Oil Spill R&D in Norwegian Arctic Waters with special Focus on Large-scale Oil Weathering Experiments

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Abstract

The blow-out on Ekofisk in 1977 showed that the Norwegian preparedness for handling offshore oil spills was limited. The release lasted for seven days and totally 13 000 tons of crude oil were released. Sampling and monitoring of this first major Norwegian oil spill showed that the evaporative loss and natural dispersion were surprisingly high for this light North Sea crude. These findings initiated several substantial national R&D programs focusing on modeling of oil drift, mechanical recovery off-shore, environmental consequences and weathering processes in marine oil spills.

In the decade from 1985 exploration in the Barents Sea, and even on Svalbard, initiated several programs to develop new or adapt existing oil spill technology to Arctic conditions. With Arctic conditions we here mean low temperatures, possible presence of ice, darkness in the winter season and often long distances and lack of infrastructure. Development of skimmers, operationalisation of in-situ burning and the use of dispersants and studies of bioremediation were important R&D activities. Due to lack of major oil discoveries, the oil companies lost interest for the Norwegian Arctic areas in the late 1990ties and the funding for Arctic related R&D dried up. At present the interest in Norway for oil spill countermeasures in northern areas is again increasing, partly due to reopening of the Barents Sea for exploratory drilling and partly due to the increasing tanker traffic outside the Norwegian coast from Russia to Europe and USA.

To study the difference between an oil spill in temperate open water and in broken ice conditions important oil properties as evaporative loss, water content, emulsion viscosity and oil density are compared for two large-scale experimental oil releases (30 and 26 m^3 of crude oil).

State-of-the-art trajectory and oil weathering models can be used to predict both oil drift and weathering processes of oil spills in cold waters (without ice) with a accuracy sufficient for most operational purposes. This is possible after several decades with full-scale field experiments in Norway combined with the effort of several R&D programs. The present situation regarding knowledge and modeling capability concerning Arctic oil spills (broken ice) is however far from this. Large-scale field experiments in broken ice are very limited and there is a lack of knowledge regarding oil weathering and the dependence of environmental conditions in a broken ice scenario.

Since both oil transport and exploration are increasing in Arctic waters increased understanding of oil weathering processes under these conditions is needed. This is important both for environmental risk assessment studies, for oil spill contingency planning and to increase the operational capability for handling oil spills in Arctic areas.

Summary of Norwegian Oil spill R&D in Arctic waters

This chapter gives a short summary of the Norwegian R&D regarding oil spill technology for Arctic conditions. This is a short review with a representative selection of papers and SINTEF reports. The Norwegian R&D effort within Arctic oil spill technology was high in the period 1985-95. The two single reports which give a good overview of this activity were written in at the end of this period. The first one is a summary report from the program "Oil spill contingency in cold and Arctic areas" - ONA I and II (Løset et al., 1994) and the second is "Oil spill response in Ice Infested waters" (Vefsmo et al., 1996).

Mechanical recovery

The Norwegian effort regarding mechanical recovery of ice in cold and ice infested waters has mainly been focused on testing of existing skimmers for low temperature use and development of new skimmers that also can handle ice. The only existing skimmer that has been thoroughly tested in Norway in cold climate and with ice present is the Foxtail rope mop skimmer. This is one of the most common skimmers in the Norwegian national contingency plans, and it is considered to have a good potential for oil-in-ice recovery (Solsberg and McGrath, 1992). Based on tank tests in ice and in temperatures down to -18^{o}C, SINTEF has recommended a series of modifications for the Foxtail in cold conditions (Jensen and Johanessen, 1993).

The MORICE (Mechanical Oil Recovery in Ice-infested Waters) project was initiated in 1995. Through several phases, organized as separate projects, MORICE included participation from Norway, USA, Canada, Germany and Finland. The project was finalized in 2002 after testing the recovery system with oil and ice at the OHMSETT test tank in Leonardo, New Jersey (Jensen, H.V. & Mullin, J., 2003).

The main objective for the MORICE was to develop new technology for ice-infested waters. An oil-in-ice spill can involve anything from very light ice conditions, where the presence of ice can be treated as a simple debris problem, similar to situations frequently encountered in open water, to heavy ice conditions where the oil is trapped between floes or is intermixed with small ice forms, which could make it virtually inaccessible for recovery.

The MORICE scenario included conditions that are fairly mild:

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

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

The concepts comprising the MORICE unit were brought to a stage where it is ready for industrialization. The unit that was built is referred to as a harbor sized unit to indicate the conditions in which this particular size and strength of unit could operate. The choices made regarding cleaning of ice before redeployment also very clearly limit the operating speed and hence the encounter rate. For these reasons the developed system would be suited for thorough cleaning of a small spill in ice in harbor conditions. To combat a larger spill in offshore conditions, the scale of the unit would have to be increased accordingly, both regarding size and strength. Further details concerning the MORICE program and the resulting skimmer is given by Jensen and Mullin (2003).

In addition to the MORICE program there has not been much focus in Norway on oil recovery under cold conditions and in ice during the last decade. Prior to this an R&D program on oil combating in northern and arctic waters (ONA, started 1989), was dealing mainly with fate and behavior of oil in cold water and ice. This program was motivated by exploratory drilling for hydrocarbons in the Barents Sea, and was funded by the Norwegian Clean Seas Association (NOFO). The program culminated in 1993 with experimental spills of crude oil (26 m^3) in the Barents Sea ice to study spread, weathering and fate of the oil (Sørstrøm et al., 1994). Due to lack of discoveries from the exploratory drilling in the Barents Sea, this R&D program came to a halt just as the focus was planned to be shifted towards improvement of combating techniques for oil in ice.

At present the interest in Norway for oil spill countermeasures in the northern areas is again increasing, partly due to new interest from the oil companies regarding exploratory drilling, partly due to the increasing tanker traffic outside the Norwegian coast from Russia to Europe and USA.

In-situ burning

In-situ burning is particularly suited for use in ice conditions, sometimes offering the only option for removal of surface oil. The limited demand for logistic support compared to mechanical recovery and the use of dispersants place in-situ burning in a special situation for use in Arctic areas.

Norwegian R&D regarding in-situ burning started on SINTEF research station on Svalbard, Norway in 1988. This research was initiated by both oil exploration on Svalbard and in the Barents Sea (Sveum and Bech, 1991a and Guénette and Sveum, 1995a). The main objectives for this research were to:

- Study processes governing burning of emulsions
- Limitations for burning of emulsions (evaporative loss/water content)
- The influence of environmental parameters (wind and waves)
- Development of igniters for emulsions
- Uncontained burning
- Burning of oil and emulsions in broken ice and snow

Different igniters were tested on a wide range of emulsions (oil types, weathering degrees) and the igniters were deployed using the Helitorch system. This work lead to development of igniters consisting of a gelled mixture of readily available fuels (bunker C, diesel and gasoline), emulsion breakers and anti foaming agents. These igniters were capable of igniting a stable 50% emulsion of 24% evaporated Statfjord crude (Bech et al., 1991, Bech et al., 1993 and Guenette et al., 1994).

