian Association of Petroleum Producers	1992	TR	X		X	X		X						H
83	Evaluation of the Foxtail skimmer in broken ice	Counterspill Research Inc.	Canadian Association of Petroleum Producers	1992	TR			X									H
84	Mechanical recovery of oil in ice	Solsberg, L.B., McGrath, M.	AMOP 1992, pp 427-437	1992	CP			X	X								H

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85	Evaluation of inshore skimmers	Counterspill Research Inc.	Canadian Coast Guard	1993	TR			X*									L
86	CISPRI Various newsletter, undated, anon.				TR	X	X		X				X				
87	Spill Prevention News, Alaska Clean Seas, Various newsletters			2E+07	TR	X	X		X		X		X				
89	Oil spill recovery systems in ice, Part A - Feb. 1984, Part B - Jun 1985	Canadian Offshore Oil Spill Research Association		2E+07	TR												
90	The 1979 Baltic oil spill	Dept. of Environ-mental Protection	A:2 Report ISBN 951-4864-1, Helsinki, Finland	1979	TR						X						
91	Environmental impact statement for hydrocarbon development in the Beaufort Sea - Mackenzie Delta Region, Volume 6 - Accidental spills	.	Dome Petroleum Ltd, Esso Resources Canada Ltd, Gulf Canada Resources Inc	1982	TR												L
92	Field research spill to investigate the physical and chemical fate of oil in pack ice	Ross, S.L. Env.Research, Dickens, D.F. Associates Ltd.	Environmental Studies Revolving Funds Report No. 062	1987	TR									X			
94	Oil spillage in Antarctica	Kennicutt, II, M.C. et al.	Environ. Sci. Technol. Vol. 24, No. 5	1990	TR												L
95	Oil spill countermeasures for the southern Beaufort Sea	Logan, W.J., Thornton, D.E., Ross, S.L.	Beaufort Sea Technical Report #31a, Department of Environment, Canada	1975	TR				X								L
97	Oil spill in Stockholm Archipelago 1979. Combat and cleanup	Sanering, Skonsult AB	Report to 1977 Govt. Commission for Combatting Oil Spills, Göteburg, Sweden	1979	TR		X				X						

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98	Theory, development and testing of an ice-oil boom	Tsang, G., Vanderkooy, N.	EPS-4EC-79-2	1979	TR			X	X								L
99	Response to oil spills in the Arctic environment: A review	Morson, B., Sobey, E.	pp 407-414	1979					X					X			L
100	A spill response system for breakup	Schulze, R., Thayer, W., Zahn, P.	pp 154-160						X	X		X -			X		L
101	An overview of potential large oil spills offshore Canada and possible response strategies	Ross, S.L.													X		L
102	Decision regarding the oil industry's capability to clean up spilled oil in the Alaskan Beaufort Sea during broken ice periods	O'Brien, P.S., Hayden, G., Butts, R., Van Dyke, W.	Prepared for Alaska Department of Environmental Conservation	1983	TR											X	L
103	Oil spill in the ice-covered water of Buzzards Bay	Deslauriers, P.C.	Journal of Petroleum Techn., The Bouchard No. 65	1979	JA		X				X			X			H
104	The grounding of the imperial St. Clair - a case history of contending with oil in ice	Beckett, C.J.	Oil Spill Conference 1979, pp 371-375	1979	CP						X						L
105	Oil in pack ice: The Kurdistan spill	Reimer, E.	AMOP 1980, pp 529-544	1980	CP						X			X			L
106	The development of countermeasures for oil spills in Canadian Arctic waters	Ross, S.L.	Ass. Europe Oceanic Petrol & Marine Environment Conf., pp 377-399	1981	CP											X	M
108	Arctic marine oil spill research	Hume, H.R., Buist, I., Betts, D., Goodman, R.	Cold Regions Science and Technology, 7, pp 313-341	1983	JA											X	L-M
109	Arctic spill response improvements: a 1985 review of arctic research and	Hillman, S.O.	Oil Spill Conference 1985, pp 411-414	1985	CP											X	L

