






Acute Oil Spills in Arctic Waters – Oil Combating in Ice

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Confidentiality: Public

Report's title Acute Oil Spills in Arctic Waters – Oil Combating in Ice	
Customer, contact person, address Research Council of Norway	Order reference 188913/I40
Project name Construction and intervention vessels for Arctic oil and gas operations	Project number/Short name 31782 /CIV Arctic
Authors Saara Hänninen, Jukka Sassi	Pages 64/
Keywords Oil combating, arctic waters, oil in ice.	Report identification code VTT-R-03638-09
<p>Summary</p> <p>This report is part of the R&D project no. 188913/I40, “Construction and intervention vessels for Arctic oil and gas operations”, funded by the Research Council of Norway. The primary objective of the project is to extend the operational season for installations and maintenance of sub sea oil and gas installations in waters with seasonal ice. The project investigates operational profiles and vessel parameters for vessels designed to operate in arctic waters with medium first year ice in the winter season.</p> <p>This report is part of the work in WP5 Ecological Footprint, led by VTT. WP5 aims at understanding and adaptation environmental aspects into marine applications. The objective of the WP5 is to evaluate ecological footprint and document emission reductions possible for a new dedicated design for an arctic construction/intervention vessel.</p> <p>It should be noted that the oil spill study was not included in the original project plan and no additional resources were allocated to carry out the task. Thus this report does not provide a comprehensive overview on the oil spill combating in ice, but rather an overview of the research on this subject has been performed mainly in Finland and in Norway in the recent years. The aim of this report is to present the characteristics of oil combating in arctic conditions. It is explained how the ice, cold climate and darkness makes the task – which is not simple in open waters – even more challenging. In addition to various recovery methods, oil spill monitoring and detection and oil behaviour issues are briefly described.</p>	
Confidentiality	Public
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Distribution (customer and VTT) Research Council of Norway 1 VTT 1	
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Preface

This report is part of the R&D project no. 188913/I40, “Construction and intervention vessels for Arctic oil and gas operations”, funded by the Research Council of Norway. The project started 1 September 2008 and will end 31 December 2011.

MARINTEK is the project owner. Other partners in the project are VTT, Aker Arctic, STX Europe Norway, Statoil and NTNU – CESOS. A four tiers management organisation includes Steering committee, Project manager, Work package leaders and Task leaders. The project is split in 7 work packages (Figure 1).

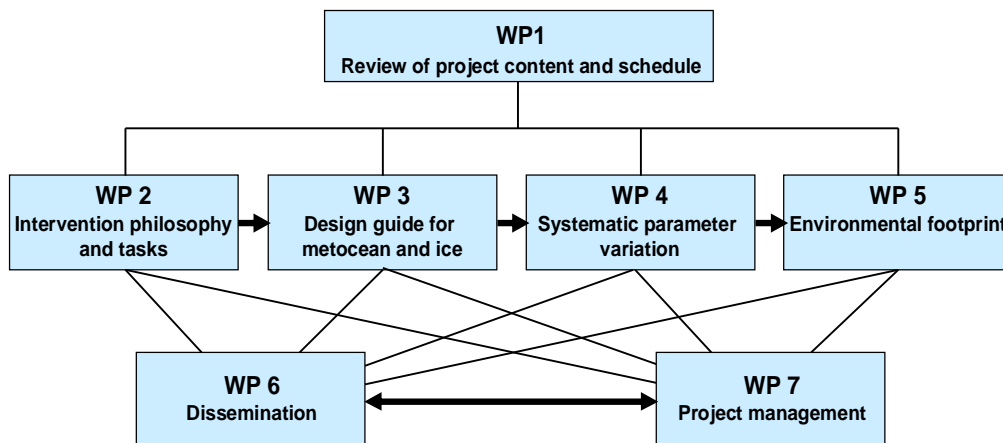


Figure 1 Work package structure.

This oil spill report is part of the work in WP5 Ecological Footprint, led by VTT. While planning the project, it was already decided in the Project Management Committee that a large-scale risk analysis proposed by VTT would be too heavy for the purposes of the project. During the project, it came anyhow clear that oil spills should be addressed in some level and it was decided that a report concerning the characteristics of oil combating in ice will be prepared by VTT. The scope of the report had to be limited, since this work was not included in the original project plan and no additional resources were allocated for the study.

The report provides an overview to the latest achievements in oil combating activities conducted mainly in Finland and in Norway. Furthermore it includes information concerning the monitoring and detection of oil spills, oil spill behaviour and challenges and features in arctic oil combating. The aim of this report is not to provide a comprehensive overview on the oil spill combating in ice.

Espoo, 1.11.2010

Authors

List of abbreviations

AIS	Automatic Identification System
API	American Petroleum Institute
CFD	Computational fluid dynamics
CSA	Canadian Space Agency
EC	European Commission
EEZ	Exclusive Economical Zone
EMSA	European Maritime Safety Agency
EPPR	Emergency Prevention, Preparedness and Response
ERRV	Emergency Response Rescue Vessel
ESA	European Space Agency
ESRI	Environmental Systems Research Institute
FLIR	Forward Looking Infrared
GL	Germanischer Lloyd
GPR	Ground Penetrating Radar
HAT	Highest Astronomical Tide
HELCOM	Helsinki Commission
IMO	International Maritime Organization
IR/UV	Infrared/Ultraviolet
ISB	In-situ burning
ITOPF	International Tanker Owners Pollution Federation Limited
JIP	Joint Industry Program
MMSI	Maritime Mobile Service Identity
NOAA	National Oceanic and Atmospheric Administration
NEDRA	Net Environmental Damage and Response Assessment
NEXT	Oceanweather's North Sea and Norwegian Sea long-term metocean hindcast
NOFO	Norwegian Clean Seas Association for Operating Companies
OSCAR	Oil Spill Contingency And Response
OSD	Oil Spill Detection System
OSRA	Oil Spill Response Analysis
OWM	Oil Weathering Model
ROV	Remote Operated Vehicle
SAR	Synthetic Aperture Radar
SLAR	Side-Looking Airborne Radar
TAP	Trajectory Analysis Planner
ULS	Upward Looking Sonar

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1 Introduction

The expected increase in oil and gas activities in cold climate regions will require dedicated designs for future arctic offshore vessels. The primary objective of this project is to extend the operational season for installations and maintenance of subsea oil and gas installations in waters with seasonal ice. To obtain the primary objective the following secondary objectives must be realized:

- Development of maintenance philosophy where unplanned intervention takes place in periods with seasonal ice,
- Definition of operational limits/weather windows for intervention tasks,
- Vessel design to optimize operational characteristics in harsh weather, and
- Design trade-offs to find a vessel with high performance in harsh weather and first year ice.

Other key objective in the project is to evaluate ecological footprint and document emission reductions possible for a new dedicated design for an arctic construction and intervention vessel.

The most important environmental effects of transport are emissions to air related to energy consumption while another is accidental pollution. The construction and intervention vessel to be designed in this project is possible to equip with oil combating devices suitable for arctic areas.

The arctic region can be defined by latitude (the Arctic Circle) or by vegetation, temperature or other geographical or political boundaries. Figure 2 shows some common delineations of arctic regions. (Nuka, 2007b)



Figure 2. Delineations of arctic and sub-arctic regions (Nuka, 2007b and references therein).

Arctic environment is vulnerable to oil spills because it recovers very slowly due to slowness of oil decomposition in cold, dark conditions. Oil combating in arctic conditions is a challenging task due to extreme environmental conditions. Rough winds and poor visibility in the darkness of the wintertime in the north together with low temperatures makes oil recovery operations especially demanding. Ice and snow decrease the oil recovery efficiency remarkably and most oil combating devices are designed for open water use only. It is quite impossible and very expensive to build a sufficient infrastructure for oil combating in the vast and uninhabited areas of the Arctic. (UNEP, 1997; Öljyntorjuntavalmius merellä, 2007)

Cold temperatures affect on the physical characteristics of oil. If the density of the oil is greater than the density of the water, the oil may stay submerged. This is the worst case scenario since even in open water conditions these kind of combating cases have not often been successful. Only the heaviest fuel oils are heavier than water and behave like this. Lighter oils typically rise to the surface and in ice infested waters fill up the cracks between ice flows. Some of the oil still stays under ice and is difficult to detect and collect from there.

In open water, oil evaporates rather quickly. Natural evaporation and oil alteration is slower in cold climate. Under ice the oil can stay fresh for a long period without any alteration. The formation of oil emulsions needs mixing energy, i.e. wave energy. (Rytkönen & Sassi, 2001)

2 Expected operational area of the project vessel

In the project description it has been stated that the project will focus on developing a vessel that is tailor-made for performing operations in arctic waters where the operational location is covered with thin or medium thick first year ice. For the vessel design purposes it was agreed that vessel study should be done for at least two different locations with varying environmental conditions.

Statoil has suggested the operational areas should both be located in Norwegian waters and they should be identified as Barents Sea South and Barents Sea North. The sites are shown on the map in Figure 3.

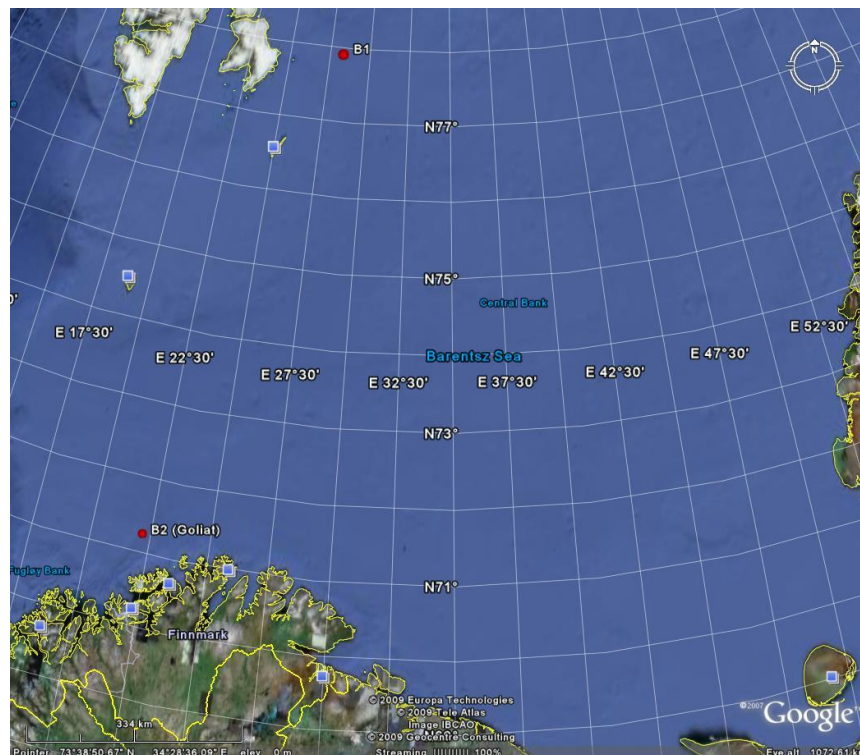


Figure 3. Suggested sites for project vessel's operational locations.

The Barents Sea South location B2 was defined as Goliat. For this site the met ocean design basis for Snøhvit will be used. The Barents Sea North location B1 was defined as Olga Basin (Figure 4).



Figure 4. The Barents Sea North location Olga Basin.

The logistic hub for serving the construction and intervention vessel will be located in Hammerfest. Sailing distance from the supply base to the work sites is estimated to be 85 km (approx. 46 nm) for the Goliat location (B2) and 820 km (approx. 443 nm) for the Olga Basin location (B1) off the Svalbard East Coast. The third location, Haltenbanken, was decided just before this report was finished. It is located in Norwegian Sea, 1 069 km (approx. 577 nm) from Hammerfest.

2.1 Metocean and ice statistics for the operational areas

The design basis for Snøhvit and metocean and ice statistics for Olga Basin is thoroughly described in the references (Mathiesen, 2007) and (Eik, 2009). Few extractions from the references are presented in this report. From the oil combating point of view, it is essential to plan the operations for prevailing conditions in the area. For example, marine operations may be delayed due to wind speeds or significant wave heights exceeding prescribed operational limits. Wave height may also cause problems in oil combating with oil booms which are not intended to be used in rough open water environment. In addition, winds and waves mix the oil into the water and the ocean currents transport spilled oil quickly. Snow and ice makes the oil recovery very difficult.

The references contain numerous statistical figures and therefore it's pointless to insert them in this document. However, some information about the Snøhvit field and Olga Basin is presented here.

2.1.1 Metocean design basis for Snøhvit field

Water depth

The water depths are in the range of 310 – 340 m.

Water level

Tidal elevation: For example, in 2007 the mean spring tidal amplitude was about 90 cm. The highest tidal amplitude was 103 cm (day 49, i.e. 19 February). Using the tidal prediction program developed as part of the NEXT (Oceanweather's North Sea and Norwegian Sea long-term metocean hindcast) study the highest astronomical tide (HAT) is found to be 1,2 m, i.e. 0,2 m higher than determined from the NAO99 tidal prediction system.

Storm surge: Storm surges in the open ocean are generally due to the increase in water level due to the reduced barometric air pressure, called pressure surge. The "rule of thumb" is that a reduction in barometric pressure by 1 hPa increases the water level by 0,01 m (1 cm). The storm surge with annual probability of exceedance of 10^{-2} is found to be about 0,8 m.

An additional increase in water level may be due to climatic effects, e.g. the increase in water level due to the general warming of the oceans. This effect is estimated to be in the range 0,1 – 0,9 m by the year 2100. Table 1 shows estimates of the total extreme water levels to be expected at the Snøhvit Field.

Table 1. Estimates of the total extreme water levels to be expected at Snøhvit.

	Annual probability of exceedance	
	10^{-2}	10^{-4}
Tidal amplitude (NEXT)	1.2 m	0.0 m
Storm surge	0.8 m	1.0 m
Wave crest height	16.6 m	21.5 m
Total water level	18.6 m	22.5 m

Snow

The maximum thickness of snow in a single fall may be taken to be 0,25 m. The snow has a density of 200 kg/m^3 initially. The snow will most likely adhere to and accumulate on horizontal and windward facing (vertical) surfaces when the air temperature is not far below $0 \text{ }^\circ\text{C}$.

Icing

Two types of icing may occur: atmospheric icing and ice accretion by sea spray. Because accumulation of snow and glazed frost occurs mostly at temperatures in the range $0 - 3 \text{ }^\circ\text{C}$ and sea spray occurs at temperatures well below these temperatures, the simultaneous occurrence of ice caused by rain and snow and ice caused by sea spray is unlikely.

