REPORT

Oil in Ice - JIP

SINTEF Materials and Chemistry
Marine Environmental Technology

SINTEF

Preface

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

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

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

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

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Funding Partners

R&D Partners

Cooperating Partners

JIP Oil in ice

REPORT

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ABSTRACT

This report gives a short "state – of –the art" of the testing oil spill dispersants in simulated cold conditions that has been undertaken by several research groups, but with different combinations of:
   low temperature;
   absence or presence of ice;
   water salinity

This to ensure transfer of newest knowledge and ensure a good planning and experimental design of the dispersant effectiveness testing in task 4.1

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Dispersant effectiveness	Effektivitet av dispergeringsmiddel
GROUP 2	Arctic conditions	Arktiske forhold
SELECTED BY AUTHOR	Review / State-of the art	Oversikt / State-of-the-art
	Ice conditions	Isforhold
	Sea salinity	Saltinnhold i sjøen

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1 Introduction

There has been periodic interest in all types of oil spill countermeasures in waters where ice is present at some times of the year. The 'shorthand' phrase "Arctic conditions" has often been used to summarise seasonally low (or sub-zero) air and sea temperatures, plus the presence of ice and is not always related to activities within the Arctic Circle or the seas within the Arctic Ocean.

The interest in oil spill countermeasures has often been stimulated by oil-related activities within the Arctic Circle such as offshore exploration in the Beaufort Sea (in the 1970s and 80s), or by increasing sea transport of crude oil and oil products in areas such as the Baltic Sea. Oil spill countermeasures in the presence of ice are also relevant to other areas that are currently relevant to the oil industry such as the Caspian Sea and the Sea of Okhotsk, off Sakhalin.

1.1 Low or sub-zero temperatures

The common feature of seasonally sub-zero air and low sea temperatures will cause the spilled oil to have a relatively high viscosity - compared to the same oil in more temperate conditions - or to be substantially below the Pour Point of the oil, and therefore effectively solid. Oil viscosity is known to influence the performance of many oil spill countermeasures, including the use of oil spill dispersants.

The relationship between oil viscosity (or emulsified oil viscosity) and dispersant effectiveness is not linear. Dispersant effectiveness, as judged by a variety of test methods, is generally high up until a limiting viscosity value and then drops to a much lower level at higher viscosity (See example in Figure1). The limiting viscosity value varies with test method and this probably reflects the effect of sea-state; higher viscosity oils can easier be dispersed in rougher seas than in a calm sea.
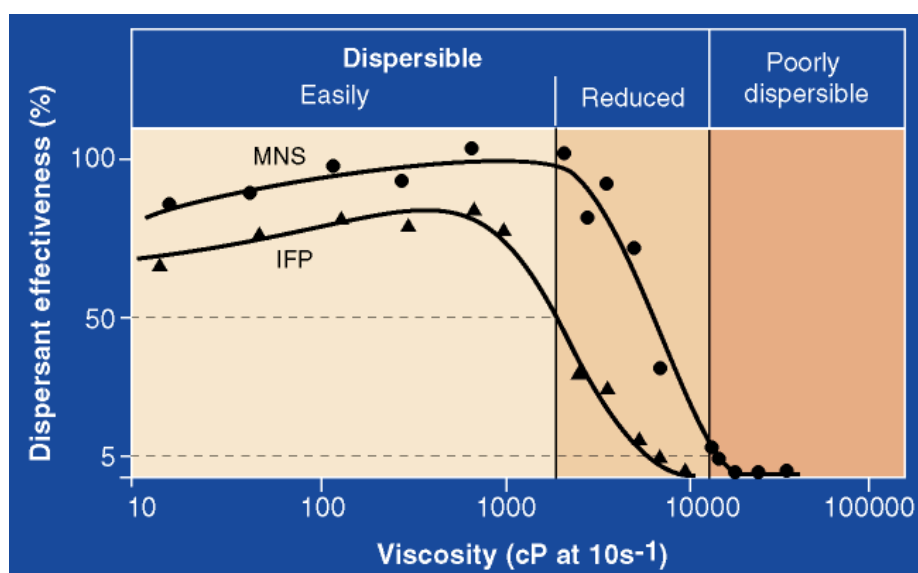
Figure 1.   Example on the effect of oil/emulsion viscosity on dispersant
effectiveness, using different test methods with different energy input.