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	development																
111	Oil pollution problem in the Baltic marine environment	Hirvi, J.-P.	AMOP 1989	1989	CP						X	X			X		L
112	Ice drift and under ice currents in the Barents Sea	Johansen, Ø., Mathisen, J.P., Skognes, K.	POAC, Luleå	1989	CP							X					N/A
113	Oljevern i nordlige og arktiske farvann (ONA) - Status: Volum I (In Norwegian)	Løset, S., Singsaas, I., Sveum, P., Brandvik, P.J., Jensen, H.	SINTEF NHL Report STF60 A94087	1994	TR											X	L
115	Spreading of crude petroleum in brash ice: Effects of oil's physical properties and water current	Sayed, M., Kotlyar, L.S., Sparks, B.D.	ISOPE	1994	CP									X			L
116	Ohmsett tests of a rope-mop skimmer in ice-infested waters	Shum, J.S., Borst, M.	Oil Spill Conference 1985, pp 31-34	1985	CP			X									H
117	A safety and reliability analysis of arctic petroleum production and transportation systems - a preliminary study	Fenco Consultants Ltd	Environment Canada, EE-44	1983	TR						X	X	X		X		M
118	Simulation tests of portable oil booms in broken ice	Suzuki, I., Tsukino, Y., Yanagisawa, M.	Oil Spill Conference 1985, pp 25-30	1985	CP			X									H
119	Development of a novel ice oil boom for flowing waters	Tsang, G., Vanerkooy, N.	Oil Spill Conference 1979, pp 377-385	1979	CP	X		X	X								L
120	Cold environment tests of oil skimmer	Wessels, E.	POAC'93, pp 741-751	1993	CP			X									M
121	Laboratory testing of a flexible boom for ice management	Løset, S., Timco, G.W.	Proc. of the 11th Intern. Conf. on Offshore Mechanics and Arctic Engineering, pp 289-295	1992	CP			X									L

No.	Title	Author	Source	Year	Ref. Type	TOPICS: Mechanical recovery of oil in ice: Field Exp.	Real Spill	Lab Test	Theor. Assess.	Plat-form	Hist. Oil Spill	Inform. on Specific areas: Env. cond	Oil activity	Oil behaviour	Spill scenar.	Misc	MORICE relevance
122	Muligheter og begrensninger for eksister-ende oljevernutstyr ved bruk i is (Testing of Foxtail Skimmer)	Jensen, H. Johannessen, B.O.	SINTEF NHL Report STF60 F92127	1993	TR			X									H
123	Experiences of coping with oil spills in broken ice	Rytkönen, J.	Petro Pioscis II'92-H-4	1992	CP	X	X	X			X	X					M
124	Oil spill research in the cold environment laboratory at SINTEF NHL	Johannessen, B.O., Løset, S., Jensen, H.	AMOP 1994	1994	CP			X									L
125	Experimental oil spill in the Barents Sea - drift and spread of oil in broken ice	Vefnsmo, S., Johannessen, B.O.	AMOP 1994	1994	CP									X			L
127	Oil in pack ice: preliminary results of three experimental spills	Buist, I.A., Bjerkelund, I.	AMOP 1986, pp 379-397	1986	CP									X			L
128	A synopsis of Canadian cold water environmental research		Mobil Oil Canada, Mobil Exploration Norway	1988	TR											X	L
129	Oljens egenskaper. Volum 1: Havklima og isforhold (Ocean environment and ice conditions in the Barents Sea)	Løset, S., Torsethaugen, K. Johansen, Ø.	SINTEF NHL Report STF60 A89072	1989	TR							X		X			L
130	A review of countermeasures for a major oil spill from a vessel in arctic waters	Environment Canada	Economic and Technical Review, Report EPS 3-EC-83-2	1983	TR				X		X	X	X		X		L
131	Oil spill response in the Arctic. An assessment of containment recover, and disposal techniques - draft	Industry Task Group		1983	TR				X	X							H
135	Experimental spills of crude oil in pack ice	Buist, I.A., Dickins, D.F.	Oil Spill Conference 1987, American Petroleum Institute, pp 373-381	1987	CP									X			L