Atmospheric icing caused by rain and snow gives a hard and even surface. The glazed frost appears on upward and windward facing surfaces between 5 m above mean sea level and the top of the structure. Ice accretion by sea spray depends mainly on wind speed and temperature.

Sea water temperature

Figure 5 shows monthly mean temperature of sea water profiles in Snøhvit.

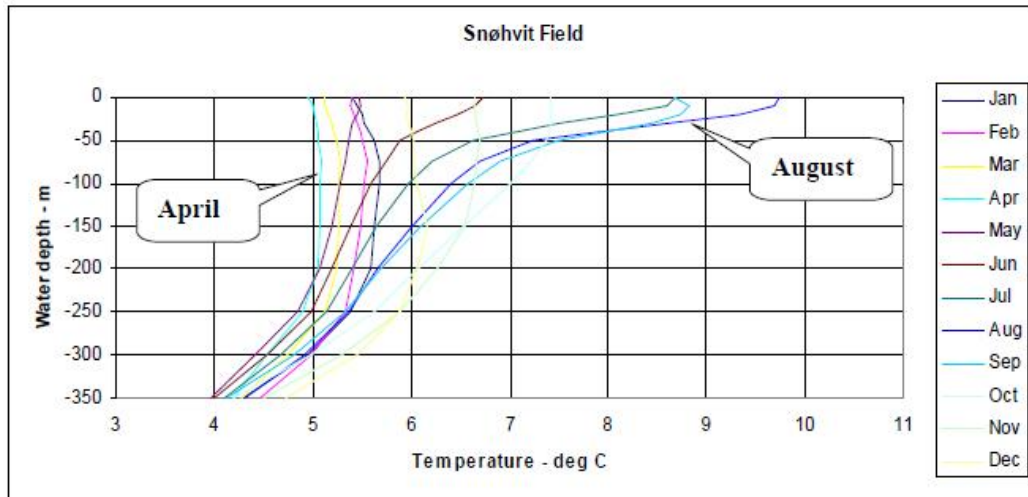


Figure 5. Monthly mean sea temperatures in Snøhvit .

Air temperature

Monthly and annual air temperatures at the Snøhvit Field are presented in Table 2.

Table 2. Monthly and annual air temperatures in Snøhvit.

T[°C]	Jan	Feb	Mar	Apr	May	Jun
Min	-12,6	-14,3	-12,4	-9,7	-4,8	-0,5
Mean	-0,9	-0,9	-0,2	1,1	3,6	6,2
Max	6,6	6,4	6,7	9,1	11,2	14,5

T[°C]	Jul	Aug	Sep	Oct	Nov	Dec	Year
Min	3,2	3,4	-0,1	-5,0	-9,3	-10,5	-14,3
Mean	8,7	9,0	7,0	3,8	1,5	-0,2	3,3
Max	16,1	16,4	15,0	11,1	8,8	7,7	16,4

Salinity

Salinity varies depending on the water depth and the season between 34,6 and 35,1 ppt.

2.1.2 Metocean and ice statistics for the Olga Basin

Water depth

The water depth in the region is about 200 m.

Wind data

Wind data for the Olga Basin are based on hindcast data produced by the Norwegian Meteorological Institute – WAM grid point 77.92N, 28.4E. The data cover the period September 1957 – December 2008. It should be noted that in periods when the location has been covered with sea ice, no wind data are available. Figure 6 shows the (all-year) wind rose. The wind rose shows the percentage of observations within each 30° sector.

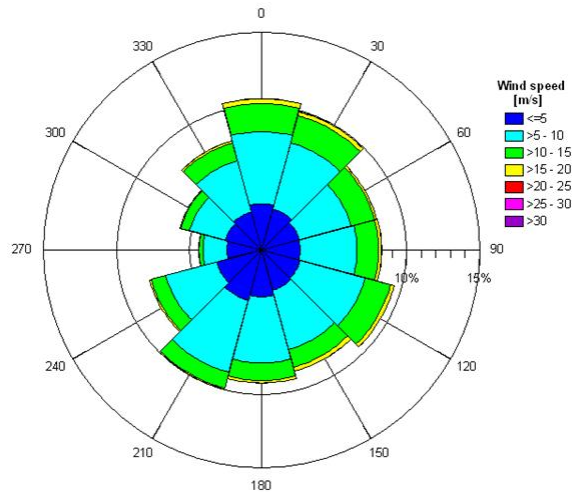


Figure 6. All-year wind rose in Olga Basin.

Wave data

Wave data for the Olga Basin are based on hindcast data produced by the Norwegian Meteorological Institute – WAM grid point 77.92N, 28.4E. The data cover the period September 1957 – December 2008. It should be noted that in periods when the location has been covered with sea ice, no wave data are available. All data corresponds 3-hour sea states. Figure 7 shows the (all-year) wave rose. The wave rose shows the percentage of observations within each 30° sector.

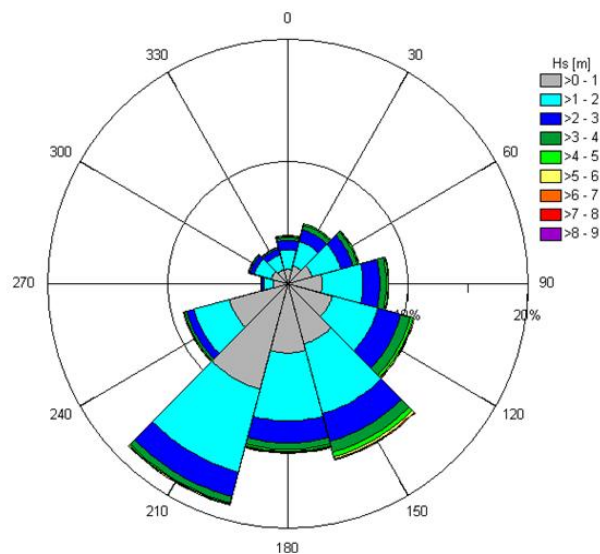


Figure 7. All-year wave rose in Olga Basin.

Current data

No data sources for surface currents have been found. Current data has been measured at 135 m water depth in the period August 1993 to August 1995 and at 99 m from August 1995 to August 1996. Due to the depths, these data are considered to have very little relevance for oil drifting at the surface.

Sea ice

Sea ice thickness was measured by the Norwegian Polar Institute by use of an Upward Looking Sonar (ULS) during the winters 1994-95 and 1995-96. This is the only long-term recording of ice drafts in the entire Barents Sea. According to time series of measured ice draft over a two year period there is a significant inter-annual variability. The average ice draft over the period with draft recordings was 2,61 during the first season and 1,56 during the second season. There are recordings where ice draft has been 5 - 6 metres. The minimum number of ice days was 21 while the maximum was 64. The mean number of days with sea ice is 53. However, care should be taken when using these numbers as the source data not is continuous.

Air temperature

Monthly mean air temperatures and an 80% confidence interval are presented in Figure 8.

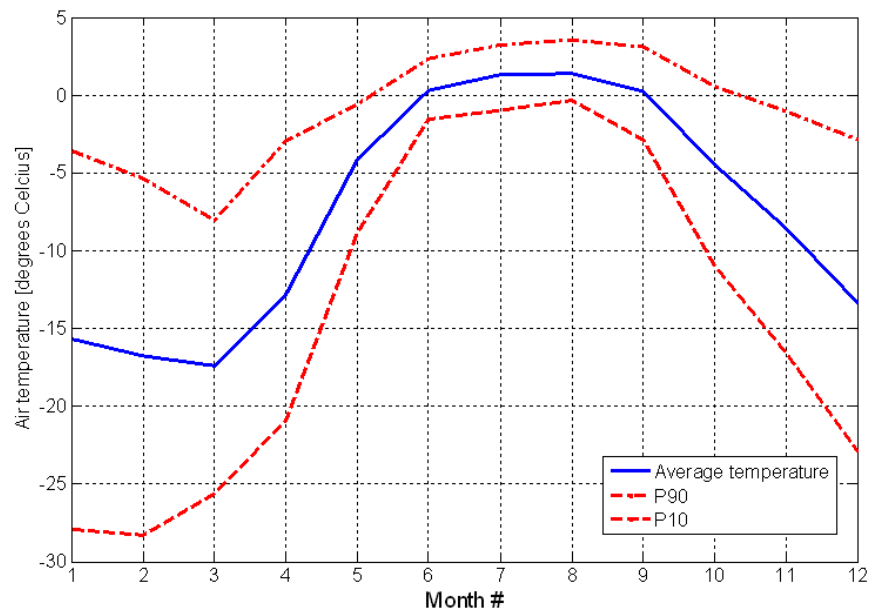


Figure 8. Monthly mean air temperatures and an 80% confidence interval. The temperatures refer to 1-hour averaged values.

3 Risk of oil spills in arctic offshore oil production

The offshore oil production is moving towards and into the ice-covered waters. The practices and solutions regarding the safety issues there have not been developed yet. Most of the practices and philosophies from open water conditions can be fairly easily adapted in ice-covered waters. In the Arctic though, one great challenge is the remoteness of the offshore oil fields. The infrastructure is not built and the field should cope with many challenges on its own. The support fleet required to serve such a field is much larger than needed at today's fields in e.g. North Sea. The required safety level and feasible support fleet for an arctic offshore oil field have been studied in (Hänninen, 2001). The example field in this reference was Prirazlomnoe in the Pechora Sea.

Typical sources of accidental marine oil spills are ruptures of underwater pipelines and ships' hull damages due to ice pressure, groundings or collisions. Underwater oil leakage may also happen in oil terminals where loading buoys are in use. Also illegal bilge water releases are a problem, but they are not accidental. They should be completely avoided in other means.

When moving the oil production from the open seas to the arctic ice-covered seas, the risks of accidental oil spills grow considerably due to more severe environmental conditions and the lack of infrastructure. The safety of offshore oil production is generally well organized with rules and regulations as well as the oil company procedures developed during over decades. There are no special regulations in place for the arctic sea areas yet. Internal safety of the platform can be assumed similar to the one in open sea platforms even though the procedures from traditional offshore industry do not directly apply to ice-covered area. Function of the support fleet is essential for the external safety of the field located far from land based infrastructure. Arctic conditions cause a great number of supplementary requirements for the support fleet.

The risk represents the magnitude of hazard of a harmful incident, expressed as product of probability and consequences:

$$R = P * C$$

where P is the probability of the event and C is the expectation value of the severeness of the consequences.

In arctic conditions, the same accident scenarios are valid as in open seas but furthermore, arctic conditions bring new hazards that can be caused by ice cover, snow, ice accretion and low temperatures. Consequences of accidents are often more fatal in the Arctic, for both people and environment. Long distances and darkness during the winter in the North increase the risk by making combating and rescuing operations more challenging.

4 Monitoring and detection of spilled oil in arctic conditions

4.1 General

Aerial observation is an essential element for effective response to marine oil spills in order to assess the location and extent of oil contamination. Additionally it is used to verify predictions of the movements and fate of oil slicks at sea. It provides information facilitating deployment and control of operations at sea, the timely protection of along threatened coastlines and the preparation of resources for clean-up. (ITOPF, 2009)

Spill detection and mapping are particularly important for arctic spills, as oil may be hidden under snow and ice during periods of almost total darkness. During situations in which weather or ice conditions can limit recovery operations, surveillance may be the only ongoing response activity. An ideal system would have the capability of operation in both airborne and ground-based modes and have the capability of determining whether oil is present as well as to map the boundaries of contamination over potentially large areas. (Sørstrøm *et al.*, 2010)

4.2 Surveillance of oil discharges in Finland

The Finnish authorities are using two Dornier aircrafts to monitor oil discharges from ships within Finnish exclusive economic zone (EEZ), which is also the Finnish pollution response zone. Finnish Environment Institute (SYKE) is responsible for the surveillance of oil discharges and has an agreement with the Border Guard on the oil discharge surveillance.

Two Border Guard's Dornier 228 surveillance aircrafts are equipped with SLAR and IR/UV scanner. SLAR (side-looking airborne radar) can detect foreign substances (e.g. oil) in the sea at distances of up to 10 or even 20 nm to either side of the aircraft. Thus, when flying along the central line of the Gulf of Finland, the whole sea area from the Finnish coast to the Estonian coast can be monitored. The IR/UV scanner (infrared and ultraviolet frequencies) is used to locate the thickest parts of the slick and for volume estimations of an oil slick.

Additionally, AIS (Automatic Identification System) transponder has been integrated into the oil spill monitoring system enabling the operator to have a real-time maritime picture overlaid on the SLAR picture. High speed satellite data connection enables data transmission from the air to ground at anytime.

The maritime surveillance radar and FLIR (forward looking infrared) camera provide important additional documentation means especially in cases where a polluter has been detected.

The Border Guard's premises in Turku (South-West Finland) have a computer with similar software as that in the aeroplanes. This so called "ground station" is used for post processing of the flight data i.e. to view the SLAR and scanner re-

cordings with different settings. It is also possible to make hard copies and create still images files from single frames of the recorded data. The data is transferred from Border Guard to SYKE using a high speed data connection.

The surveillance equipment enables the crew to have, even in darkness or in bad visibility, a real-time view of Finnish waters and possible foreign substances floating on water surface. When Border Guard is carrying out border patrol flights, they also survey for illegal oil discharges.

In addition, Navy and Border Guard vessels, as well as merchant vessels inform about oil observations they make. Finland is using also CleanSeaNet monitoring service of EMSA (European Maritime Safety Agency) to detect oil pollution at sea. CleanSeaNet is a satellite based monitoring system for marine oil spill detection and surveillance in European waters. The service provides a range of detailed information including oil spill alerts to Member States, rapid delivery of available satellite images and oil slick position. (SYKE, 2010b; EMSA, 2010)

According to the experience of the SYKE experts the utilization of SLAR, IR/UV and FLIR equipment is defective when solid ice-cap or close packed ice floes is present. In some specific environmental conditions IR/UV scanner might observe temperature differences between oil and ice but normally ice will balance the temperatures thus adequate differences does not occur (Haapasaari, personal communication, 12.8.2010). These findings support the conclusions of the JIP Oil in Ice program presented in the following chapter.

4.3 Findings from the JIP Oil in Ice program

The key findings from the JIP (Joint Industrial Programme) Oil in Ice indicated that a flexible combination of sensors operating from aircraft, helicopters, vessels, satellites and from the ice surface is recommended for future arctic oil spill emergency preparedness.

The most useful remote sensors and systems applicable to arctic oil spill are the following:

- Side-Looking Airborne Radar (SLAR),
- Satellite based Synthetic Aperture Radar (SAR),
- Aircraft and vessel-based Forward Looking infrared (FLIR),
- Trained dogs, and
- Ground Penetrating Radar (GPR) operated from helicopters and/or from the ice surface.