Series of burning experiments with up to 8 m^3 of oil were performed to study the effect of waves, currents, and wind when burning of emulsion in broken ice. These experiments were performed in April-May on basins up to 180 m^2 cut out in 1.2 meter thick fjord ice outside SINTEFs field station on Svalbard. Experiments were both performed with open water and with the presence of ice (up to 50% ice coverage). Both the effect of currents and waves can be studied in such a basin by mounting wave makers and current generator. Waves (30 cm high, 3 m long) had little impact on the burning of fresh and evaporated oils, but made ignition and burning of emulsions difficult to impossible. The effect of currents was studied by containing oil and emulsion slicks against a barrier in a 0.3ms-1 current. Weathered Statfjord crude (25% evaporated, 25-50% water) burned with efficiencies of up to 90% under the conditions tested (Guénette, et al., 1994, Guénette and Sveum, 1995b, Guénette et al., 1995 and Guénette and Vighus, 1996).

Experiments were also performed to study uncontained burning of crude oil and emulsions. These experiments were performed during the summer season. The oil and emulsion were initially contained in a 10 m steel ring floating at the water surface. The oil/emulsion were ignited inside the ring and then released. Spill sizes ranging from 0.5 to 8 m3 for fresh and emulsified crude (25% evaporated, 50% water). The main conclusion from these experiments was that uncontained burning of crude oil and emulsions is feasible if the slick is sufficiently thick, and in case of emulsions, if a large enough area can be ignited. Burning efficiencies up to 92% for the fresh crude and up to 75% for the emulsions were obtained (Gunette et al., 1995).

The University centre at Svalbard (UNIS) has in cooperation with SINTEF performed in-situ burning of a wide range of oil products and weathering degrees the last 7 years. This activity has been performed in small scale on open water and in broken ice and is a part of UNIS' master degree program within Arctic environmental technology.

Use of dispersants

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

Very little fieldwork has been performed with dispersants (and emulsion breakers) and oil in ice. The Norwegian studies with dispersants under "arctic" conditions have been performed by SINTEF through the ONA-program (Daling et al., 1991) and the DIWO-program (Brandvik et al., 1993 and Nerbø and Brandvik, 1993). "Arctic" conditions are in this context defined as low temperatures (0 to -20°C) both in the presence of ice and without ice. The effectiveness of dispersants is dependent on temperature and seawater salinity. Dispersants that earlier have shown high effectiveness at high salinity (3.5%) can give very low effectiveness at low salinity (0.5%) (Brandvik et. al., 1993). This is an important aspect under "arctic" conditions as the salinity of the surface water can vary e.g. during melting periods. The effect of low temperature on the effectiveness of a dispersant will vary for different dispersants (Daling et al., 1991). Some products are not very sensitive to temperature reductions, and even positive effects have been registered. Changes in physical/ chemical properties of the oil (pour point etc.) as a result of low temperature can be more significant. The physical/chemical properties of the dispersant itself can also be important for the effectiveness. Especially the viscosity of the dispersant at low temperatures will be important, for instance during application by a helicopter bucket at low temperatures.

Only modern concentrates are actual for use under arctic conditions. Strict requirements concerning physical properties have to be applied in order to fulfill the requirements of viscosity, precipitation, cloud-point and pour point at low air temperatures. Many dispersants show quite low effectiveness at low temperatures and salinity compared to North Sea conditions, and only products tested and approved for "arctic" conditions should be used. Laboratory and meso-scale flume experiments show that oils can disperse even with ice floes and slush ice present, provided that the level of energy is sufficient (Daling et al., 1991). Dispersibility testing on specific oil types in accordance with for instance Norwegian regulations for use of dispersants is also strongly recommended because the effect of dispersants and the time window of opportunity for effective use of dispersants will be different for different oil types.

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

Bioremediation

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

Natural biodegradation is a major process determining the fate of the oil in the marine water column. It was found that the transformation half-lives (t_{50}) of the water-accommodated fractions (WAF) was 2-3 days, and 10-60 days for various groups of C_{10}-C_{36} alkanes of mechanically dispersed oil or thin oil films (Brakstad and Faksness, 2000; Brakstad et al., 2002). However, the mineralisation of the oil compounds is considerably longer, and very little is known about the metabolites and the effects of these on the marine biota. Thus, biodegraded compounds may have significant impact on the marine biota since the degradation process increases the bioavailability of the compounds. Studies have shown that biodegradation of oil hydrocarbons in seawater at 0-1°C was slower, but more extensive than at 10-12°C (Leahy and Colwell, 1990).

Several studies regarding natural biodegradation and -remediation were initiated at SINTEFs field station on Svalbard in the late 1980ties. These projects were initiated by Norwegian oil companies when they were performing exploration drilling onshore at Svalbard. The main objectives for these projects were to:

- Study natural biodegradation and photo oxidation of oil under Arctic conditions
- Study the potential of different bioremediation methods under Arctic conditions

The first field experiments were performed in 1985 with Statfjord crude that had been left under ice for three months on a sandy substrate on Svalbard (78º North). No significant biodegradation was recorded after the period under the ice (Halmø et al., 1985). In 1986 a combined weathering and biodegradation experiment was performed with Statfjord crude confined in boom systems in a saltwater lagoon outside Ny Ålesund at Svalbard. The main findings were a large effect of photo oxidation (extensive oxygenation). The biodegradation was very slow and no effect was found by the added fertiliser Inipol EAP22 (Halmø and Sveum, 1987). Later the field station was moved to Svea in van Mijen fjorden and the focus was moved towards oil spill on an Arctic tundra environment. Several project were performed in the early nineties including both field experiments and laboratory simulations. A broad range of fertilisers was tested to enhance the natural biodegradation rate of petroleum products under Arctic conditions. Some of these fertilisers gave enhanced biodegradation, but also varying physical and environmental conditions influenced on the results (Sveum, 1991 and Sveum and Faksnes 1991).

Later projects were initiated with focus on biodegradation and remediation of petroleum hydrocarbons in an Arctic marine beach environment. The ESARC (Esso SINTEF Arctic Research Program) was one of the larger programs in this period. The main objectives with this program were to study biological and chemical fate of oil in and under ice and on Arctic shoreline sediments. The data and findings from this program are available in several publications and SINTEF reports e.g. Sveum and Beck, 1991.