No.	Title	Author	Source	Year	Ref. Type	TOPICS: Mechanical recovery of oil in ice: Field Exp.	Real Spill	Lab Test	Theor. Assess.	Plat-form	Hist. Oil Spill	Inform. on Specific areas: Env. cond	Oil activity	Oil behaviour	Spill scenar.	Misc	MORICE relevance
136	Laboratory and field studies related to oil spill behaviour	El-Tahan, M.	Report submitted to SINTEF NHL	1992	TR									X			L
137	Oil spill scenario for the Labrador Sea	LeDrew, B.R., Gustajtis, K.A.	Environment Canada, Environment Protection Service, EPS 3-EC-79-4	1979	TR										X		
138	Oil in sea ice	Lewis, E.L.	Pacific Marine Science Report, Inst. of Ocean Sciences, Environment Canada	1976	TR												
139	The application of existing oil spill abatement equipment to cold regions	Schultz, L.A., Deslauriers, P.C.	Oil Spill Conference 1977	1977	CP				X								M
140	A field guide for Arctic oil spill behaviour	Schultze, R.	Arctic Ins., Columbia, Md.	1984	TR									X	X		
141	An overview of a field guide for arctic oil spill behavior	Schulze, R., Lissauer, I.	Oil Spill Conference 1985, pp 399-403	1985	CP									X	X		L
142	The physical interaction and cleanup of crude oil with slush and solid first year sea ice	Nelson, W.G., Allen, A.A.	pp 37-59													X	L
143	Cold water oil spills	Etkin, D. S	Cutter Information Corp., Arlington, MA, ISBN 0-943779-55-3	1990	TR				X					X			L
144	Bibliography, Canadian Petroleum Association Publications	Canadian Petroleum Association	Canadian Association of Petroleum Producers	1992													N/A
145	Oil-spilled cause by MT Antonio Gramsci 6th February in 1987 - summary of events		National Board of Waters and Environment, Helsinki, Finland	1987	TR		X				X			X			L-M
146	Behaviour of oil spilled in ice-covered rivers	Chen, E.C., Keevil, B.E., Ramseier, R.O.	Environment Canada, Scientific Series No., 61	1976	TR									X			N/A

No.	Title	Author	Source	Year	Ref. Type	TOPICS Mechanical recovery of oil in ice Field Exp.	Real Spill	Lab Test	Theor. Assess.	Plat-form	Hist. Oil Spill	Inform. on Specific areas Env. cond	Oil activity	Oil behaviour	Spill scenar.	Misc	MORICE relevance
147	Oil spill at Deception, Bay, Hudson Strait	Ramseier, R.O., Gantcheff, G.S., Colby, L.	Environment Canada, Scientific Series No. 29	1973	TR						X						L
148	Oil on ice. How to melt the Arctic and warm the world	Ramseier, R.O.	Environment Canada, Reprint No. 314.	1974	TR						X			X	X		L
149	Combatting marine oil spills in ice and cold conditions	National Board of Waters and the Environment	Proceedings from seminar in Helsinki, Finland	1992	TR											X	
150	Oil pollution in ice-infested waters	Ramseier, R.O.	Inland waters branch, Dep. of the environment, Reprint No. 163		TR						X			X			L
151	Statistical description of pack ice in the Beaufort Sea, Lancaster Sound and the Labrador Sea	Dickins, D., Diskinson, A., Humphrey, B.	Environment Canada, May 1985, AA 00 62	1985	TR							X					L
152	Site visit of oil spill under multi-year ice at Griper Bay, N.W.T.		Environment Canada, January 1983, AA 00 42	1983	TR						X			X			
153	Ice Conditions		Environment Canada, March 1982, AD 81 8	1982	TR							X					
154	Oil, ice and gas		Proceedings ,Workshop in Toronto, Canada, 10 - 11 Oct 1979, CZ 79 1	1979	CP												
155	Oil recovery systems in ice	Ross, S.L.	S.L. Ross Environmental Research LTD., Feb. 1984, DB 84 1	1984	TR												
156	Model tests of various oil/ice separation concepts by Arctec Canada Ltd.	Arctec Canada Ltd.	Video, April 1978, HG 78 1	1978				X									
157	Research needed to respond to oil spills in ice-infested waters - findings and recommendations of the U.S. Arctic	U.S. Arctic Research Commission	May 1992, DB 92 02	1992	TR											X	L