The current generation of all-weather SAR satellites can have a valuable support role in mapping detailed ice conditions and direct marine resources.

Existing commercial GPR systems can be used from low flying helicopter to detect oil trapped under snow on the ice and to detect oil trapped under solid ice.

Trained dogs are able to reliably detect very small volumes of oil and to map oil boundaries on solid ice and in sediments on arctic shorelines under cold conditions.

According to the findings the detecting of isolated oil patches trapped among closely packed ice floes is a major challenge with any current remote sensing system, particularly during periods of extended darkness. (Sørstrøm *et al.*, 2010)

4.4 Examples of modelling tools

During the last decades large numbers of numerical models have been developed to provide supporting information for oil spill response planning. The aim of these models is to help planners and decision-makers answer many important questions such as which are the areas that could be affected by the spilled oil and how long it will take for a spill to reach a specific location.

OSRA (Oil Spill Response Analysis) model was developed to support in estimating the environmental hazards of oil resources in Outer Continental Shelf lease areas. OSCAR (Oil Spill Contingency And Response) model was developed to supply the public and private sectors with a tool providing an objective analysis for alternative oil spill response strategies. NOAA (National Oceanic and Atmospheric Administration) developed the Trajectory Analysis Planner (TAP) to analyze statistics from potential spill trajectories generated by an oil spill trajectory model. Skognes and Johansen developed a model to estimate statistics on the spatial distribution of pollutants in the water column. All these models utilise trajectory model to simulate oil spill trajectories under different environmental conditions. (Abascal *et al.*, 2010, references therein)

The study presented in the reference (Abascal *et al.*, 2010) focused on the development of a statistic oil spill model and its validation by means of actual oil slick observations reported during the Prestige accident and drifter buoys trajectories. The model has been applied to the Bay of Biscay (Spain) to support spill response planning along the Cantabrian coast which was most affected by the Prestige oil spill.

Another model to forecast the behaviour and spreading of oil at sea, also in cold water and in ice conditions, is the model developed by professor Ovsienko (Ovsienko *et al.*, 1999). Example of oil spreading in the Gulf of Finland on a typical autumn day has been presented in Figure 9.

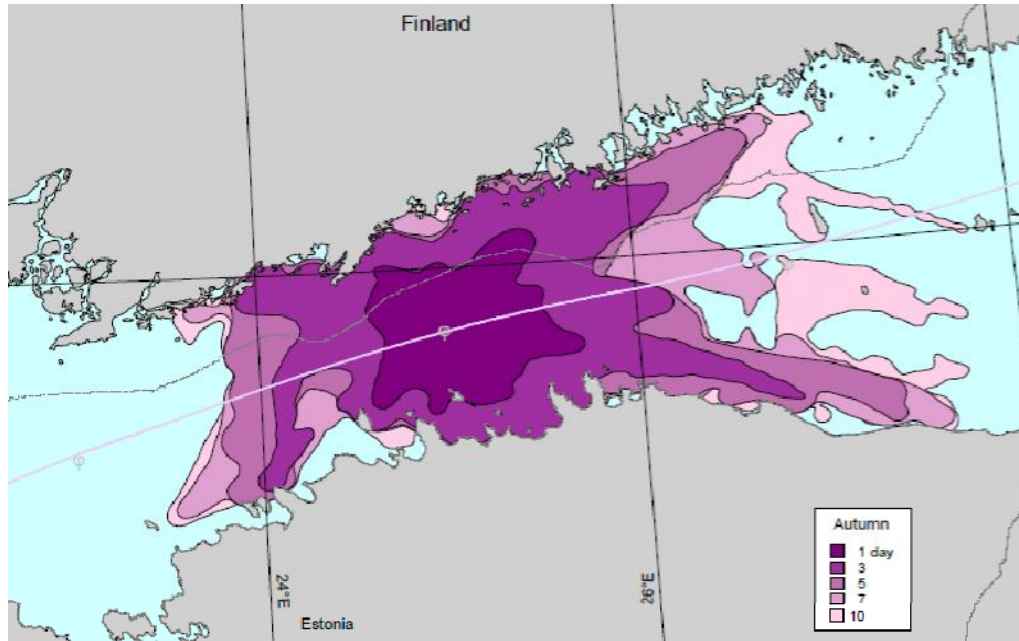


Figure 9. Schematic illustration of imaginary oil spill in the Gulf of Finland according to the model developed by prof. Ovsienko (Tahvonon, 2008).

Also ice movements can be forecasted and new ice services are being developed in Polar View program. Polar View is an earth observation or satellite remote-sensing program, focused on both the Arctic and the Antarctic. Polar View is supported by the European Space Agency (ESA) and the European Commission (EC) with participation from the Canadian Space Agency (CSA). Polar View offers integrated monitoring and forecasting services in the Polar Regions, as well as mid-latitude areas affected by ice and snow. (Polar View, 2010)

Additionally, Gjøsteen (2003) developed a model for oil spreading on sea based on forces acting in the horizontal dimension. It consists of conservation laws for volume and momentum. The model is valid for a complex slick geometry, and is suitable for coupling to a discrete element ice model or other complex boundaries, for example coast lines.

SINTEF is utilizing a NEDRA (Net Environmental Damage and Response Assessment) approach when conducting oil spill analysis for the oil industry. The 3D Oil Spill Contingency And Response (OSCAR) model developed at SINTEF, is used to predict a mass balance (i.e. surface, water column and shorelines) with or without response. When combining the mass balance with vulnerable natural resources (e.g. fish eggs and larvae during spawning periods, see bird activity), the effects of different response strategies will be evaluated. (Singsaas, personal communication, 15.9.2010)

4.5 Examples of remote sensing equipment providers

There are several providers worldwide for remote sensing equipment for oil spill detection. One provider is the Kongsberg Satellite Services (KSAT), a commercial satellite centre situated in Tromsø, Norway. They have ground stations in

Tromsø, Svalbard, Grimstad and the Antarctic and they have provided a service utilising satellite radar images for detection of oil spill since 1994.

According to the reference (KSAT, 2010) the centre utilises satellite based Synthetic Aperture Radar (SAR) which can provide large coverage of the Earth's surface independent of weather and light conditions and has therefore become one of the most important sensors for operational monitoring of the marine environment.

The satellite based information is used in combination with other surveillance methods, e.g. dedicated aircraft equipped with radar (SLAR) and IR/UV scanner, and it helps optimise the use of coastguard vessels and surveillance aircrafts.

The current service has been developed in close cooperation with key end users such as pollution control authorities in Northern Europe. The Oil spill detection service can be applied on a global scale. (KSAT, 2010)

Another provider for oil spill detection system is a company called Miros, who has a radar based product called Miros OSD. It can be used for continuous oil spill surveillance, as a stand alone system or as complement to satellite systems for monitoring of high risk areas such as off-shore installations, oil terminals and ports. According to the marketing material it provides continuous local surveillance and ensures progress in an oil recovery operation in time periods when no aerial data are available. The Miros OSD System has been developed in cooperation with NOFO (Norwegian Clean Seas Association for Operating Companies). (Miros, 2010)

According to the experiences from Norway and Finland the equipped mentioned above have not demonstrated their ability to detect oil in ice conditions.

A novel solution for oil spill monitoring and response called SECurus is introduced by Aptomar AS from Norway. According to the reference (Aptomar, 2010) the SECurus active infrared camera detects and visualizes an oil spill by:

- Automatically calculating the spill location and displaying its boundaries on a sea chart;
- Estimating the thickness of the oils pill up to 2,2 nm away to pinpoint the optimal area for combating actions;
- Sharing spill location and status information in real time with all responding parties on sea, land and in the air.

The SECurus system has been tested in several field trials and is implemented aboard several ships operating outside Norway. The system is able to detect the extent and thickness of oil at sea under dark and cold conditions. The project was financed by the Norwegian Research Council with support from Statoil, ENI and NOFO. The Norwegian oils spill response authority NOFO has specified SECurus technology in their ERRV class notation for all new oil response vessels commissioned to operate in Norwegian waters. (Aptomar, 2010; Johnsen, personal communication, 27.9.2010)

Another new system developed by Rutter Inc. from Canada is called Sigma S6 Oils Spill Radar. The system is able to detect oil from both moving vessels and stationary platforms early for improved response and containment. It includes automatic archiving of ESRI file data, AIS target and chart overlay capability and horizontally and vertically polarized antennas are available.

In September 2010 Rutter Inc. received an official notification from NOFO confirming that Sigma S6 Oil Spill Response Radar is compliant with the NOFO standard. The NOFO standard applies to the design of and the equipment carriage requirements for oil spill response vessels operating on the Norwegian Continental shelf. (Rutter, 2010)

In addition to the products mentioned above at least the suppliers such as SeaDarQ, Sea-Hawk, VisSim and Consilium are developing radar based oil spill detection products.

5 Oil spill behaviour

5.1 Weathering and behaviour of spilled oil

Weathering is the combination of physical and chemical processes that change the properties of the oil after a spill has occurred and the oil has been exposed to environmental degradation (Figure 10).

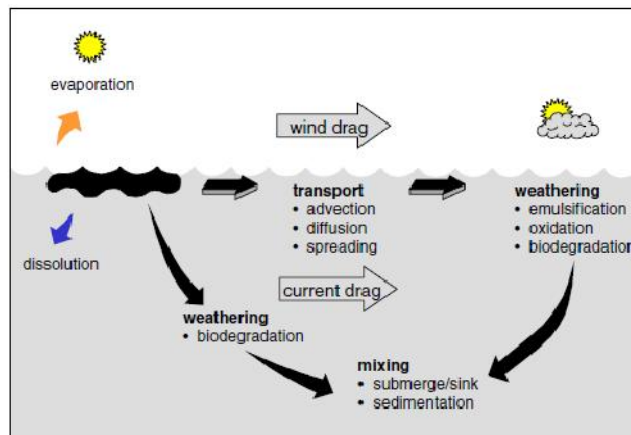


Figure 10. Oil weathering processes (EPPR, 1998).

Natural processes that occur initially and are important for response operations are:

- oil-in-water (O/W) dispersion,
- water-in-oil (W/O) emulsification,
- evaporation,
- spreading, and
- sinking or sedimentation.

Processes that are predominant in the later stages of weathering, and that usually determine the ultimate fate of the spilled oil, include biodegradation and oxidation.

The rate of weathering depends on:

- oil type (physical properties, such as viscosity and pour point; chemical properties, such as wax content),
- the amount of spilled oil,
- the proportion of the surface area of the oil that is exposed,
- wave, current, ice and weather (temperature and wind) conditions, and
- the location of the oil (on the water surface or submerged; on, in, or under ice; on a shoreline or buried in shore sediments).

Non-persistent oils, such as gasoline, aviation fuel and diesel usually evaporate rapidly, provided that they are exposed to the air, i.e. they are not buried or covered. These refined oils contain only light fractions and weather primarily through evaporation. The evaporation rates increase as the temperature rises and as wind speed increases. In calm conditions, between 5 - 20% of diesel fuel will evaporate in 2 days on warm water (0 to 5 °C) and in 4 or 5 days on very cold water (-20 to 0°C). Also the thickness of oil has a strong effect on evaporation.

Diesel oil may also contain heavier fractions and then the evaporation is slower than for gasoline. In open water conditions natural O/W dispersion can be even more important weathering parameter to remove refined products from the surface than evaporation, especially in strong winds. In ice conditions it's more dependent on spill scenario.

Persistent oils weather and break down more slowly. If emulsification occurs, an increase in the volume of the oil results as water and oil mix. The physical properties of the oil also change, which in turn can affect the choice of response options that will be successful, i.e., skimming, in-situ burning and dispersion. (EPPR, 1998; Singaas, personal communication, 25.8.2010)

5.2 Oil on water

The behaviour of oil on water and in ice depends on the relative densities of the oil and water. Oil that is less dense than water will float on the surface and is subject to weathering. Oil which is denser than water will submerge and is subject only to dissolution which is usually a minor weathering process. Submerged oil will degrade slowly. Floating oil with almost same density as sea water may submerge if the oil meets less dense freshwater. (EPPR, 1998)

Sea water with salinity of 25‰ has a density of 1 025 kg/m³ and in those conditions all oil types floats initially. (Singaas, personal communication, 25.8.2010)

5.3 Oil in ice

Buoyant oil under ice will migrate to the underside of a floating ice sheet, which typically has an uneven surface. A current of 0,4 m/s is usually required to move oil along the underside of the ice. Oil will tend to migrate to pockets on the underside (Figure 11, number 1) unless lateral movement is stopped by ice ridges or keel (Figure 11, number 2).

Ice forms by freezing at the ice-water interface. Oil at that interface can become frozen into the ice sheets. As the ice melts on the upper surface and continues to form on the underside, oil will move up through the ice sheet (Figure 11, number 3) and eventually appear to on the upper surface. The primary mechanism by which oil migrates upwards is through brine channels or cracks in the ice (Figure 11, number 4).

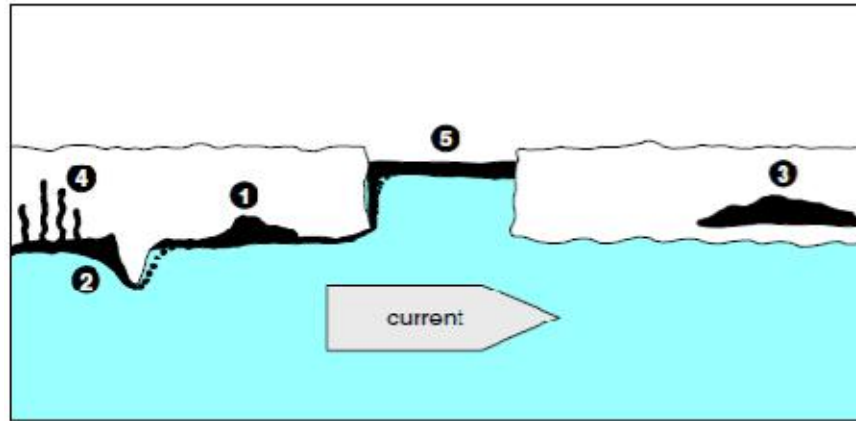


Figure 11. Oil in and under ice (EPPR, 1998).

If the oil finds a break in the ice sheet, such as lead or a seal hole, it will flow into the open water (Figure 11, number 5) and may spill over onto the surface of the ice. Oil in broken ice will tend to collect in leads, unless lateral movement is prevented on the underside of an ice floe. During freeze-up, new ice can form on the underside of a slick. (EPPR, 1998)

The JIP Oil in Ice Program concluded that oil spills in ice spread much slower and occupy a much smaller area than a similar spill in open water. Oil will have a slower weathering in ice which will be an advance and contribute to the enhancement of response effectiveness for certain types of oil spill scenarios. SINTEF has performed various weathering studies for different crude oils from Norwegian oil fields (Figure 12).