The next larger project was the In-Situ treatment of Oiled Shorelines Program (ITOSS), performed in cooperation between SINTEF and several research institutions in US and Canada. The main objective was to evaluate the effectiveness of in-situ shoreline cleaning techniques to accelerate natural recovery. These techniques were; sediment relocation (surf washing), mixing (tilling), bioremediation (fertilizer application), and bioremediation combined with mixing. The main work were performed 1996 and followed up in 1997-98. The long-term degradation of the reference plot has later been monitored by SINTEF and UNIS until present time. The results from this extensive program is available in several project reports and publications e.g. Guenette et al., 2003. .

SINTEF has the last years developed a laboratory system for simultaneous determination of natural depletion (dissolution and biodegradation) of hydrocarbons on the oil-seawater interphase in cold seawater and ice slurries, using bacterial cultures enriched at 5 or 0.5°C (Brakstad et al., 2002). The system is based on immobilisation of thin oil films (< 10 µm) on hydrophobic fabrics and enabled studies both in static and flow-through systems. Initial results from the project showed that transformation of C_{10}-C_{36} alkanes in a paraffinic model oil were >90% at 5°C after 30 days, but considerably reduced at 0-0.5°C (35 % transformation after 60 days). The results indicated that oil characteristics were the limiting factor on biodegradation at low seawater temperatures rather than reductions in microbial metabolism. The results from this laboratory system are now compared to field experiments performed during the 2004/05 seasons at SINTEF field station on Svalbard. This work is a part of a research project financed by the Norwegian governmental grants and funding from Norwegian oil companies.

Weathering processes

The interest in Norway regarding weathering processes in marine oil spills was initiated by the offshore blow-out on the Ekofisk field in 1977. The release lasted for seven days and totally 13 000 tons of crude oil were released. SINTEF participated in the sampling and monitoring of this first major Norwegian oil spill and the evaporative loss and natural dispersion were reported as surprisingly high this light North Sea crude (Audunson et al., 1977). These findings initiated a large R&D effort in Norway focusing on modeling of oil drift, mechanical recovery offshore and weathering processes in marine oil spills.

Already the year after, in 1978, the first experimental oil release was performed to verify the findings from the Ekofisk blowout. 25 m^3 of Ekofisk crude were released under cold conditions at

Tromsøflaket in Northern Norway. Similar evaporative loss, natural dispersion and emulsion viscosities were measured as with the Ekofisk blow-out (Sørstrøm et al., 1978). In the years to follow several large experimental oil releases were performed to study surface oil drift and weathering processes; e.g. the 100 m^3 Statfjord crude at Haltenbanken in 1982 (Sørstrøm et al., 1984).

In the following period 1982-86 the focus was on the operational use of dispersants. Weathering studies were combined with dispersant applications in 1982, 7 x 2 m^3, in 1984 with 6 x 10 m^3 releases of bunker fuel and 4 x 10 m^3 weathered Statfjord crude in 1985. Most of these field trials were a part of the National Oil Pollution Control, Research and Development program (PFO) and details can be found in their summary report (PFO, 1985)

Then the focus was shifted back on oil weathering processes and drift trajectories with experimental releases on Haltenbanken with 30 m^3 of Oseberg crude in 1989 (Daling et al., 1989), in 1991 3 x m^3 Statfjord and Gullfaks crude and in 1993 the release of 26 m^3 Oseberg crude under Arctic conditions in broken ice in the Barents Sea (Sørstøm et al, 1994).

These field experiments and studies of oil weathering in the laboratory showed clearly that different oils have different weathering properties at sea. Field observations regarding weathering at low temperatures and in broken ice (Sørstrøm et al, 1994) were also studied in small and meso-scale lab facilities (Singsaas et al, 1993 and 1994).

Changes in some oil properties e.g. pour point, flash point, water uptake and viscosity of emulsion is important information for a spill response operation. The data from the laboratory and field experiments briefly listed above have been used to develop and calibrate the SINTEF Oil Weathering Model (see *Figure 1*). This weathering model predicts these properties based on input from a standardized step-wise weathering study performed at SINTEF. The model predicts weathering properties at selected temperatures, wind speeds and spill scenario.

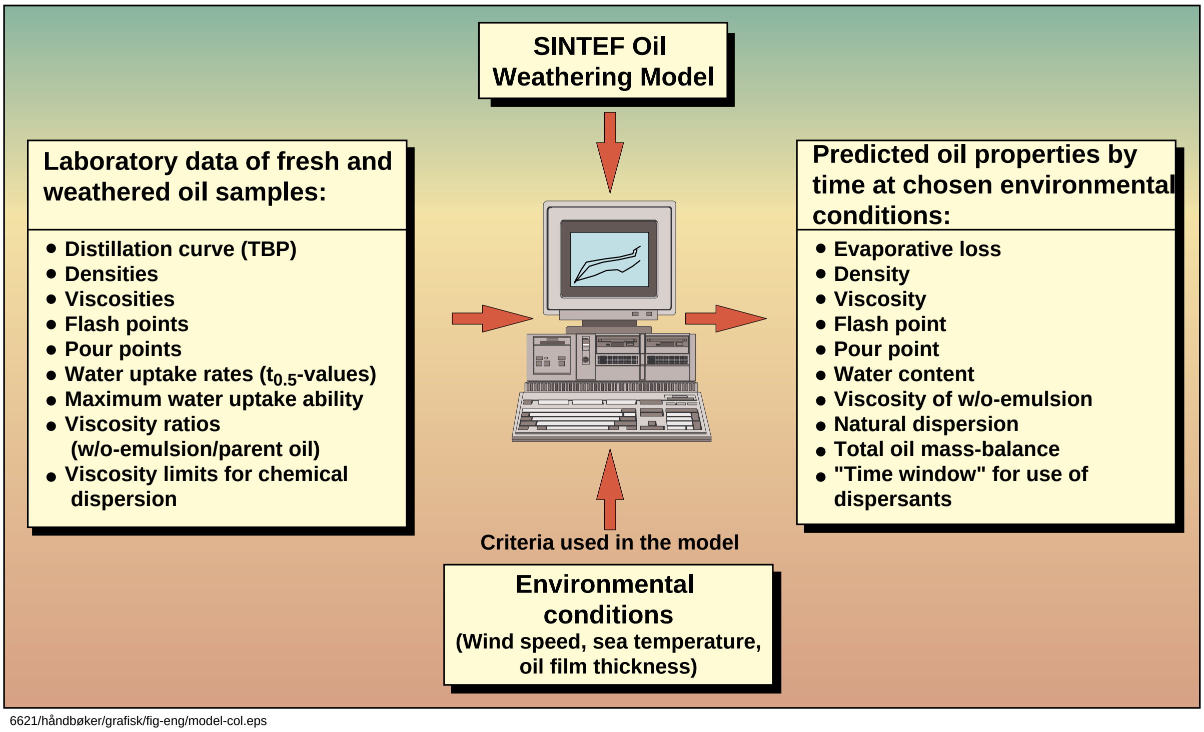

Figure 1: SINTEF Oil Weathering Model.