Low air and sea temperatures and the presence of ice will slow down the rate of evaporation of the more volatile oil components (Figure 2), compared to that which takes place in more temperate conditions, and this aspect of oil 'weathering' will be retarded. The comparison in Figure 2 is of oil

weathering properties measured in the high ice coverage MIZ (Marginal Ice Zone) of the Barents Sea in 1993 and similar experiments made in the open ocean (ice free) at Haltenbanken in 1989.
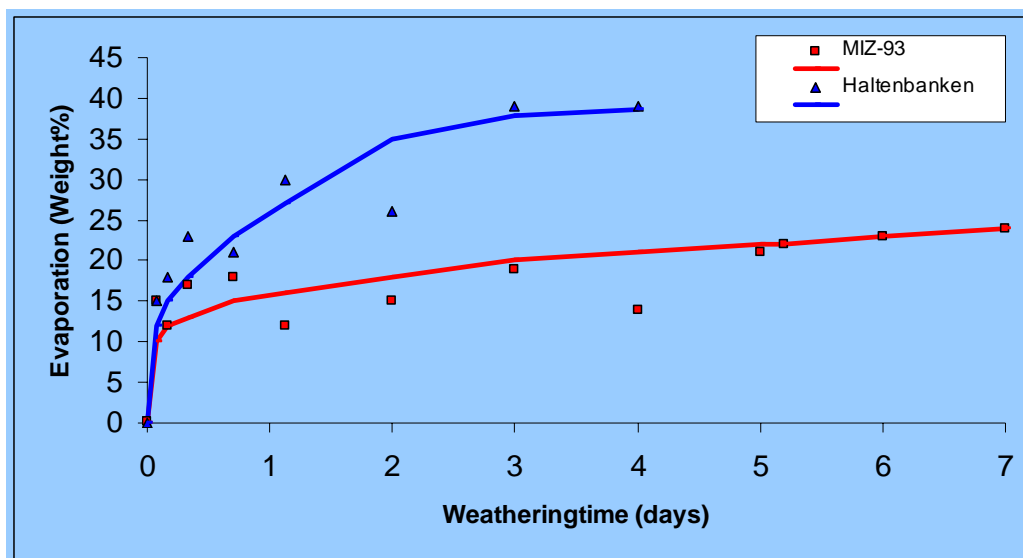
Figure 2.   Effect of Arctic conditions on the rate of evaporative loss from spilled oil

The rate of water-in-oil emulsification is also greatly reduced in cold, icy water compared to more temperate conditions (Figure 3).
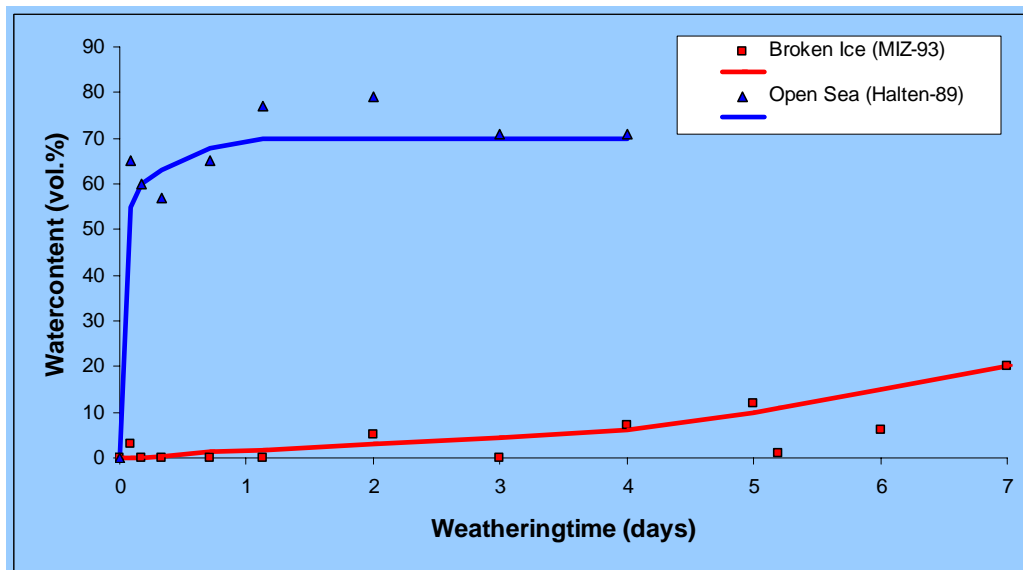
Figure 3.   Effect of Arctic conditions on the rate of emulsification of spilled oil