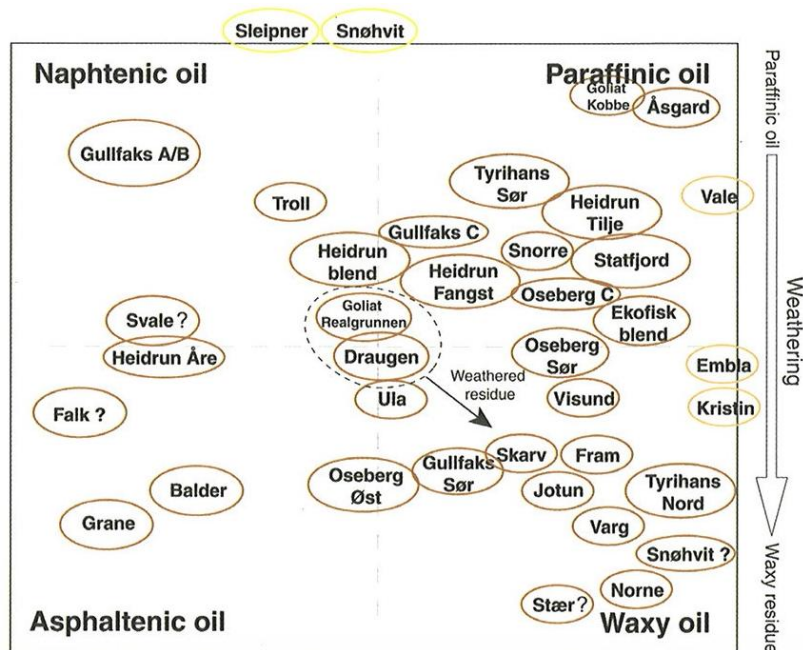


Figure 12. Illustration of different crude oil properties based on earlier weathering studies performed at SINTEF (Sørstrøm et al., 2010).

The Oil Weathering Model (OWM), developed by SINTEF, can be used to predict the behaviour of various types of oil in ice in order to help plan different response scenarios. OWM is the only model verified by large-scale field experiments with oil in ice.

In order to design an effective spill response organization, SSPA Sweden AB has developed “Oil in Ice Code” to define the main design criteria and identify operational conditions (Table 3). The code is a decision backing support system that systematically structures expected ice conditions, concentration (ice coverage), thermal regimes, spill types, the logistical resources available, expected weather conditions and the expected oil types to be handled.

Table 3. Oil in Ice Code (SSPA, 2010)

F / C / T / D		
Iceform / Concentration / Temperature / Dynamics		
F – iceform, -type 0 = ice free water 1 = slush < 2 cm 2 = small brash < 40 cm 3 = brash < 2 m 4 = bigger pieces < 6 m 5 = floes ≥ 6m 6 = large floes / pack ice	C – concentration 0 = no ice 1 ≤ 1/10 concentration 2 ≤ 2/10 3 ≤ 3/10 4 ≤ 4/10 5 ≤ 5/10 6 ≤ 6/10 7 ≤ 7/10 8 ≤ 8/10 9 ≤ 9/10 10 > 9/10, incl. ridges	T – temperature - = freezing 0 = close to 0°C + = melting D – Dynamics 0 = calm 1 = oil and ice drifting 2 = severe movements, ridging, waves

SSPA recommends that the code approach becomes an integral part of operational planning based on the Ice Master support. Ice Master is a risk-based decision support tool for the dimensioning and safe delivery of customised services for off-shore operations in the Arctic. (SSPA, 2010)

6 Specific features and challenges in oil combating in arctic conditions

In the ice-covered sea areas the behaviour of oil differs substantially from open water conditions. Ice restrains oil to spread around freely since oil mainly spread via cracks and with drifting ice field. In cold climate evaporation is considerable slower and oil remains quite fresh for longer time, especially if oil enters under the ice cover (Figure 13).

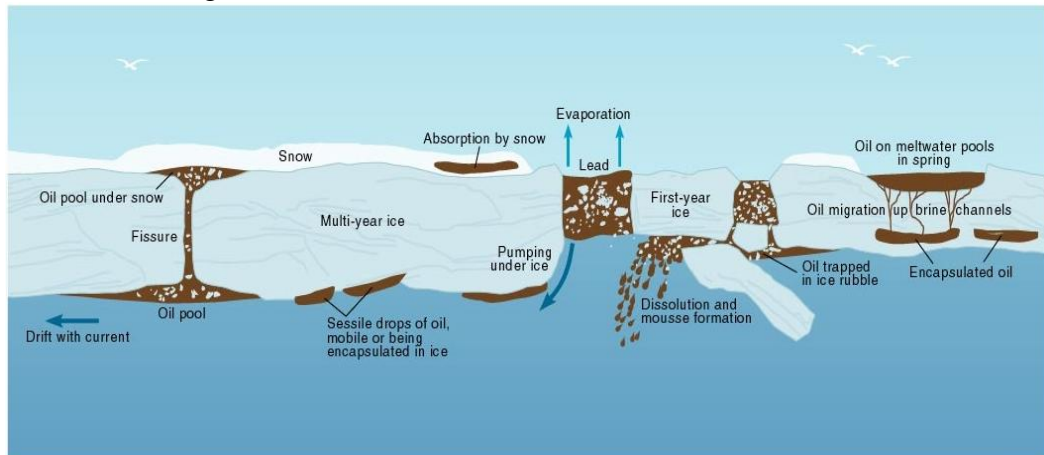


Figure 13. Oil-Ice interaction (AMAP, 1998).

Depending on wind and current conditions long-term ice can move hundreds or thousands of kilometres from the spill site before the ice starts to melt. Oil then fills up the open water areas between the ice floes and causes trouble for birds and other animals. It is therefore important to gather the oil from the ice already during the winter. Natural cleaning takes decades in arctic conditions, compared to a few years in a temperate climate.

Catching the oil from ice infested waters is slow and laborious. Detecting oil and predicting its movements is more difficult than in open waters. Working in the coldness and darkness of the Northern winter is demanding. On the other hand, ice has one good quality for oil combating: it works as a natural oil boom and restricts the spreading of the spilled oil (Öljyntorjuntavalmius merellä, 2007).

When the ice concentration is higher than “close pack ice” – over 60%¹ of the sea surface is ice-covered – the ice floes physically limit spreading. The spreading increases as the ice concentration decreases until it reaches the open water state in open drift ice (30% and less ice covered). (Buist & Dickins, 2000)

In case when oil gets into the sea water which is about to freeze, oil may form different forms of oil/ice states and partly frozen inside the ice. Oil can also move along the salt water channels inside the ice and penetrate through the ice cover.

¹ Comment by Ivar Singaas: Close pack ice higher than 60%, more like 90%.

Sea currents and coarseness of the underneath ice cover have an effect on the diffusion of oil that has entered under the ice cover. The ice cover makes the observation and collection of oil more difficult. If the ice field starts to move and split into smaller parts, effective oil combating activities are demanding and often unsuccessful.

Cold climate convert fluid oil fractions into stiff ones and this feature must be taken into the consideration when selecting appropriate combating equipment. Oil qualities with high viscosity and solidifying temperature cannot be pumped with conventional pumps. Oil combating activities require heavy-duty equipment operated by motivated and high-skilled professionals. Additionally, when operating in extreme cold environment 24/7 operation is required since the re-starting and set-up of the combating devices might be complicated and time-consuming. (Rytkönen, 2001; Högström, personal communication, 20.1.2010)

Since the properties of crude oils vary between different oil fields, the composition of the oil to be extracted from the operational area need to be classified. The properties of the oil have effect on selected combating technologies and equipment.

When oil needs to be removed under the ice sawing of cracks or holes through the ice is one possibility. This operation needs special “ice saws” that has been developed at least in Finland and in Canada. The Finnish device can saw 19 cm wide cracks into maximum of 1,3 meter thick ice. Different sorbents can be placed into the cracks or the oil can be removed by skimmers or pumps.

Also some attempts have been made to move the oil by compressed air and currents generated by azimuth-type propulsion of vessel. The experiences from the actions have not been too encouraging since the control over the air flow appears to be difficult. In some specific cases, such as limiting of oil spill in harbour area, a submerged compressed air pipeline has been utilized successfully in oil combating (Rytkönen, 2001). Table 4 summarises typical arctic conditions and their potential impacts on spill response options.

Table 4. Typical arctic conditions and potential impacts on spill response options (Nuka, 2007b).

Conditions	Potential impacts on spill response			
	General constraints	Mechanical recovery	In-situ burning	Dispersants
Sea ice²	Ice can impede access to the spill area, making it difficult to track and encounter oil. Remote sensing techniques are being improved and refined to detect oil under and among sea ice, but they are not yet mature. Ice can impede or limit vessel operations, especially for smaller work boats. Boats without ice-capable hulls should not operate in heavy ice conditions. Slush ice may clog seawater intakes or accumulate in vessel sea chests.	<p>Containment boom can be moved, lifted or torn by ice.</p> <p>Skimmer encounter rate may be reduced by ice chunks, and skimmers and pumps may clog.</p> <p>Limited manoeuvrability may prevent or delay accurate skimmer or boom deployment.</p> <p>Attempts to deflect the ice from recovery areas may also deflect the oil.</p> <p>Ice must be separated from recovered oil.</p> <p>Ice may provide natural containment.</p> <p>Reinforced vessel hulls or ice scouts may be required. Ice movement can be unpredictable or invisible.</p> <p>Vessel operators must be experienced in the ice conditions of the area.</p>	<p>Certain ice conditions (i.e. slush ice) may reduce burn effectiveness or impede ignition.</p> <p>Fire boom deployment may become difficult or impossible.</p> <p>Residue recovery requires vessel support.</p> <p>Ice may provide natural containment, and burning in ice leads may be possible.</p>	<p>Oil under ice is inaccessible to dispersant application.</p> <p>Ice can dampen required mixing energy.</p> <p>Dispersants generally less effective at lower salinities.</p> <p>In most regions, dispersants are not considered an operational technology for use in sea ice.</p>
Wind	High winds can make it difficult to deploy effectively the crew, vessels, equipment required for a response. High winds can make air operations difficult or unsafe.	High winds can move boom and vessels off station or tear boom off the anchor point.	In-situ burning is not generally safe or feasible in high winds.	Accurate application of dispersants is difficult in high wind conditions.

² Sea ice is a prominent feature of the arctic marine environment. The generic term “sea ice” encompasses a wide range of ice conditions. Sea ice may be present year-round, or it may follow an annual freeze-melt cycle. Ice conditions may be described in terms of the formation of the ice or the percentage coverage. The World Meteorological Organisation’s ice classification system and terminology has been used in reference (Nuka, 2007b).

Conditions	General constraints	Mechanical recovery	In-situ burning	Dispersants
<p>Temperature</p>	<p>Prolonged periods of subfreezing temperatures can impact personnel safety, or require more frequent shift rotations.</p> <p>Extreme cold temperatures may be unsafe for human operators.</p> <p>Cold may cause brittle failure in some metals.</p> <p>Cold air may freeze sea spray, creating slick surfaces. Icing conditions may make vessels unstable.</p>	<p>Skimmers freeze up.</p> <p>Freezing sea spray can accumulate on boom and cause it to tear, fail or overwash.</p> <p>Increased oil viscosity makes it difficult to recover and pump.</p>	<p>Extreme cold temperatures may make ignition more difficult or ineffective, and may cause burn to slow or cease.</p>	<p>Cold temperatures and increased oil viscosity may reduce dispersant effectiveness.</p>
<p>Limited visibility (including months of darkness in far northern areas)</p>	<p>Any condition that reduces visibility may preclude or limit oil spill response operations, particularly any involving aircraft or vessel operations.</p> <p>Limited visibility may make it difficult or impossible to track the spill location and movement.</p> <p>Fog banks make vessel or aircraft operations extremely dangerous.</p>	<p>Accurate deployment of vessels and equipment requires sufficient visibility to deploy and operate equipment.</p> <p>Work lights may be used during darkness, if safety allows.</p>	<p>In-situ burning is not recommended during darkness.</p> <p>Aerial ignition and/or aerial monitoring require visual flight conditions.</p>	<p>Aerial application and/or aerial monitoring requires visual flight conditions.</p> <p>Vessel application requires visual confirmation of slick location.</p>
<p>Sea state</p>	<p>Waves can have varying impacts depending on their form. Short, choppy waves generally have a greater impact on a response than long ocean swells. Currents and tidal changes may also affect response operations.</p>	<p>Booms and skimmers do not function well at high sea states. Equipment must be suitable (rated) for typical sea states.</p> <p>Fast currents, changing tides and short period waves can make it difficult to keep boom and vessels on station.</p> <p>It is dangerous to manoeuvre booms and skimmers in rough seas.</p> <p>A common rule-of-thumb limitation for boom is a 2-3m significant wave height.</p>	<p>High sea states make containment and ignition difficult and potentially unsafe</p>	<p>High sea states typically enhance the effectiveness of chemical dispersants to disperse the oil.</p>

In the reference (Solsberg, 2008) the countermeasures for oil in ice have been presented as a table containing mechanical recovery methods, in-situ burning and dispersant applications to a specific range of ice cover (Figure 14). The problem with this approach is moving ice or other dynamic recovery circumstances.

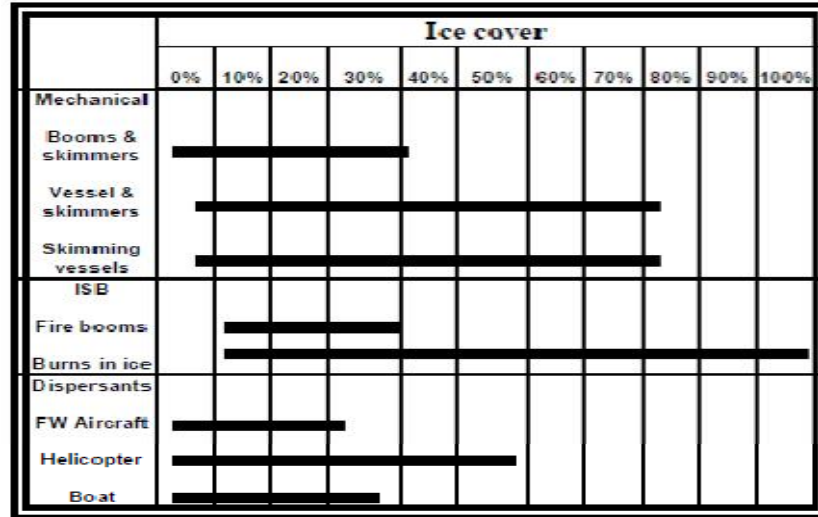


Figure 14. Countermeasures for oil in ice (Solsberg, 2008).