In 2003 SINTEF and the University Centre at Svalbard (UNIS) and other co-workers initiated a research program to study selected weathering processes in Arctic oil spills for a wide range of oil types. This three-year program if funded by Norwegian authorities and oil companies. The objective with this program is to focus on the weathering processes; biodegradation, release of water-soluble components to the seawater and photo oxidation. This program contains both laboratory studies at SINTEFs laboratories in Trondheim, UNIS laboratories in Longyearbyen and field activities on Svalbard.

Large-scale experimental oil releases

To illustrate weathering processes in oil slicks under Arctic conditions we have in this paper chosen to compare two large-scale experimental oil releases performed with a similar oil type. The first experiment is the Haltenbanken experiment in 1989 performed outside mainland Norway under North Sea conditions (open water with 10ºC and no ice). The second experiment is the Marginal Ice Zone experiment in 1993 performed in the Northern Barents Sea (broken ice conditions and water temperature of –1.8ºC). Further details can be found in earlier reports (Daling et al., 1989 and Sørstrøm et al., 1994).

Oil types

The crude oils used under these two experiments were relatively similar in chemical composition and expected behavior at sea. At Haltenbank-89 an Oseberg crude was used while a Sture Blend was used during the MIZ-93 experiment. Since the Oseberg crude was the major constituent in the Sture Blend in 1994, the physical and chemical properties of these two oil types are relatively similar as described in table 1 below. The Sture Blend used in MIZ-93 has a higher wax content compared to the Oseberg crude and a corresponding higher pour point and lower density.

Table 1: Selected physical and chemical properties for the two oil types (Oseberg crude and Sture Blend) used under the Haltenbanken 1989 and the Marginal Ice Zone 1993 experiment.

Oil type	Density (g/ml)	Viscosity (cP)	Pour Point (ºC)	Wax (wght.%)	Asphaltene (wght.%)
Sture Blend	0.847	32	-3	4.3	0.07
Oseberg crude	0.855	12	-22	2.8	0.10

Haltenbank experiment 1989

This experiment was a continuation of two earlier experimental oil releases performed in 1982 and 1985 Sørstrøm et al, 1982 and 1985). The project was organized by the Norwegian oceanographic research company OCEANOR with SINTEF and the Norwegian Institute for nature Research (NINA) as partners.

This large-scale experimental oil spill was carried out to study several objectives:

1. Evaluation of different types of oil spill drifters (Argos positioned buoys) versus oil drift
2. Intercalibration of different aerial surveillance systems
3. Study of weathering processes of the Oseberg crude
4. Study interactions between a drifting oil slick and sea birds

Only some of the available data concerning the oil weathering study is included here. More data concerning oil weathering and also oil drifters, modelling of oil drift, surveillance systems or oil-bird interactions are available from the original data report (Sørstrøm et al., 1989).

Release conditions

The oil was released at Haltenbanken outside the middle part of Norway (65º 00 N, 08º 00 E) at 10.05 July 1st 1989. The oil was released from a small tanker by a hose hanging 1-3 meter above the sea surface. The release of total 30 tons took 16 minutes, forming a small and concentrated oil slick in the beginning.

Harsh weather conditions were a problem during this experiment. The oil release had to be postponed several times due to high wind/waves. Also during the actual experimental period of four days the wind varied between 3-25 m/s (see figure 2 below). This made logistical operations like surface oil sampling from small boats difficult.

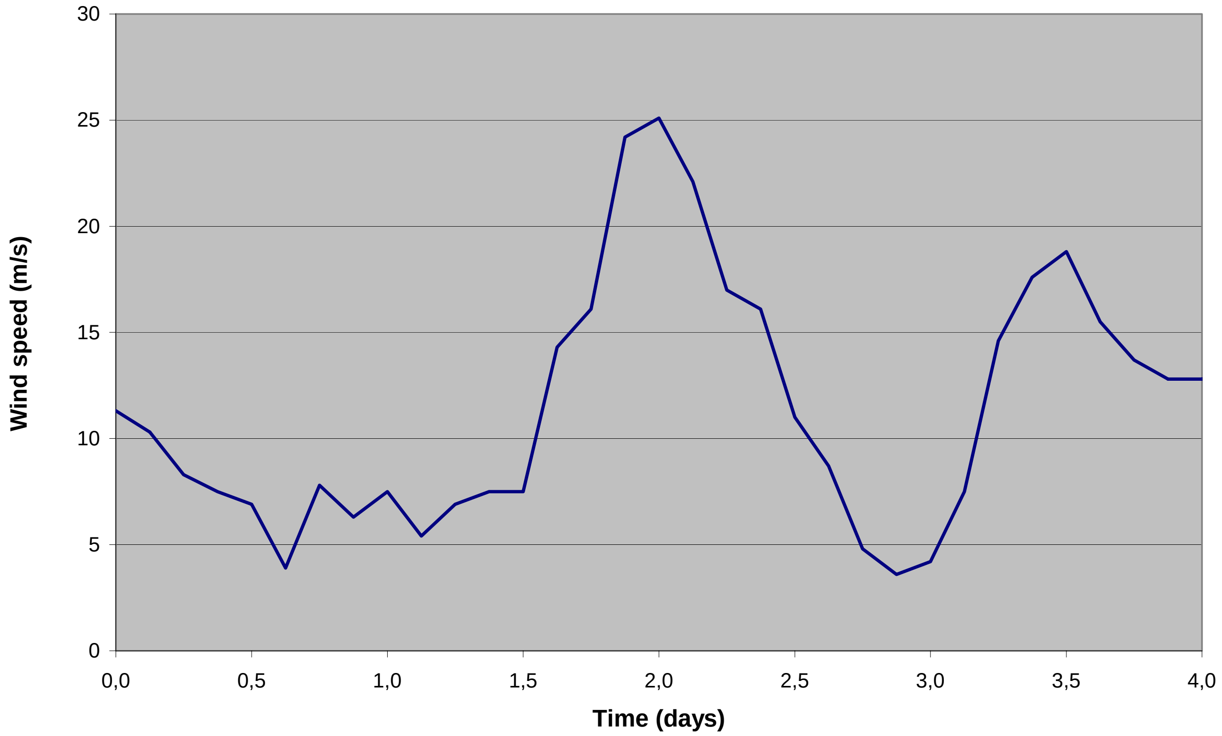

Figure 2: Wind speed for the period of the Haltenbank-89 and experiment (time zero = release of oil)

Oil sampling program

The first samples were collected 5 minutes after the oil was released and a comprehensive sampling program was carried out during the next four days. Both surface oil and water samples were collected. The surface oil samples were taken from a small surface boat with a net. Surplus, free water in the collected sample was drained off in a separation funnel, before the emulsified oil was stored on glass bottles. The analysis of the physical and chemical properties of surface oil were performed in a laboratory container onboard the main vessel. The results presented in this study are average values of 2-3 replicate samples.