The rate of spilled oil viscosity increase caused by the loss of volatile oil components by evaporation and by the uptake of water to form water-in-oil emulsions is therefore much lower in high ice coverage in Arctic conditions than in more temperate conditions (Figure 4).

Figure 4.   Effect of Arctic conditions on the rate of viscosity increase of spilled oil

The time "window of opportunity" for dispersant use (the period of time after an oil is spilled onto the sea surface when dispersant use is likely to be effective) can therefore be longer in Arctic conditions than in more temperate conditions, even though the lower prevailing temperature will cause higher oil viscosity.

1.2 The presence of ice

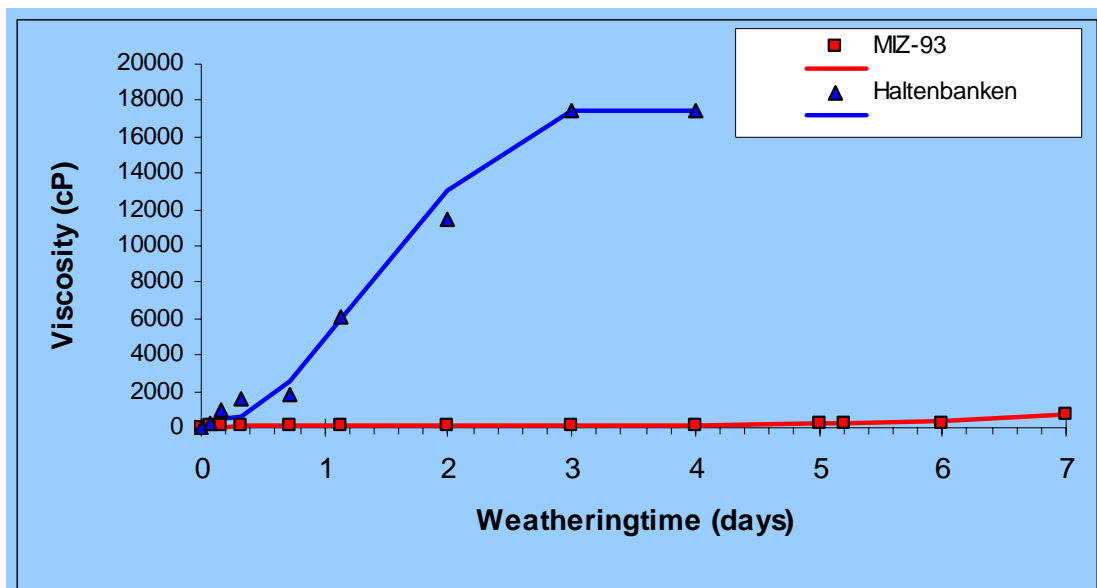The presence of ice on the sea surface will also have a great effect on oil spill response. If there is solid sheet of ice on the sea surface, any oil spill response measures will depend on whether the oil has been spilled on or under the ice. If there is only partial ice cover on the sea surface, then the response will be affected by the degree of coverage and the form of the ice. The presence of ice will retard the spreading rate of the spilled oil, compared to ice-free conditions. The seasonal cycle of freeze-up and melting if ice will have important practical implications for any oil spill response method.