Based on the findings from the JIP Oil in Ice Program boat application of dispersant can be utilized in high ice concentration providing that artificial turbulence can be supplied. Additionally, helicopter is able to spray dispersants on the ice when the ice coverage is around 40-60%. (Singsaas, personal communication 25.8.2010)

In addition to the environmental aspects related to oil combating activities, also the health and safety issues must be addressed. When conducting in-situ burning humans and environment may be put at risk by flames and heat, emissions generated by the fire and residual materials left on the surface after the fire extinguishes. The ergonomic issues for experts operating with cranes and other heavy equipment should be considered in order to avoid accidental injuries.

Additional concerns in arctic regions may also include cold stress (including hypothermia), increased risks of slips, trips and falls when operating on icy surfaces and even sunburn. In some cases also wildlife might bring some surprises for the response experts. (SL Ross, 2004; Högström, personal communication, 20.1.2010)

7 Oil combating technologies for ice-covered sea areas

7.1 General

This report focuses on the oil combating in arctic conditions and especially the latest activities in mechanical oil combating conducted in Finland and in Norway. Additionally other response options such as sorbents, dispersants and in-situ burning are presented.

In open sea areas the oil is removed from water using following methods:

- oil is collected mechanically and pumped into the tanks.
- oil is processed with chemical disintegrators (dispersants). Toxic hydrocarbons become neutral when oil is dispersed and diffused.
- by using porous material, oil can be absorbed into seabed where hydrocarbons diffuse naturally.
- oil is coagulated physically by using light, porous material (absorbent) that is then collected.
- oil is burnt afloat.

Some of the methods can be partly adapted in arctic conditions. The utilization of these methods is always case-specific issue and depends on e.g. following matters:

- oil type and amount of oil spilled,
- air and water temperatures,
- wind, current and wave conditions, and
- location of the spill.

Currently IMO does not have any special environmental regulations for the Arctic area (Kämäräinen, 2009). However, Norway submitted a paper entitled “Environmental aspects of polar shipping” (MEPC 60/21/1) to the IMO MEPC60 meeting in March 2010. The paper provides an overview of environmental issues to be considered in relation to the development of a code for ships operating in polar waters (Polar Code). The inexhaustive list of questions presented in the paper includes *inter alia* the issue of sufficient amount of fuels to manage safe passage and a certain potential for oil spills in maritime trade and challenges of oil combating.

After the MEPC60 meeting Norway revised the document for IMO subcommittee on ship design and equipment meeting (DE54) scheduled on 25-29 October 2010. Norway carried out a high level assessment of whether regular opera-

tional discharges from ships pose a particular environmental threat in polar areas compared to other areas. (IMO, 2010)

Arctic Council's Emergency Prevention, Preparedness and Response (EPPR) program has published a document named Field Guide for oil spill response in Arctic Waters (Emergency Prevention, Preparedness and Response (EPPR, 1998). Field Guide was developed to provide circumpolar countries with oil spill response guidance specific to the unique climatic and physiographic features of arctic environment. The Guide focuses on practical oil spill response strategies and tools for application to open water, ice and snow conditions in remote areas during cold weather.

7.2 Sorbents

Sorbents are insoluble materials or mixtures of materials used to recover liquids through the mechanism of *absorption*, or *adsorption*, or both. *Absorbents* are materials that pick up and retain liquid distributed throughout its molecular structure causing the solid to swell (50% or more). The absorbent must be at least 70% insoluble in excess fluid. *Adsorbents* are insoluble materials that are coated by a liquid on its surface, including pores and capillaries, without the solid swelling more than 50% in excess liquid.

To be useful in combating oil spills, sorbents need to be both oleophilic (oil-attracting) and hydrophobic (water-repellent). Sorbents can be divided into three basic categories, i.e. natural organic, natural inorganic and synthetic.

Natural organic sorbents include peat moss, straw, hay, sawdust, ground corncobs, feathers and other readily available carbon-based products. Organic sorbents can adsorb between 3 and 15 times their weight in oil. Some organic sorbents tend to adsorb water as well as oil, causing the sorbents to sink. Many organic sorbents are loose particles such as sawdust, and are difficult to collect after they are spread on the water.

Natural inorganic sorbents consist of clay, perlite, vermiculite, glass wool, sand, or volcanic ash. They can adsorb from 4 to 20 times their weight in oil. Inorganic sorbents, like organic sorbents, are inexpensive and readily available in large quantities. These types of sorbents are not used on the water's surface.

Synthetic sorbents include man-made materials that are similar to plastics, such as polyurethane, polyethylene, and polypropylene and are designed to adsorb liquids onto their surfaces. Other synthetic sorbents include cross-linked polymers and rubber materials, which absorb liquids into their solid structure, causing the sorbent material to swell. Most synthetic sorbents can absorb up 70 times their own weight in oil. (EPA, 2010)

Sorbents are usually used for small amounts of oil that are difficult to recover by mechanical methods. Widespread use of sorbents or their usage on large spills will be limited by costs, labour intensiveness and the amount of solid waste generated. In general, the use of sorbents is appropriate during the final stages of clean-up or to aid in the removal of thin films of oil from locations not accessible for mechanical cleaning methods. Sorbents can also be utilized to protect and/or clean environmentally sensitive areas. (SL Ross, 2004)

7.3 Chemical dispersants

Chemical dispersants are designed to enhance natural dispersion by reducing the surface tension at the oil/water interface, making it easier for waves to create small oil droplets. Modern chemical dispersants are a blend of surfactants (surface active agents) in a solvent. The solvent has two functions: it reduces the viscosity of the surfactant which enables it to be sprayed and it promotes the penetration of the surfactant into the oil slick.

The surfactant molecules are made of two parts: an oleophilic part (oil-loving) and hydrophilic part (water-loving). When dispersants are sprayed onto the oil slick, the solvent transports and distributes the surfactants through the oil slick to the oil/water interface where they re-arrange so that the oleophilic part of the molecule is in the oil and the hydrophilic part is in the water. This creates a sharp reduction in the surface tension of the oil/water interface and small oil droplets break away from the oil slick with the help of wave energy. Re-coalescence is minimised by the presence of the surfactant molecules on the droplet surface and the reduced probability of encountering other oil droplets as they move apart. The smaller droplets will remain suspended and they will be diluted by turbulence and subsurface currents.

The chemical dispersion process is presented in Figure 15. Dispersant droplets containing are sprayed onto the oil (A). The solvent carries the surfactants into the oil (B). The surfactant molecules migrate to the oil/water interface and reduce surface tension (C) allowing small oil droplets to break away from the slick (D). The droplets disperse by turbulent mixing, leaving only sheen on the water surface (E).

In order to achieve an efficient dispersion, oil droplet size must be between 1 μm to 70 μm with the most stable size being less than 45 μm . Smaller droplets are better as they remain suspended in the water column where they will be diluted rapidly in the top few meters of the sea to below harmful concentrations. The increased surface area provided by the small droplets also enhances the opportunity for biodegradation of the oil. The process of natural dispersion takes place in moderate rough seas with breaking waves and winds above 5 m/s.

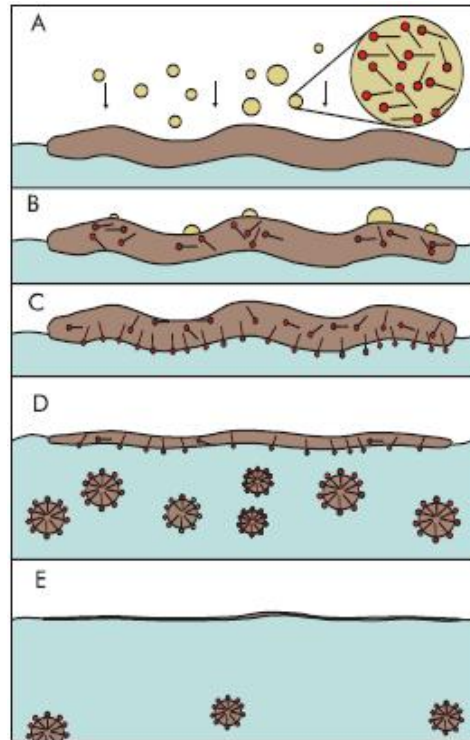


Figure 15. The chemical dispersion process (ITOPF, 2005).

The dispersants on the market today comprise a solvent and a blend of two or three surfactants. The most common surfactants used are non-ionic (fatty acid esters and ethoxylated fatty acid esters) and anionic (sodium alkyl sulphosuccinate). Generally two main compositions are encountered, i.e. hydrocarbon-based dispersants and concentrate or self-mixing dispersants.

In the hydrocarbon-based dispersants the solvent is a hydrocarbon with a low or no aromatic content. These dispersants typically contain between 15-25% surfactant and are intended for neat application to oil. They should not be pre-diluted with sea water since this renders them ineffective. They also require a high application rate of between 1:1 to 1:3 (dispersant to oil). Hydrocarbon-based dispersants are less effective and may be more toxic than concentrate dispersants and, as a consequence, in many countries are not commonly in use.

Concentrate or self-mix dispersants contain a blend of different surfactants with both oxygenated and hydrocarbon solvents. They contain a higher concentration of surfactants (25% to 65%) and can be applied either undiluted (neat) or pre-diluted with sea water although it is more common to apply them undiluted. A typical dosage ranges between 1:5 and 1:30 (undiluted dispersant to oil).

The dispersants are manufactured primary for use in the marine environment since their efficiency will be optimum in waters with salinity of around 30-35 ppt. The

efficiency will decrease rapidly in salinity levels below 5-10 ppt, especially when pre-diluted. Efficiency is also affected when salinity rises above 35 ppt.

Dispersant effectiveness is limited mainly by sea state and oil properties. A minimum amount of wave energy is required to achieve successful chemical dispersion but on the other hand in severe sea conditions the oil will be submerged by breaking waves. This situation prevents the direct contact between dispersant and oil. Field trials have indicated that optimum wind speed is between 4-12 m/s.

International Tanker Owners Pollution Federation Limited (ITOPF) has developed a simple approach for estimating dispersant effectiveness. This approach is primarily based on the fresh-oil density of the spilled oil. This variable was used in the correlation because the properties of the spilled oil are usually not known except for density of the oil or its API gravity³ (Table 5).

Table 5. Dispersibility of oil vs. API (American Petroleum Institute) gravity and pour point (SL Ross, 2004).

Dispersibility factor	Oil gravity and pour point	Oils description
1	API Gravity > 45°	<ul style="list-style-type: none"> - Very light oil - No need for chemically disperse - Oil will dissipate rapidly
2	API Gravity 35 - 45°	<ul style="list-style-type: none"> - Light oil - Relatively non-persistent - Easily dispersed
2W	API Gravity 35° - 45° Fresh oil pour point > 40°F (4°C)	<ul style="list-style-type: none"> - Light oil - Very difficult to disperse if pour point of fresh oil greater than water temperature
3	API Gravity 17 - 34°	<ul style="list-style-type: none"> - Medium density oil - Fairly persistent - Dispersible while fresh and unemulsified
3W	API Gravity 17 - 34° Fresh oil pour point > 40°F (4°C)	<ul style="list-style-type: none"> - Medium density oil - Fairly persistent if pour point of fresh oil less than water temperature - No dispersible if pour point of fresh oil greater than water temperature
4	API Gravity < 17° or Fresh oil pour point > 75°F (24°C)	<ul style="list-style-type: none"> - Heavy or very high pour point oil - Very difficult or impossible to disperse

Ignoring the problem of high pour point oils, Table 5 indicates that oils with fresh-oil API gravity of 18° (special gravity of 0,95) or greater should be chemically dispersed. This method is intuitive and indeed very simple but makes sense for predicting the dispersibility of fresh, unemulsified oil. (SL Ross, 2010)

³ °API = $\frac{141,5}{\text{special gravity}} - 131,5$.

In the reference (ITOPF, 2002) physical characteristics of three typical crude oils and additionally classification of oil according to their specific gravity has been presented. Viscosity and pour point of oil provide a good indication of its dispersability. As a general rule, light and medium crude oils are considered to be readily dispersible whereas highly viscous oils are not. It's anticipated that dispersants are ineffective for oil above 10 000 cSt at the time they are spilled. Generally oil with a pour point of 10-15°C below sea temperature will be difficult to disperse chemically. (ITOPF, 2005)

Some properties for a relevant oil quality to be used in CIV Arctic studies are presented in Table 6.

Table 6. Physical and chemical data for crude oil. Properties of fresh oil (Myhre, personal communication, 4.5.2010).

Specific Gravity (60F/60F)	0,7965
°API	46
Pour Point °C	-39
Reference temperature #1 °C	5
Viscosity at ref. temp #1 (cP)	22
Alphatenes (wt. %)	0,03
Wax Content (wt. %)	3,42
Maximum water content (%)	75

The objective of dispersant use is to enhance the amount of oil that physically mixes into the water column, reducing the potential that a surface slick will contaminate shoreline habitats or come into contact with birds, marine mammals, or other organisms that exist on the water surface or shoreline. Conversely, by promoting dispersion of oil into the water column, dispersants increase the potential exposure of water-column and benthic biota to spilled oil. Dispersant application thus represents a conscious decision to increase the hydrocarbon load (resulting from a spill) on one component of the ecosystem (e.g., the water column) while reducing the load on another (e.g., coastal wetland).

Therefore, decisions to use dispersants involve trade-offs between decreasing the risk to water surface and shoreline habitats while increasing the potential risk to organisms in the water column and on the seafloor. This trade-off reflects the complex interplay of many variables, including the type of oil spilled, the volume of the spill, sea state and weather, water depth, degree of turbulence (thus mixing and dilution of the oil), and relative abundance and life stages of resident organisms.

Dispersants can be applied by boats or by aircraft. Large multi-engine aircraft are best suited to deal with major off-shore spills whereas boats, single-engine aircraft and helicopters are suitable for smaller spills that are closer to the shore. In the

right circumstances helicopters are able to reload dispersants from a vessel or offshore oil platform for open water response.

The droplet size is important since it needs to be sufficiently large to overcome the effects of wind and evaporation loss but not too large that it will result in the droplets to punch through the oil slick. The optimum droplet size is between 600 and 800 μm . The key to the successful response with dispersants is the ability to target the thickest part of the oil slick within a short time and before weathering or sea state render the oil undispersable.