The following analysis were performed:

1. Evaporative loss of light components (weight %)
2. Water content of w/o-emulsion (Volume %)

3. Viscosity of emulsion and water free oil (cP/10ºC at shear rate 100 for water-free and low viscous samples and shear rate 10 for emulsified samples)
4. Density of emulsion and water free oil (g/ml)
5. Chemical dispersability of surface oil/emulsion (simplified field test)
6. Pour point of water free oil (ºC)
7. Flash point of water free oil (ºC)
8. Interfacial tension between water and oil
9. Thickness of surface oil/emulsion

The last 4 analysis (bullet point 6-9 above) were done at SINTEF laboratories after the field experiment was terminated. Only selected variables describing the weathering processes in the surface oil slick will be presented here (evaporative loss, water uptake, viscosity of emulsion and density of water-free oil). The full dataset is available from other sources (Sørstrøm et al., 1989).

Marginal Ice Zone experiment 1993

The activity related to oil exploration was high in the Norwegian sector of the Barents Sea in the 1980ies and early 90ies. The Marginal Ice Zone experiment in 1993 was organised by SINTEF and funded by Norwegian oil companies through Norwegian Clean Seas Association for Operating Companies (NOFO). The main objectives were to gain more knowledge regarding the behaviour of oil spilled under Arctic conditions and to acquire knowledge about the specific environmental conditions (wind, waves, ice conditions, drift and spreading) in the marginal ice zone.

Release conditions

The experimental oil spill was performed in dynamic broken ice condition in the period of 19-26th of April 1993 in the northern Barents Sea (N75, E24). 26 m^3 of Sture blend was released approximately 45 km inside the ice edge at an ice concentration of 93%. The oil was gently release into the ice with a hose trough an over-flow chamber located on an ice floe. During the 7-day period of sampling and analysis of the surface oil/emulsion, the slick drifted to a position approximately 6 km from the ice edge, and the ice concentration varied from 93-75% (see figure 3). The dominant wind direction was from the ice towards open water, and the wave energy conditions were relatively low most of the time. The wind speed was relatively low (6-10 m/s) and the temperature varied between -16°C and -0°C (see figure 3). The water temperature was close to -1.8°C during the experimental period.

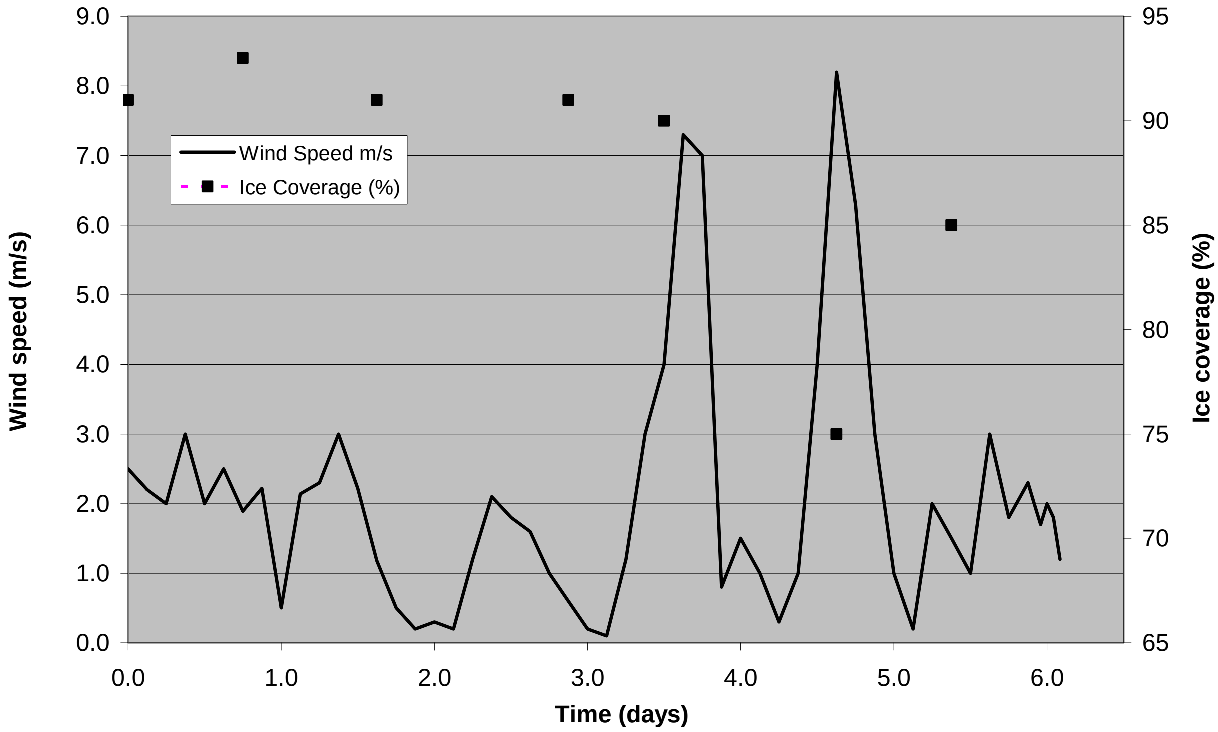

Figure 3: Wind speed (m/s) and ice coverage (% ice) for the period of the Marginal Ice Zone experiment (time zero = release).

Oil sampling program

The oil drifted in relatively high ice coverage (93 - 75%) during the seven-day period. This caused the oil to be distributed between the ice floes in relatively thick layers (0.5-12 cm). The wave damping effect of the ice did also cause reduced energy input causing oil-in-water emulsification from waves or moving ice. The first surface oil samples were collected after 4 hours and a comprehensive sampling program was carried out during the next seven days. The analyses of the collected oil samples were similar to the ones performed during the Haltenbank-89 experiment (sea earlier chapter).

As for the open water experiment described in the previous chapter, only selected variables describing the weathering processes in the surface oil slick will be presented here. These variables are evaporative loss, water uptake, viscosity of emulsion and density of water-free oil. The full dataset regarding both oil weathering and environmental data is available from other sources (Sørstrøm et al., 1994 and Daling et al., 1989).