No.	Title	Author	Source	Year	Ref. Type	TOPICS: Mechanical recovery of oil in ice: Field Exp.	Real Spill	Lab Test	Theor. Assess.	Plat-form	Hist. Oil Spill	Inform. on Specific areas: Env. cond	Oil activity	Oil behaviour	Spill scenar.	Misc	MORICE relevance
	Research Commission																
158	LORI ice cleaner trials and equipment evaluation - trip report	Latour, J.	Canadian Coast Guard, Jan. 1991, DI 91 02	1991	TR	X											
159	Novel countermeasures for an Arctic offshore well blowout	Abdelnour, R., Nawwar, A.M., Hildebrand, P., Purves, W.F.	Environment Canada, Aug. 1977, AB 00 28	1977	TR											X	L
160	Development and testing of a high tensile strength spill containment barrier for use in a protected sea ice environment		DI 92-09	1992	TR	X											
161	Crude oil spreading in brash ice - data report	National Research Council of Canada, PERD	DA 93-03	1993	TR									X			
162	Evaluation of pumps and separators for Arctic oil spill cleanup		Environment Canada, April 1979, AB 00 55	1979	TR												
163	Arctic oil spill countermeasures logistics study: summary report		Environment Canada, Dec. 1978, AB 00 48	1978	TR										X		
164	Probabilities of blowouts in Canadian arctic waters		Environment Canada, Oct. 1978, AB 00 46	1978	TR							X	X		X		
165	A study of on-board self help oil spill countermeasures for arctic tankers	Ross, S.L.	S.L. Ross Environmental Research LTD., March 1983, DB 83 1 (c.2)	1983	TR												
166	Development of an offshore self-inflating oil containment boom for arctic use - Part II - Boom fabric testing	McAllister Engineering	DI 00 01		TR												

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167	United States Coast Guard Arctic Oil-Pollution Program	Getman, J.H.	Oil Spill Conference 1975	1975	CP												
168	Kurdistan - an unusual spill successfully handled	Duerden, F.C., Swiss, J.J.	Oil Spill Conference 1981	1981	CP						X						L
169	Oil spill countermeasures in landfast sea ice	Allen, A.A., Nelson, W.G.	Oil Spill Conference 1981	1981	CP				X					X			M
170	KOMI oil spill: an assessment by a multinational team	Devenis, P.	AMOP 1995	1995	CP						X						L
171	Response and management strategies utilized during the Kenay pipeline crude oil spill, Nikiski, Alaska	Sienkiewicz, A.M., O'Shea, K.	AMOP 1992	1992	CP		X				X						
172	Deflection of open pack ice in oil spill recovery area	Løset, S., Carstens, T., Jensen, H.	AMOP 1991	1991	CP			X	X								L
173	Environmental atlas for Beaufort Sea oil spill response	Dickens, D.F., Bjerkelund, I.	AMOP 1987	1987	CP							X					
174	Countermeasures for dealing with spills of viscous, waxy crude oil	Potter, S.G., Ross. S.L.	S.L.Ross Environmental Research & Hatfield Consultants ltd	1986	TR				X								M
175	The Alaskan Clean Seas research, development and engineering program	Shafer, R.V.	AMOP 1987	1987	CP											X	L
176	Oil spreading in broken ice	Schulze, R.	AMOP 1985	1985	CP									X			L
177	Tests of oil skimmer at low temperatures	Schwarz, J.	Intern. conf. on Technologies for Marine Environment Preservations (MARIENV'95), Vol. 1, pp 295-298, Tokyo, Japan	1995	CP			X									L

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178	Research on oil spill in HSVA's new environmental test basin for cold regions	Wessels, E.	HELCOM-Seminar "Combatting Marine Oil Spills in Cold and Icy Conditions", Helsinki, Finland	1992	CP												L
179	Cold environment tests of oil skimmer	Wessels, E.	Proceedings 12. Int. Conf. on Port and Ocean Engineering under Arctic Conditions (POAC), Vol. 2, pp 741-751	1993	CP			X									L
180	Response to a major gasoline release into the Mississippi River	Hartley, J.M, Hamera,D.F.	Oil Spill Conference 1995, pp 453-458	1995	CP						X						L
181	Development of a high capacity rotating brush/rope mop skimer	Prier,D.L.	Exxon Production Research Company, EPR.40PS.88	1988	TR			X	X								M
182	Anticipated oil-ice interactions in the Bering Sea	Martin, S.	Arctic Spills and Countermeasures, Chapter 8	1980										X			L
183	Alaska Clean Seas, A 1984 status report in arctic spill response	Hillman, S.O.	Sohio Alaska Petroleum Company													X	L
184	The behaviour of oil in ice	Fingas, M.F.	HELCOM-Seminar "Combatting Marine Oil Spills in Cold and Icy Conditions", Helsinki, Finland	1992	CP									X			L
185	Cold weather reponse F/V Ryuyo Maru No. 2 St Paul, Pribiloff Islands, Alaska	Reiter, G.A.	Oil Spill Conference 1981, pp 227-231	1981	CP						X						L

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