One of the main challenges for the application of the dispersants lies in the estimation of the volume of oil to be treated and hence the calculation of the appropriate application rate. Concerning the average thickness and volume of the oil slick assumptions must be made. The ratio of dispersant to oil required for effective dispersion varies between 1:3 and 1:50 depending on the type of dispersant, the type of oil and the prevailing conditions. (NRC, 2005)

Laboratory and field experiments from the JIP Oil in Ice -Program have verified that oil spilled in ice-covered water is dispersible by use of oil spill dispersant. Furthermore, the weathering process of oil is slowed down when ice is present, enabling a larger window of opportunity⁴ for dispersant use. Some oils remain dispersible several days. A new dispersant unit which was developed in the JIP Oil in Ice -programme opens up the possibility of new strategies for the operational use of dispersants in high (80-90%) ice coverage. (Sørstrøm *et al.* 2010)

7.4 In-situ burning

In-situ burning (ISB) in oil spill response has been utilized since 1960's. ISB involves the controlled burning of oil that has spilled from a vessel or a facility, at the location of the spill. Generally ISB has proven its efficiency for oil spills in ice conditions in Alaska, Canada and Scandinavia. When conducted properly, ISB significantly reduces the amount of oil on the water and minimizes the adverse effect of the oil on the environment.

In order to burn spilled oil three elements must be present: fuel, oxygen and 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's the hydrocarbon vapours above the slick that burn, not the liquid itself.

Figure 16 illustrates the heat transfer processes that occur during the ISB of an oil slick on water. 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

⁴ The opportunity for the use of various oil spill countermeasures changes with time. The time before we reach this point is called "window of opportunities" in reference (Sørstrøm *et al.*, 2010).

that rise to mix with the air above 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.

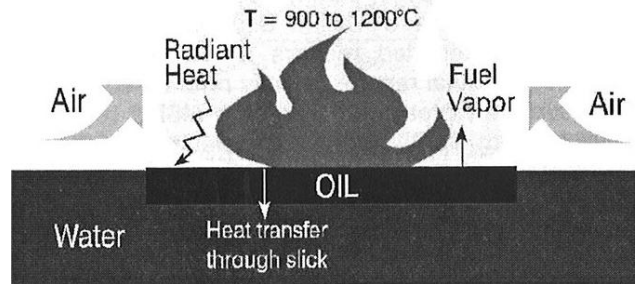


Figure 16. Heat transfer processes that drive ISB (SL Ross, 2004).

Flame temperatures for crude oil burns on still water are about 900–1 200°C. The temperature at the oil/water interface is never more than the boiling point of the water and is usually around ambient temperatures.

The key oil slick parameter that determines whether or not the oil will burn is slick thickness. If the oil slick 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 “hot zone”. As the slick thins increasingly more heat is passed through it. Eventually, enough heat is transferred through the slick to drop the temperature of the surface oil below its fire point, at which time the burns stops. The reference (SL Ross, 2004) presents “rules-of-thumb” concerning minimum ignitable thickness of oil slick in relative calm and quiescent conditions (Table 7).

Table 7. Minimum ignitable thickness (SL Ross, 2004).

Oil type	Minimum thickness
Light crudes and gasoline	1 mm
Weathered crudes, diesel and kerosene	2-3 mm
Residual fuel oils and emulsified crudes	10 mm

ISB can remove thick oil slicks from water surface with efficiency rate of 90% or more. Removal rates of 2 000 m³/hr can be achieved with a fire area of about 10 000 m² or circle of about 100 m in diameter. There is a limited window of opportunity for using ISB and this window is defined by the time it takes the oil slick to emulsify. Once oil emulsifies and the water content exceeds about 25%, most slicks are unignitable. (SL Ross, 2004; NOAA, 2010)

Successful ignition of oil on water requires heating of oil to its flash point so that sufficient vapours are produced to support continuous combustion, and providing an ignition source to start burning. Technologies for conducting ISB include heli-torches, handheld igniters, ad-hoc igniters, ignition promoters and fire-resistant

booms. The choice of igniter for a given application depends mainly on two factors:

- degree of weathering or emulsification of the oil, which will dictate the required energy level of the igniter,
- size and distribution of the spill, which will determine the number of ignitions required to ensure an effective burn.

As with all response methods, the environmental tradeoffs associated with ISB must be considered on a case-by-case basis and weighed with operational tradeoffs. ISB can offer important advantages over other response methods in specific cases, and may not be advisable in others, depending on the circumstances of a spill. According to the reference (NOAA, 2010) the advantages and disadvantages of ISM can be summarized as presented in Table 8.

Table 8. The advantages and disadvantages of ISB (NOAA, 2010).

<p>Advantages of ISB:</p> <ul style="list-style-type: none"> • ISB is one of the few response methods that can potentially remove large quantities of oil from the surface of the water with minimal investment of equipment and manpower. • Burning may offer the only realistic means of removal that will reduce shoreline impacts in areas where containment and storage facilities may be overwhelmed by the sheer size of a spill, or in remote or inaccessible areas where other countermeasures are not practicable. • If properly planned and implemented, ISB may prevent or significantly reduce the extent of shoreline impacts, including exposure of sensitive natural, recreational, and commercial resources. • Burning rapidly removes oil from the environment, particularly when compared to shoreline cleanup activities that may take months or even years to complete. • ISB moves residues into the atmosphere, where they are dispersed relatively quickly. • Control of burn activities is relatively simple, provided containment is appropriate
<p>Disadvantages of ISB:</p> <ul style="list-style-type: none"> • ISB, when employed in its simplest form, generates large quantities of highly visible smoke that may adversely affect humans and other exposed populations downwind. • Burn residues may sink, making it harder to recover the product and to prevent the potential exposure of benthic (bottom-dwelling) organisms. • Plant and animal deaths and other adverse biological impacts may result from the localized temperature elevations at the sea surface. While these affects could be expected to occur over a relatively small area, in specific bodies of water at specific times of the year, affected populations may be large enough or important enough to reconsider burning as a cleanup technique. • The long-term effects of burn residues on exposed populations of marine organisms have not been investigated. It is not known whether these materials would be significantly toxic in the long run. • The burn must be carefully controlled in order to maintain worker safety.

The window of opportunity for ISB of oil in the Arctic can be larger in ice-covered waters than in the open sea. ISB has been tested and proven to be effective for the elimination of both free floating oil in ice and oil collected in fire resistant booms. Findings have shown that the presence of cold water and ice can enhance the effectiveness of ISB by limiting the spreading of oil slowing weathering processes. Additionally the efficiency of ISB in dense ice conditions can be higher compared to mechanical recovery options. (Sørstrøm *et al.*, 2010; Singaas, personal communication, 25.8.2010)

7.5 Concerns related to use of chemical dispersants and ISB

According to the reference (EMSA, 2006) the utilization of chemical dispersants or ISB for oil combating is controversial. The potential risk of using dispersants is that marine organisms will be exposed to higher levels of dispersed oil (and soluble components from the dispersed oil) than they would have been, if dispersants had not been used. The degree of harm that might be suffered by marine organisms exposed to dispersed oil is a function of exposure conditions (dispersed oil concentration, duration of exposure and the rate of dispersion and dilution) plus the inherent sensitivity of the particular organism to dispersed oil.

The small amounts of residue from ISB of oil on water, particularly if the residue sinks, can cause environmental concerns. Results of laboratory tests suggest the possibility that, for about 40 - 60% of crude oils worldwide, burn residues may sink. However, it's not known if the results can be extrapolated to large-scale spills. Burn residues have little to no acute aquatic toxicity. Their greatest impact would likely be to the benthos from smothering. For most ISB applications, impacts would be very localized because of the small volumes of residues generated and their dispersal by currents. (NOAA, 2010)

Helsinki Commission (HELCOM) has adopted a recommendation 22/2 to restrict the use of chemical agents and other non-mechanical means in oil combating operations in the Baltic Sea area. The recommendation stipulates that mechanical means are the preferred response measures, and that chemical agents may only be used in exceptional cases, after authorization has been granted in each individual case. (HELCOM, 2001)

Vessels under Finnish or Swedish flag do not have required equipment for dispersant use. In Finland dispersants has been utilized only once in the case of Antonio Gramsci⁵ in 1979. (Högström, personal communication 20.1.2010)

⁵ May 4 1979, 5 500 tn crude oil spill, 650 tn collected from shore line in the Åland Island.

7.6 Mechanical oil combating options

Even though the dispersants are the number one method in Sakhalin and in situ burning is popular in North America, in Europe and in the Baltic Sea area the long term trend has been to avoid them⁶. Instead, the aim is to develop mechanical methods that could be applied also in arctic conditions. While suitable mechanical combating options for arctic environment will be developed, these technologies might have priority also in arctic areas since they are not controversial, like ISB and dispersants (Lampela, personal communication, 18.1.2010).

In the reference (Nuka, 2007a) the existing mechanical recovery technologies which may improve response capabilities in ice conditions are presented.

The Finnish Environment Institute (SYKE) supports R&D activities to develop novel devices for oil recovery operations in the cold environment in Finland. There have been a variety of different apparatus tested in both laboratory and full scale. Some of these devices have also been taken to operative use.

In the following chapters some of the mechanical oil combating methods developed in Finland are described.

7.6.1 A method to recover oil under the level ice – JML Ice Scraper

In his licentiate's thesis in 1999, Jari M. Lahtinen studied a new oil recovery method. This method is based on ice underside ploughing and oil flow into the collecting tank by using damming effect. The method is developed for fast ice conditions where oil will likely drift under ice.

According to the thesis it is reasonable to recover oil from under ice, since ice restricts and slows down drifting. Also the quickly evaporating substances from crude oil can thus be recovered. Fast ice forms very stable conditions, since waves or ice movements do not exist. When oil is under ice, it is warmer than below zero air above and its viscosity is lower which facilitates recovering. In process of time the oil gets soaked into ice or water continues to freeze under ice and in this case, the oil can only be recovered after the ice has melt.

Model tests were carried out in a small tank. The results of the experiments were measured results as well as visual observations. The main conclusion was that the oil recovery method works and it is possible to collect oil from under solid ice cover. The highest achieved efficiency was about 20 %. Based on the measured results, the mathematical models of oil behaviour in front of the plough and the rate of oil recovery efficiency were formulated. Also the need for further investigation was specified in the thesis. (Lahtinen, 1999)

⁶ Comment from Statoil/Hanne Greiff Johnsen: Dispersants have been used in Norway, UK and France.

After the model tests in laboratory scale, the real size prototype of the device was constructed and tested in full scale under natural ice (Figure 17). The test was performed in level ice in Archipelago Sea in 2001.



Figure 17. JML Ice Scraper during the field tests in 2001 (Rytkönen & Sassi, 2001).

The aim of the full-scale test was to study the performance of the device in cold conditions and in ice. Heavy fuel oil was used in the tests that were performed in the assistance of the oil recovery vessels Halli and Linja.

JML Ice Scraper contains a recovery box connected to the side molding boards. The device has positive buoyancy, thus when under ice, it compresses against the ice. For the test, the apparatus was driven by a winch. The model scale tests of the device already showed that it is very difficult to collect all the oil. In case the velocity is smaller than the critical velocity, no oil will flow into the recovery basin but will pass the device. The best efficiency was achieved when the velocity of the device was approximately 1,8 times the critical velocity. With the density of the heavy fuel oil used in the tests (POR-180), the critical velocity was near 0.6 m/s and the optimum velocity near 1,10 m/s.

In the full scale tests, the recovery velocity was 0,75 m/s. The throughput efficiency was near 90%. The throughput efficiency is defined as the ratio of oil recovered to oil encountered (Schultze, 1995). The observation was made that approximately half of the oil remained outside the collector box and approximately half was inside the box.

The full-scale performance is strongly dependent on the thickness of the oil slick under ice and the roughness of the level ice. Due to the fact only one test with 200

liters of heavy fuel oil was made, the estimates of the recovery efficiency are not precise. However, the following conclusions can be drawn:

- the device is very sensitive to under-ice ruptures, and
- operation of the device was very laborious, especially the emptying and cleaning phases, which will need further development.

To recover oil from under ice, it has to be found first. There are different kinds of solutions that have been developed for this. The devices can utilize for example ultra sound or fluorescence phenomenon with multifrequency laser beam. Also underwater ROVs (Remotely Operated Vessel) can be used. When measuring the geometry of ice lower surface in arctic areas, the oil has verified to store $0.010\text{--}0.130\text{ m}^3/\text{m}^2$ under ice (Goodman & Holoboff, 1987). In that case the thickness of oil layer would be 10-130 mm. (Rytkönen & Sassi, 2001)

7.6.2 Ice Vibrating Unit

The Ice Vibrating Unit is designed to operate in rubble ice conditions. The idea of the vibrating unit is to use a vibrating grid to force the ice blocks submerged under the recovery unit to move upside down and possibly to rotate by moving the grid. The objective is to enhance the separation of oil from ice by increasing the relative movement between oil-covered ice blocks and water (Figure 18, Figure 19).

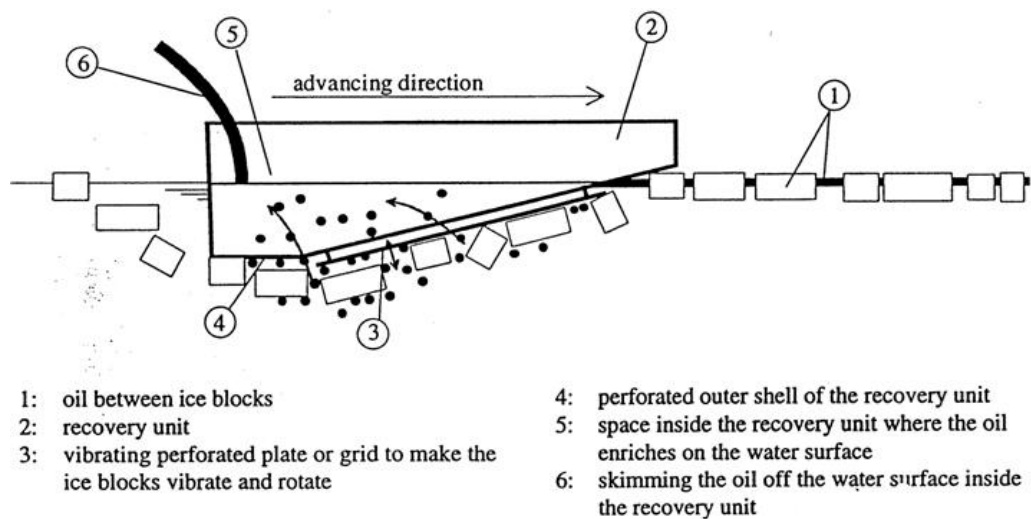


Figure 18. The principle of the vibrating unit (Lampela, 2008).