Weathering of oil spills in an Arctic environment

The main factors influencing the fate of a marine oil spill are; the chemical composition of the oil, the release and the environmental conditions. In this paper we will focus on the differences caused by the environmental conditions. Several of the major weathering processes with respect to both volume of oil on the sea surface and concentration of oil in the water masses are strongly dependant on environmental conditions. Both the rate and the final levels of weathering processes like evaporative loss and w/o-emulsification in an oil spill are strongly dependent on the environmental conditions. Both evaporation and leaking of water-soluble components from the oil into the seawater are surface phenomena and are strongly dependant on the volume to surface ratio or the spreading of the oil slick. Other processes like w/o-emulsification or natural dispersion are strongly dependent on the energy input from breaking waves.

Comparison of Haltenbanken-89 and MIZ-93

In this chapter we present a comparison of important variables describing weathering processes from the two large-scale oil experiments. These variables are; Evaporative loss, Density of water-free oil, water uptake and viscosity of emulsified oil.

Evaporative loss

Figure 4 below shows the evaporative loss (weight percent) as a function of weathering time at sea (days). The open water scenario (dashed line) shows a high evaporative rate during the first hours with an evaporative loss around 20% after 4-6 hours and a total of almost 40% when the experiment was terminated after 3.5 day. The evaporative rate is much lower for the broken ice scenario with a total evaporative loss of 20-25% after 7 days and only 8% after 4 hours.

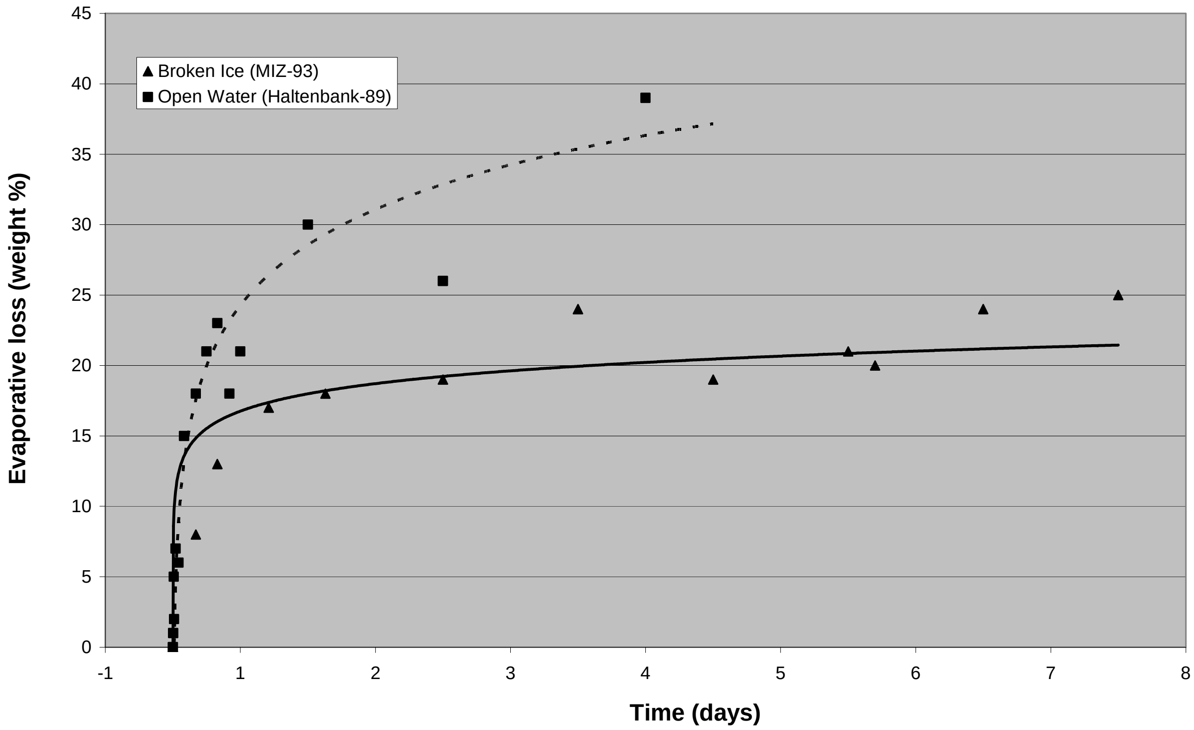

Figure 4: Evaporative loss (weight %) of the crude oil as a function of time for both the Haltenbank-89 and the Marginal Ice Zone 1993 experiment

Density of water-free crude oil

The density of the water-free oil was measured after the w/o-emulsion is broken. This was done by adding emulsion breaker to the emulsion and heating the samples. The natural occurring stabilizing components was then disturbed by the surfactants in the emulsion breaker and the emulsion de-stabilized. This will cause the water droplets to merge, forming larger more unstable droplets and settle out of the emulsion. The density (g/ml) for the two field experiments is presented in figure 5.