The study of the formation and fate of sea ice is a scientific discipline in its own right and many institutes specialize in this topic. The National Snow and Ice Data Center (http://nsidc.org/) in Colorado, USA is such a centre of expertise and the brief summary below has been abstracted from their web-site.

Fresh water freezes at 0ºC, but the freezing point of sea water varies with salinity. For every 5 psu increase in salinity, the freezing point decreases by 0.28ºC degrees. Seawater with a salinity of 35 psu begins to freeze at -1.8ºC.

Sea ice formation follows a development through different stages; from "frazil" and "grease" ice crystals, through "nilas" (transparent, dark, grey and white) in calm conditions, or "pancake" ice in rougher conditions, to ice sheets or ice floes of "first-year ice".

New ice is a technical term that refers to ice less than 10 cm thick. As the ice thickens, it enters the *young ice* stage, defined as ice that is 10 to 30 cm thick. Young ice is sometimes split into two subcategories, based on colour: *grey ice* (10 to 15 cm thick) and *grey-white ice* (15 to 30 cm thick). *First-year ice* is thicker than 30 cm, but has not survived a summer melt season. *Multiyear ice* is ice that has survived a summer melt season and is much thicker than younger ice, typically ranging from 2 to 4 meters thick.

The presence of ice modifies the wind-induced wave action at sea; short wavelength waves are damped by the presence of pieces of ice as the moves very slightly out of phase with the water. Long wavelength swell persists inside broken ice fields, but shorter wavelength waves are suppressed by the presence of ice. The degree of cresting or breaking wave action at a particular wind speed is less in the presence of ice, compared to ice-free conditions.

Response with some ice present on the sea will therefore be seasonal; during freeze-up, with ice present or during the melting of the ice. Oil spill response in ice-free conditions (summer in the north) would be very similar to response in other parts of the world, albeit at lower temperatures. The onset of freeze-up, the progress of ice formation and the onset and progress of the thaw at any location are very dependent on the prevailing local conditions. Predicting ice conditions with a high degree of accuracy is very challenging (for example; Oasis and Dickins, 2006).

The ice condition, that is the stage of development and form of the ice, will be different at different locations:

- In the shallow waters of most Arctic Seas the polar ice pack is never far away and ice cover in the long winter will be a continuous layer of ice broken up by tidal movements and with a lot of fast ice attached to the shore in the shallow water. Pressure ridges will be formed where the ice is forced upwards by the relative movement of the pieces of ice.

- A large tidal range and fast currents, such as occur in Cook Inlet on the northern coast of the Gulf of Alaska, will rapidly break up the ice into pieces of a wide range of sizes.

- At other, more open ocean locations such as the Barents Sea, the ice will be present as ice floes that have been formed as pack ice elsewhere and which have been carried to the location by the influence of wind and currents.

- Arctic icebergs are calved mainly from the glaciers on the west and east coast of Greenland and from the glaciers of Ellesmere Island. Approximately 25 000 are calved each year with a typical depth of 50 m. They drift southward on the Labrador Current towards the Grand Banks of Newfoundland. Only about 400 icebergs, however, manage to complete the journey and appear at the Grand Banks and occasionally in the main North Atlantic sipping lanes.

1.3 Salinity

A characteristic of some specific areas, in addition to low temperatures and the presence of ice, is lower than usual seawater salinity.

On average, seawater in the world's oceans has a salinity of approximately 35 psu (practical salinity units), ranging from 32 to 37 psu in different parts. In Polar Regions, the salinity may be less than 30 psu. The salinity of the upper (30-50 metre) surface waters of the Arctic Ocean (including Baffin Bay, Barents Sea, Beaufort Sea, Chukchi Sea, East Siberian Sea, Greenland Sea, Hudson Bay, Hudson Strait, Kara Sea, Laptev Sea, Northwest Passage, and other tributary water bodies) ranges from greater than 34 psu near the North Atlantic to below 29 psu near river deltas.