Figure 19. The installation of the vibrating unit (VTT, 2003).

The first version of the device was tested in March 2001. During these test trials a lot of small ice cubes were accumulated through the bars into the vibrating unit and finally into the oil recovery chamber. For the next test trials (2002) the free space between the bars was decreased and also the fixed mounting system in the stern-side end of the system was modified. This allowed the lifting or lowering of the end in vertical direction. The angle between the still water level and the vibrating screens can be adjusted allowing the operator to find out suitable driving angle for different ice conditions and for different speeds.

The vibrating unit was mounted on the portside of the vessel. The unit's front part was connected to the horizontal beam with a hinge. The recovery unit is supported by a long hydraulic actuator from the back of the device.

The bottom of the unit contains three parts. The bow part is fixed and the other two parts connected to the hydraulic actuator. The stroke of the actuator causes the up and down movement of the bottom grid, which separates the oil from the ice blocks. The oil is then free to rise inside the device to be recovered using the vessel's brush-recovery system, which removes the ice cubes back to the sea (Figure 20).



Figure 20. The brush-recovery system of the LOIS Ice Vibrating Unit (VTT, 2003).

The width of the bottom grid is 200 cm and the angle between the still water level and the vibrating screens is 8 degree. The operational speed, i.e. speed of the vessel during combating operation, is around 1-2 knots and the mass of the unit is around 45 tons. The device has been developed by the Finnish company Lamor and the Finnish Environmental Institute (SYKE). (VTT, 2003; Högström, personal communication 20.1.2010)

According to the experience of Lamor the ice vibrating unit operates quite well in new ice with thickness of 20-30 cm and in moderate temperature. Some problems with accumulation of small ice cubes still exist. The device is designed for oil spills over 100 tons and must be installed to a vessel side. Thus, fittings for the device need to be done before the use of the unit. (Högström, personal communication 20.1.2010)

SYKE owns the patent of the Oil Ice Separator. A Finnish company LAMOR Corporation has the manufacturing rights and is marketing the device worldwide. The commercial name of the device is the Lamor Oil Ice Separator “LOIS”. (SYKE, 2010a)

The LOIS device was also assessed as part of the technology assessment for ice processing presented in the reference (Nuka, 2007a). The reference concluded that oil/ice separation technologies on the market are fairly limited and LOIS is fairly new to the market. The reference also noted that the technology has been developed primary for vessels capable of operating in ice conditions with built-in oil recovery systems but can also be delivered with a Lamor brush skimmer installed.

7.6.3 Oil recovery skimmers

Oil recovery bucket skimmer was developed by SYKE in the 1990's for oil collecting from water surface and from onshore and it has been successfully utilized in both applications. The skimmer adhere the oil to the stiff, rotating brushes and as the drum rotates, the oil is swept from the brushes and the oil enters the bucket. A screw pump transfers the oil to recovery tanks. The oil recovery bucket collected successfully oil among ice in March 2006 in Estonian waters after the sinking of 'Runner 4' (Figure 21).



Figure 21. Oil recovery bucket in operation (SYKE, 2010a).

Oil recovery bucket skimmers exist in three different sizes. The smallest device has sweeping width of 60 cm, the medium size's sweeping width is 1.6 m and the largest has sweeping width of 3 meters. The two larger buckets can be connect to and operated by hydraulic crane or hydraulic excavator. The largest bucket is developed to be operated by crane of large oil recovery vessel. (SYKE, 2010a)

Lamor Company has developed several skimmers for oil combating purposes in arctic conditions. Lamor LRB 150 and 300 types were tested in Svalbard as part of the Joint Industrial Programme (Oil in Ice – JIP) in 2008. LRB 150 and 300 are designed to be operated from an excavator arm type crane or similar, when the operation of skimmers is more dynamic and handy when comparing to hanging system of a crane.

Lamor MABS (Figure 22) and Artic skimmer are designed to be installed hanging in the crane wire rope and moved around in the free water and ice blocks. They can also be equipped with floats and used as free floating skimmer with limited ice cover on the water. (Högström, personal communication 20.1.2008)



Figure 22. Lamor MABS in operation (Högström, personal communication, 20.1.2010).

The mechanical recovery part of the JIP on Oil in Ice -program (chapter 7.7) included laboratory scale testing of five different skimmer options. As the result two skimmers, i.e. Ro-Clean Desmi Helix 1000 and Lamor LRB 150, were selected for field test trials in Barents Sea in May 2008.

The test results indicated that the Helix 1000 skimmer (Figure 23) works best in low ice concentrations up to 40–50% and might also have a potential for application alongside larger ice floes. Cohesive oil slicks can be effectively drawn into the brushes provided that the drum speed is not too high (5–10 rpm during the test trials). (Singsaas, *et al.*, 2008)



Figure 23. Testing of the Helix 1000 skimmer during the experimental field trial in May 2008 (Singsaas *et al.*, 2008)

The manufacturer of the Helix 1000 skimmer is presently building a larger version of this skimmer with a hexagonal shape rather than the helical shape of the Helix Skimmer. The new skimmer will also contain improvements like “winterisation”, floating elements, umbilical for hoses etc. However, the Helix Skimmer can still be a versatile device for smaller oil spills in ice-covered waters. (Singsaas, *et al.*, 2008)

Concerning the Lamor LRB 150 skimmer (Figure 24) it was concluded that it represents the state-of-the-art technology for oil recovery in ice. When using the original intended excavator crane and an experienced operator, the LRB 150 skimmer is expected to have the potential to recover oil in ice up to ice covers of 60–70%. (Singsaas, *et al.*, 2008)



Figure 24. Testing of the LRB 150 skimmer during the experimental field trial in May 2008 (Singsaas, et al., 2008).

The Ro-Clean Desmi Polar Bear and Framo skimmers were tested during the experimental field trials in the eastern part of the Barents Sea in May 2009. The Polar Bear skimmer (Figure 25) consists of six brush drums in a hexagonal shape and is a further development of the Helix 1000 skimmer.



Figure 25. The Polar Bear skimmer in operation during the 2009 trials (Desmi, 2009).

The results indicated that the Polar Bear skimmer can be effective in collecting flowing oil when positioned in oil of varying slick thickness (several mm to several cm) among ice pieces. Cohesive oil slicks can be effectively drawn into the brushes provided that the drum speed is not too high (5–10 rpm in these tests) and the sump lip remains above the sea surface. The skimmer works best in the presence of low concentrations of smaller ice pieces and slush ice (< 50–70 %) and might also have the potential for application alongside larger ice floes. (Singsaas, *et al.*, 2010)

The Framo skimmer, as presented in the trials described in the reference (Singsaas *et al.*, 2008), requires more development on basic skimmer components to ensure that a fully functional machine is developed. The bristles and the scrapers must be improved and modifications to buoyancy are required. The triangular shape (Figure 26) together with its thrusters was a successful combination and allowed the skimmer to move very well in ice.

It was concluded that a skimmer with thrusters that utilizes brush drum technology would be a highly useful mechanical recovery device for oil spills in ice infestations. The Framo skimmer is expected to ultimately have the potential to effectively recover oil in small ice concentrations up to 70%.

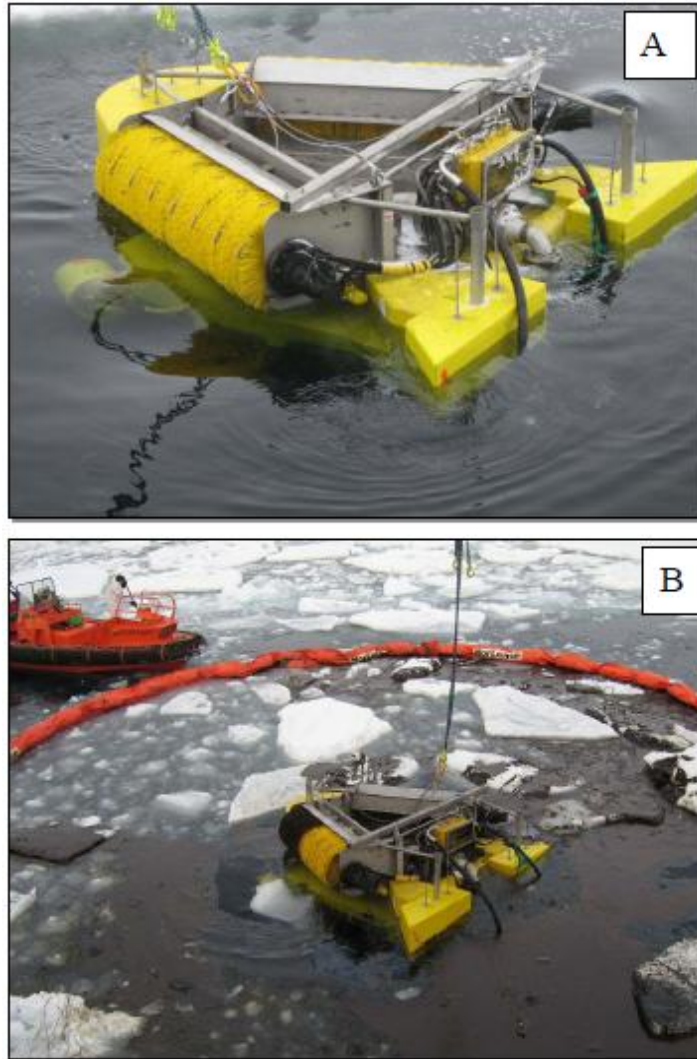


Figure 26. Testing of the Framo skimmer during the experimental field trial in May 2009. A) in water outside the boom and B) in the boom with oil present (Singsaas et al., 2010).

Framo has continued to develop the skimmer as part of the DEMO 2000 –project⁷. The development work takes into the account the recommendations from the field experiments and also a lighter frame will be built. (Singsaas et al., 2010)

⁷ Research Council of Norway: Project related technology development in the petroleum sector.

7.6.4 OilWhale oil recovery system

OilWhale oil recovering system is developed in Finland by Mr. Markku Järvinen. The process is based on the difference of specific gravity and viscosity of the materials and they are organised and separated from each other during the process. The first pool experiments were conducted in 2005 with low viscosity low weight vegetable oil and high viscosity heavy weight machinery grease. After the successful experiments the first full-size prototype vessel for shallow waters was tested in October 2007, and additional experiments were carried out in ice conditions in November 2007 and in March 2008. The experiments proofed that the procedure functions operated as planned.

According to the marketing material OilWhale method does not require any mechanical contact with the recovered material. The basic construction includes one collection space called the collector while a more sophisticated construction comprises two different spaces, namely the collector and the restorer, i.e. the restoring place for recovered material (Figure 27).



Figure 27. The intake (left) and recovery area (right) of the OilWhale vessel (Kappelinranta, 2010).

When the recovery process starts both spaces are filled with water. The vessel is then lowered to the recovery draft and the trim of the vessel is fixed with ballast water. The recovered material floats into the collector through a gate which is opened and lowered below water surface or the layer of the material to be recovered. The recovered material enters the collector exactly in the same phase as it is in the water. The risk of mixing the materials and produce dispersion or emulsion during the recovery work can thus be minimized and the material flow can be kept as laminar as possible during the recovery process.

The recovered material can then be transferred from the collector to the restorer(s) without any external transfer methods such as pumps. The remaining extra water is continuously removed from below of the collector and restorer utilising natural through pass flow. No additional pumps or similar methods are required during the operation since the movements of the vessel or the current act as pump during the recovery process. The recovered material can be off-loaded either to another vessel or to a barge while the main ship is still recovering oil.

The background material provided by the company Kappelinranta Oy Ltd, the developer of the OilWhale system, inform that the OilWhale procedure works well in all conditions including polar regions, and the system can obtain a high recovery speed, capacity and efficiency. The system can be applied to varying sizes and types of vessels, also to vessels operating in waters covered with ice. The capacity of the system is not depending on mechanical transfer methods available, in principle the thicker the oil layer the higher recovery capacity. A capacity of over 1 000 t/h is suggested to be possible with an OilWhale equipped vessel.

The reference vessel is catamaran (50 x 20 x 3 m) with sweeping width of 27 m and recovery efficiency of 99%. The total capacity depends on the volume and amount of barges for intermediate depot. OilWhale capacity calculations for wave height of 2 metre assuming that recovery can be made as continuous process and emptying is possible to a barge has been presented in Table 9.

Table 9. OilWhale capacity calculations (Kappelinranta, 2010).

Material	Oil [%]	50	10	1	1
	Water [%]	50	90	99	99
Restoring draft [m]		0,2	0,1	0,1	2,0
Speed [kn]		2	6	6	1
Sweeping area [m ² /h]		100 000	300 000	300 000	50 000
Recovery capacity [m ³ /h]		10 000	3 000	300	1 000

Additionally, examples of the restoring capacities in open water for OilWhale system has been presented in Table 10.

Table 10. Restoring capacity examples in open water (Kappelinranta, 2010).

Restore oil tank capacity: 6 000 m ³ Offloading to a pusher barge available onsite. Seawater pump output, one pump per restore tank: 600 m ³ /h per pump					
Composition of sludge, including:	Oil [%]	50	10	1	1
	Seawater [%]	50	90	99	99
Restoring depth [m]		0,2	0,2	0,1	2,0
Ship's speed [kn]		2	2	5	1
Intake volume [m ³ /s]		3	3	3,85	15
Loading time [hours]		1	5	421	11
Total time per one loading / offloading [hours]		3	7	44	13
Total capacity of restored oil per day [m ³ /d]		44 000	16 500	3 150	11 000

According to the background material provided by the developing company temperature, pumping capability, stiffness or viscosity of the recovering material does not decrease the performance of the system, and even recovery of dispersed and emulsified materials, debris, blue-green algae and contaminated ice is possible. Due to the operation principle the recovered material must be floating or otherwise close to the surface.

Additionally, the functionality of the system in larger ships installation has been confirmed by theoretical CFD studies conducted in Finland. The first catamaran design vessel (dimensions 13 x 3 x 1 m) has been manufactured in Finland (Figure 28). Several international applications for patents are pending for the OilWhale procedure. (Kappelinranta, 2010)



Figure 28. The catamaran design OilWhale vessel (Kappelinranta, 2010).

During the Gulf of Mexico oil spill in 2010 one method that was proposed for cleanup method is called the “A Whale” skimmer, retrofitted to the world’s largest oil skimming vessel. The Liberian flagged vessel (IMO code 9424209, MMSI code 636014465) is approx. 340 metres long and 60 metres high (Figure 29).