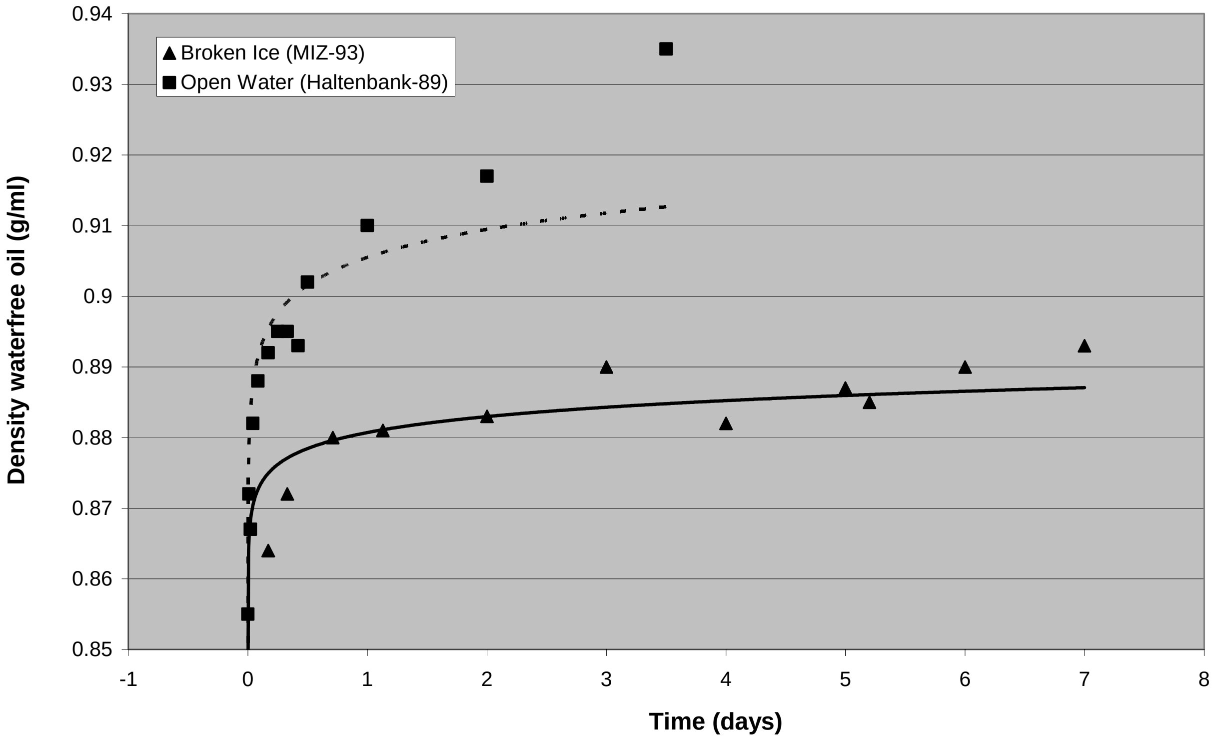

Figure: 5: Density (g/ml) of the crude oil as a function of time for both the Haltenbank-89 and the Marginal Ice Zone 1993 experiment

W/o-emulsification

Water-in-oil emulsification is the process of mixing small droplets of water into the oil phase. In the initial phase these water droplets can be large (>0.2 mm??) and the emulsion formed is usually unstable with low viscosity. Later the larger droplets settle out while the smaller droplets are stabilised and stays in the oil. The content of natural occurring surface-active components in the oil (mainly resins, waxes and asphaltenes) is important for the stabilisation of the smaller droplets and the formation of a more stable emulsion. The main hypothesis concerning the formation of w/o-emulsions is as follows:

1. Breaking waves hits the surface oil and force parts of the surface oil slick down into the seawater as small droplets.
2. Larger droplets and lumps of oil resurface and merge into the surface oil slick again
3. Water is then trapped between the two layers of oil (surface oil and resurfacing earlier submerged oil)
4. Larger droplets of water settle out due to high sinking speed, but smaller droplets of water will stay in the oil
5. As this process continues the water content will increase (rate is dependant on sea state) and the droplet distribution in the oil will shift towards smaller water droplet sizes as larger and unstable droplets sinks out.
6. The water content will stabilize at a certain level dependant on the chemical composition of the oil. Mainly the content of surface-active components, which can stabilise the water droplets in the continuous oil phase.

In figure 6 are both the water uptake for the open water scenario from Haltenbanken–89 and the broken ice scenario from MIZ-93 presented as a function of weathering time at sea. The open water oil spill ends up with a water content in the area of 70-80% while the broken ice oil spill ends up with and water uptake around 20% towards the end of the experiment when the ice field opens up.

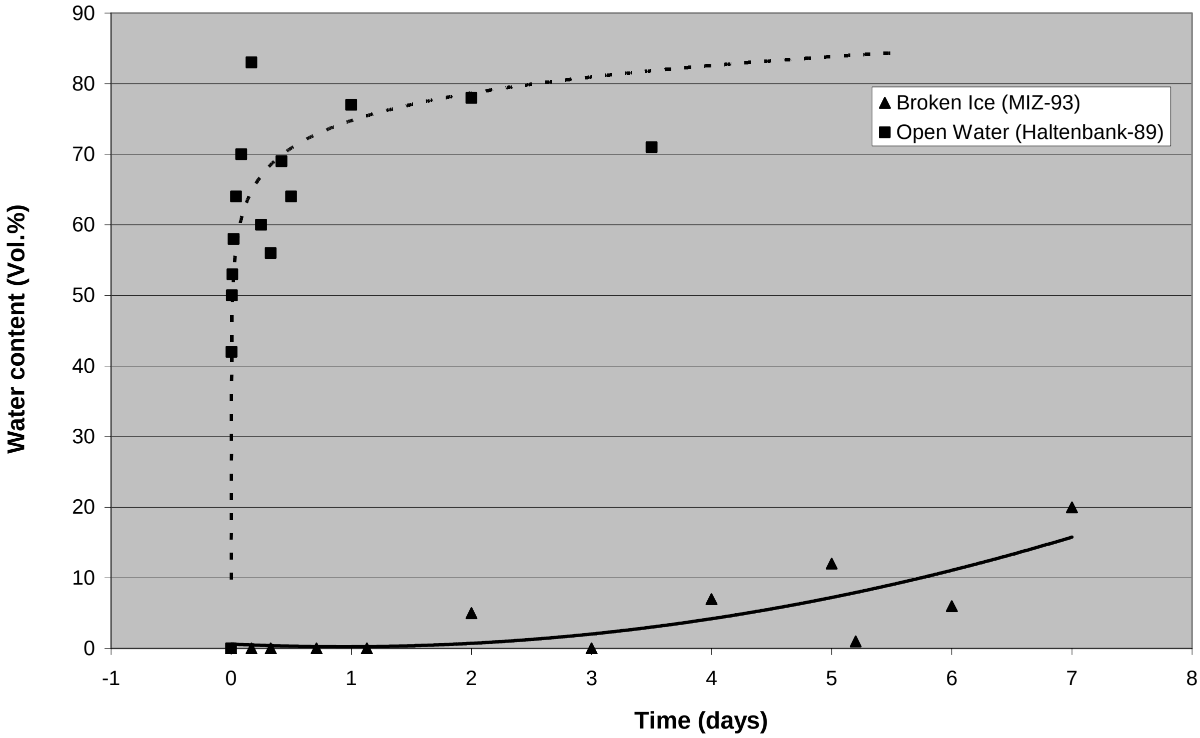

Figure 6: Water uptake (volume %) of the crude oil as a function of time for both the Haltenbank-89 and the Marginal Ice Zone 1993 experiment

Viscosity of w/o-emulsion

The viscosity of the w/o-emulsion in the weathered oil slick is mainly dependant on the inner friction between the discontinuous water droplets and the continuous oil phase. The viscosity is strongly dependant on the water content of the emulsions and on the chemical composition of the oil (number and size distribution of water droplets). Both the emulsion viscosity from the open water scenario from Haltenbanken–89 and the broken ice scenario from MIZ-93 is presented in figure 7. The maximum viscosities measured in broken ice were 400-600 Cp, while the corresponding values in the open water oil slick were 15000 – 18000 cP after 3.5 days.