Figure 29. A Whale vessel anchored on the Mississippi River in Boothville, Louisiana, (Associated Press, 2010).

The vessel is designed to collect up to 500 000 barrels (approx. 79 490 m³) by taking in water through 12 vents, separating the oil and pumping the cleaned sea-water back into the sea (Figure 30).



Figure 30. The intake vents on the side of the A Whale vessel (Associated Press, 2010).

The converted oil tanker has the capacity of holding 2 million barrels, but would limit its holding tanks to 1 million barrels for environmental reasons.

Before the vessel can start the oil recovery the officials wanted to test its capability as well as have the federal Environmental Protection Agency sign off on the water it will pump back into the Gulf, which will contain trace amounts of crude oil. (Associated Press, 2010; China Press, 2010)

Additionally, another new response method utilised in the Gulf of Mexico oil spill is the Big Gulp skimmer (Figure 31). The size (area) of the vessel is around 4 400 m² (size of an American football field).



Figure 31. The Big Gulp collecting oil in the Gulf of Mexico (Fox8live.com, 2010).

In the Big Gulp oil enters the skimmer through a big mouth cut into the bow of the barge, building up against a bulkhead and finally spilling over into a holding tank. From there, oil is pumped into two holding tanks, where gravity separates the oil from the heavier water. Clean water will be discharged back to the sea, while captured mixture containing 98% oil. According to the reference (Deep Water Horizon Response, 2010) the skimmer is able to collect 300 00 gallons (around 1 100 m³) of oil in a day.

It seems that the A Whale vessel and Big Gulp are utilising similar operational principle than the Finnish OilWhale concept. The systems do not include any ice processing option which is essential in arctic response actions.

7.6.5 Novel oil recovering equipment onboard new Finnish multipurpose vessel

Finnish Environment Institute (SYKE) in co-operation with the Finnish Navy has ordered a new multipurpose vessel which is under construction in UKI Workboat Ltd in Uusikaupunki, Finland. The vessel should be in operation in spring 2011.

The main dimensions of the vessel are the following:

- L = approx. 71,4 m,
- L_{ewl} = approx. 67,4 m,
- B_{mld} = 14,5 m,
- T = 5,0 m,
- H = 7,0 m, and
- V = 13,5 kn.

The main engines are 4 x Wärtsilä 8L20, 1 800 kW / engine, main generators are 4 x 2 125 kVa and propulsion units 2 x Rolls-Royce 2 700 kW / unit.

Trial speed of the vessel is 13,5 knots and bollard pull 60 tonnes. The ice-going properties are the following:

- to move ahead at a speed of 7,5 knots in 0,5 m thick level ice with 20 cm snow cover,
- to move ahead at a speed of 3 knots in 1,0 m thick level ice with 20 cm snow cover,
- to penetrate a ridge of 5 m thickness ahead with a single ram, starting from 7,5 knots, and
- to keep a speed of about 9,5 knots in 1 m thick channel and shall be able to move continuously in 2,3 m thick channel.

The vessel shall be designed and built according to class notations of Germanischer Lloyd (GL) as follows:

- GL 100 A5, E4, NAV-OC, Tug, Supply Vessel, Marine Pollution Response Vessel, Oil Recovery Vessel, Chemical Recovery Vessel,
- The notation for the machinery is: GL MC, E4, AUT, FF1
- Ice class is according to Finnish-Swedish Ice Class Rules, with the notation 1A Super.

Special consideration shall be made for the dimensioning of the propulsion and hull to meet the ice-going requirements set in the specifications.

The main tasks of the vessel include oil and chemical recovery, fire fighting, rescue operations, emergency towing and diving and ROV-operations. Additionally, the tasks for navy activities include transport of fuel (less than 1 000 m³), work as a support and platform vessel, mine laying vessel, transport of deck cargo, laying and servicing of marine cables, minesweeping in special circumstances and towing.

The open water oil recovery equipment are designed to be able to collect oil at vessel speed of 1,5 knots. The collecting system consists of brush belts on both sides of the vessel, inside of the hull. The vessel shall be able to collect oil up to 2,0 m significant wave height. In waves conditions over 1,0 m a shorter oil boom will be used and the oil is guided through the dampening channel to the brush belt on the other side of the ship. The oil recovery equipment has to be fully mechanized and shall have radio control and has to be operational mode in 10 minutes per side. Additionally, the vessel will be equipped with four portable and detachable drum skimmer units on the stern of the vessel (Figure 32).

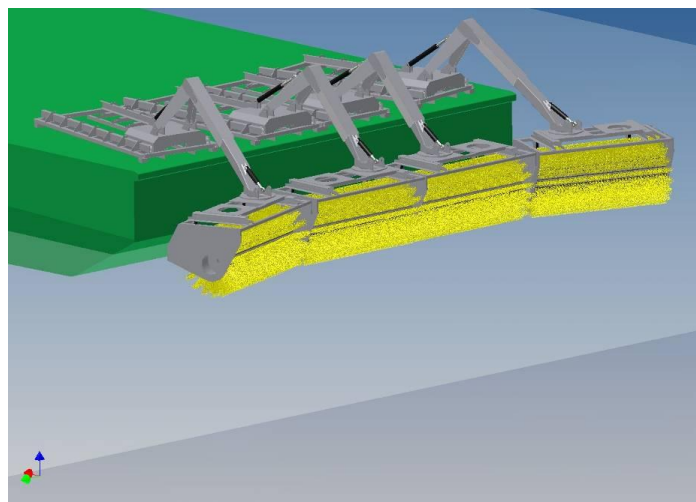


Figure 32. Schematic illustration of the brush recovery system at the stern side of the vessel (Lampela, personal communication 9.7.2010).

These skimmers are installed on container platforms and are designed to be operated in ice conditions. During oil recovery operations in ice the vessel will reverse. (Lampela, personal communication 9.7.2010)

7.7 JIP Oil in Ice program

The Joint Industry Program on oil spill contingency for Arctic and ice-covered waters (JIP on Oil in Ice, <http://www.sintef.no/Projectweb/JIP-Oil-In-Ice/>) was established in 2006 and completed by the end of 2009. It was sponsored by the Norwegian Research Council (NRC) and six oil and gas companies, i.e. Shell, Chevron, Statoil, Total, ConocoPhillip and Agip KCO. The program was coordinated by SINTEF Material and Chemistry (Norway). SL Ross Environmental Research Ltd. (Canada) and DF-Dickins Associates (USA) were the main R&D partners for SINTEF. The total value of the program was NOK 65 million (around 8,18 m€).

The program was divided into nine project and total of 25 sub-projects. The program included the following sub-tasks:

- Fate and behaviour of oil in ice,
- In-situ burning,
- Mechanical recovery,
- Dispersants,
- Remote sensing,
- Oil spill response guide,
- Field experiments, and
- Oil distribution and bioavailability.

The key findings from the program can be summarised as follow:

- each response tool evaluated during the program demonstrated some merit in responding to an oil spill in arctic environment;
- the availability of all the response options is considered as being the key to a successful oils spill response operation under arctic conditions;
- a systematic way to predict the operational time frame for various response options was identified, thereby demonstrating that efficient oil spill response may be accomplished whether the techniques are used individually or in combination;
- large-scale field experiments proved to be an important verification of results from a number of small- and medium scale laboratory experiments being performed during the program;

- laboratory and field experiments have verified that ISB and chemical dispersion can be highly effective response methods;
- the presence of cold water and ice can enhance response effectiveness by limiting the spread of oil and slowing the weathering process;
- the window of opportunity for ISB and the use of dispersant operations in ice-covered waters can significantly increase compared to open water scenario in certain circumstances;
- new technologies for mechanical oil spill recovery and dispersant application, when combined with a large set of test data will improve response planning and response operations.

As a result from the program a significant amount of data was collected in order to better understand the behaviour of oil in ice. These issues included oil weathering, the window of opportunity for various oil spill actions, the interaction between oil-ice and water, the bio-availability of released oil in ice and information on oil-ice drift. This information will serve as the basis for model development, technical information to support further development of new oil recovery technologies, and practical experience that will be utilized in oil spill response contingency planning strategies (Sørstrøm *et al.*, 2010)

7.8 MORICE project

MORICE (Mechanical Oil Recovery in Ice Infested Waters) was initiated in 1995 to develop new technologies for the oil recovery in ice and the project ended in 2002. The focus was to deal with a situation in which oil was floating on water that also had ice floes. The operational principles of skimmers for open water were adapted to the situation by designing an apparatus that would float and mechanically lift the ice floes on a conveyor belt, above the water level, and then would rinse the oil off of the ice floes, and the resulting oil-water mixture would be subjected to normal oil-water separation technology. (NRC, 2003)

The recovery system developed during the project includes the following main components:

- A closed in and heated work platform, or vessel to operate from, with ice feeder and various auxiliary equipment (Figure 33),
- The Lifting Grated Belt (LGB) with ice washing system, defecting and washing of ice pieces larger than about 5 cm (Figure 34),
- The different recovery units operated one at the time, the LORI recovery unit and the MORICE brush-drum recovery unit (Figure 35).

The components are the most important results from the development process together with the experience gained during the project.



Figure 33. Work platform in Prudhoe Bay during freeze-up (Jensen *et al.*, 2002)

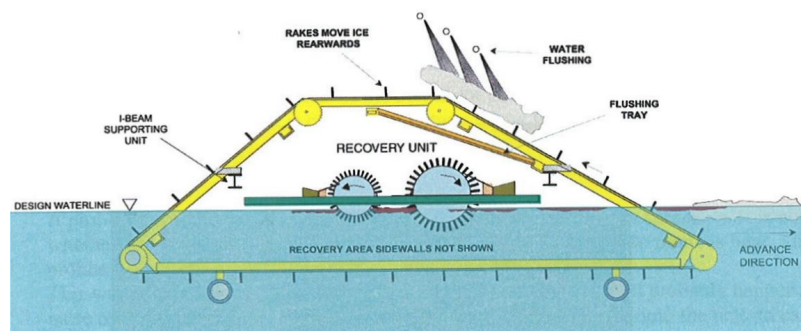


Figure 34. Lifting Grated belt with flushing system and recovery unit (Jensen *et al.*, 2002).

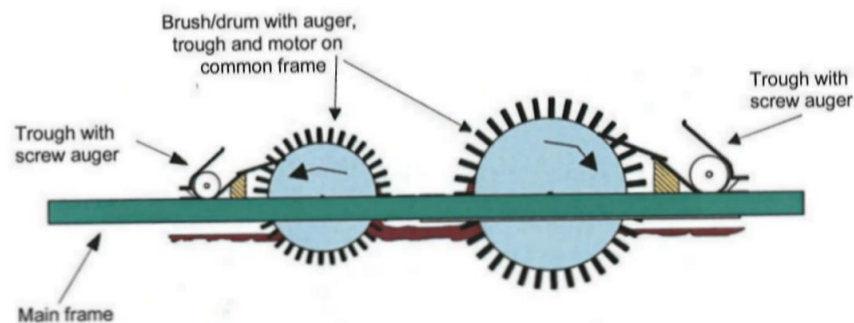


Figure 35. The brush-drums with one large drum at the front and one small at the rear (Jensen *et al.*, 2002).

The reference (Jensen *et al.*, 2002) concludes that MORICE recovery system worked as intended during the oil and ice tests at Ohmsett testing facilities and the system is ready for industrialization. However, it was assumed that all the components will require some degree of redesign and optimization to reach the prototype level.

8 Conclusions

The oil production activities are moving towards ice-covered waters where safety practises in marine operations are yet untrained. The ongoing discussions in the IMO indicate that the environmental issues related to polar shipping will have a high priority in many agendas during the forthcoming years.

The operational areas defined for the CIV Arctic project vessel, i.e. Goliat in the south Barents Sea and Olga basin in the north Barents Sea contain thin or medium thick first year ice. The third area, Haltenbanken in Norwegian Sea, is ice-free. Environmental conditions in the operational areas will be varying and challenging due to sea ice, extreme coldness, remoteness, limited visibility, state of sea and wind conditions.

The behaviour of oil in the ice-covered sea areas is crucially different compared to open water situation. Free moving of spilled oil is restricted by ice and weathering rate of oil is slower compared to open water and temperate climate conditions. Thus, quality and quantity of spilled oil, environmental conditions and location of oil spill have effect on the selection of combating technology.

Several non-mechanical and mechanical response options have been tested for arctic conditions in the JIP Oil in Ice program. The results indicated that each response method demonstrated some merit in oil spill response and all the response options should be available for response operations. Efficient oil spill response may be achieved by utilization of techniques individually or in combination. The results from various small and medium scale laboratory trials were verified in the program including ISB and dispersants which can be effective response options. Different type of oil recovery skimmers has been developed both in Finland and in Norway and the two most promising technologies were included in the field trials of the JIP Oil in Ice program.

In addition to skimmers, also a method for recover oil under ice and ice vibrating unit have been offered as mechanical oil combating options. OilWhale concept presents a novel oil recovery method that has been developed in Finland. It utilises the difference of gravity and viscosity of the recovered materials, and floating or otherwise material close to the surface can be collected. Similar technological applications have also been employed in the oil recovery actions at the Gulf of Mexico in 2010. The winterization of the method needs to be accomplished before the applicability of the system to arctic conditions can be verified.

The new Finnish multipurpose vessel to be mobilized in 2011 will be equipped with innovative oil recovery technology. The movable drum skimmer units in addition to brush belts and oil booms will offer improved response preparedness also in ice-covered waters compared to the present situation in the Gulf of Finland.

Before the possible oil spill response actions can be implemented, the oil must be detected. Different radar and scanner solutions, i.e. SLAR, SAR, GPR, and IR/UV offer options for oil spill detection but their operational constraints in extreme arctic conditions must be recognised. In addition to state-of-the art radar and sensor technologies, trained dogs have potential in oil spill detection since they are capable to detect small amounts of oil. Various modelling tools provide valuable means for experts dealing with oil spill contingency planning and response actions although the models designed for ice-covered waters are rare.

In the Baltic Sea area the utilization of dispersants and ISB has been restricted by the recommendation adopted by HELCOM. Although the trend in the Baltic Sea area is towards development of mechanical oil recovery methods, chemical dispersants and ISB are potential options for arctic oil recovery operations. The selection of the response options for the scenario in question should be carefully considered taken into the account oil characteristics and environmental conditions. The decisions should be based on sound scientific data, experience and documented facts, and the doors in the contingency plan should be kept open for all response options. Evaluation tools for selecting suitable response technologies could be NEDRA (Net Environmental Damage and Response Assessment) or EPPR field guide.

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