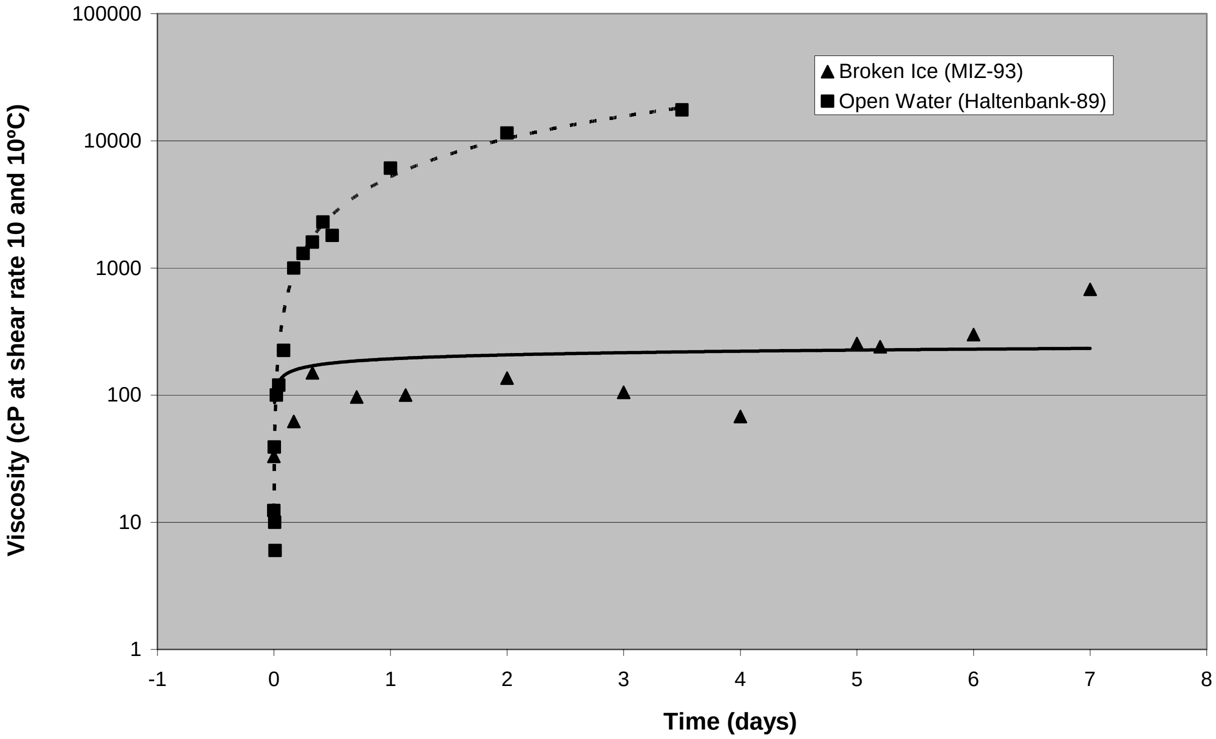

Figure 7: Viscosity of emulsion (cP, shear rate 100 or 10 at 10ºC) of the crude oil as a function of time for both the Haltenbank-89 and the Marginal Ice Zone 1993 experiment

Discussions

Since the physical and chemical properties of the oils used in the two experiments presented in this paper (open water versus broken ice) are relatively similar, and their release conditions are relatively similar (both are surface releases) the differences in oil weathering could mainly be explained by other factors. These factors could be the different environmental conditions between the open water scenario from Haltenbank-89 and the broken ice scenario in MIZ-93.

Both the evaporative loss and the water-free density show a significant difference between the two different scenarios (see figure 4 and 5). Since all the emulsified water is removed the main process causing changes in density is the evaporation of the light components, we would expect a correlation between the changes in evaporative loss and density. The difference in evaporative loss is mainly explained with the restricted spreading of the surface oil during the MIZ-93 experiment due to the ice floes (75 to 93% ice coverage, se figure 3). The film thickness of the Haltenbanken-89 spill was ranging from a few microns to 10 mm in the emulsified area (Daling et al, 1989) while the surface oil during the MIZ-93 experiment varied between 10 to 120 mm (Sørstrøm et all, 1994). Since oil evaporation is a surface phenomena reduced surface to volume ration (increased thickness) will lower the evaporative loss. Low temperature (-1.8 versus 10ºC) will also reduce the molecular diffusion of the light and volatile components in the oil and could create a gradient from the surface into the bulk phase of the oil.

Also regarding the water uptake a significant difference can be observed (figure 6) between the two scenarios both with respect to uptake rate and the final levels of water content. The open water scenario gives a high water uptake rate for the first 12 hours due to breaking waves (5-8 m/s wind, see figure 2), while the broken ice scenario have a very low uptake rate probably due to high ice coverage and low energy input from the waves (see figure 3). After 3.5 days the open water oil slick has stabilised its water uptake around 70-75% while the corresponding oil slick in broken ice has water content in the range of 8-10%. After 7 days. At the end of the broken ice experiment, the oil slick starts to take up water as it reach the ice edge and the ice coverage reduces (see figure 3) and some wave action can occur in the open water between the ice floes.

Since the viscosity of the emulsified oil (figure 7) is closely linked to the total water content a significant difference between the two scenarios can be seen in figure 6. The evaporative loss (35-40% versus 20-25%) and the temperature difference (10 versus –1.8ºC) between the two scenarios also influences the viscosity of the weathered oil, but the difference viscosity (15-16000 versus 400-600 cP) is mainly caused by the difference in water content (70-80% versus 20%)

Conclusions and Recommendations

The comparison of these two large-scale field experiments have shown that weathering properties like evaporation, oil density, water uptake and viscosity in broken ice are strongly influenced by the reduced oil spreading and wave action caused by the high ice coverage.

State-of-the-art trajectory and oil weathering models can be used to predict both oil drift and weathering processes of oil spills in cold waters (without ice) with a accuracy sufficient for most operational purposes. This is possible after several decades with full-scale field experiments in Norway combined with the effort of several R&D programs. The present situation regarding knowledge and modeling capability concerning Arctic oil spills (broken ice) is however far from this. Large-scale field experiments in broken ice are very limited and there is a lack of knowledge regarding oil weathering and the dependence of environmental conditions in a broken ice scenario. Both oil transport and oil exploration are increasing in Arctic waters, also with the presence of ice, and more data is needed to increase our understanding of oil weathering under these conditions. An increased understanding is important both for environmental risk assessment studies, for oil spill contingency planning and to increase the operational capability for handling oil spills in Arctic areas.

These data can be provided both by laboratory studies in temperature controlled meso-scale facilities, but can only be verified by full-scale field experiments and should be performed under different ice-conditions.

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