1.3.1 The effect of river inflow on offshore salinity

The outflow of freshwater from rivers into the sea in cold regions will be seasonal. The freshwater flow will cease when the rivers freeze in winter and there will be a large release of freshwater into the sea when the river ice melts and freshwater from melting ice on the land is transported into the sea in summer. Because of its low salinity, this freshwater remains close to surface and is first to freeze up in autumn. This will cause a temporary reduction in the salinity of the seawater close to the river estuary.

The degree of reduction in salinity and the area of sea affected will depend on water depth and water flows; the effect will be most noticeable in the upper layers of shallow, semi-enclosed seas. In several areas, offshore oil E&P activities are taking place in the shallow Arctic seas.

- The salinity of the Kara Sea will be temporally and locally reduced by several psu because of freshwater inflows from the rivers Ob and Yenisey. The salinity of the Laptev Sea will also be temporally and locally reduced by freshwater flow from the river Lena during the short Arctic summer.

- The salinity of the shallow waters of the Beaufort Sea, particularly the near-shore regions where oil exploration took place in the 1970s and 80s and is planned for the future, is greatly affected by the inflow of freshwater from the Mackenzie River and the melt-water from ice on the land (Dickins and Owens, 2002).

- The salinity of the Sea of Okhotsk is reduced by a large influx of freshwater from the Amur river and in winter navigation becomes very difficult because of the formation of large ice floes

Semi-enclosed or enclosed seas have a lower salinity than open oceans because of a high level of freshwater input.

- The Baltic Sea is brackish and has a much lower salinity than the ocean's as a result of abundant freshwater runoff from the surrounding land and a very limited exchange and sporadic exchange of seawater . The salinity varies from 1 psu in the exteme north to 6-8 psu in the centre. Below a depth of 40 - 70 metres, the salinity can be as much as 15 - 20 psu. About 45% of the area of the Baltic Sea is covered in ice in the winter.

- The Caspian Sea has an average salinity of approximately 12 psu caused by 80% of the inflow being freshwater from the Volga river and the salinity is lower in the shallow waters of the northern region. The northern part of the Caspian Sea freezes during winter and in the coldest winters ice can also be found at south.

- Low salinity is not limited to cold climates. The salinity of the surface waters of the Black Sea is approximately 18 psu. There is a net inflow of seawater through the Bosporus, 200 km³ per year and there is an inflow of freshwater from the surrounding areas, especially central and middle-eastern Europe, totalling 320 km³ per year. The most important river entering the Black Sea is the Danube.

These seasonal salinity reduction effects will not be experienced far offshore in deeper, open seas without localised freshwater inflow, such as the Barents Sea.

1.4 Sea ice and salinity

Sea ice formation and melting has a significant effect on the localized salinity of the seawater in areas where ice occurs. The temperature and salinity in the very top layer of the sea (a few centimetres) can, locally and seasonally, vary as the ice cover forms and melts; salt is expelled from the ice into the water during freeze-up and low salinity or freshwater is released into the sea when the ice melts.

When frazil ice crystals (needle-like crystals, typically 3 to 4 mm in diameter) form, salt accumulates into droplets of brine (water nearly saturated with salt, with greater than 50 psu salinity). Most of the brine is expelled back into the ocean and this raises the salinity of the near-surface water. This is called brine rejection. By losing this brine, the sea ice becomes less salty, while the underlying water becomes more salty. This changes the way the water currents move under the ice as this cold salty water sinks to the bottom of the sea.

As the floating sea ice is blown southward by the wind, it reaches an area of water which is above freezing, where the ice melts rapidly. As the ice melts, it creates a layer of fresher (less salty) water on the surface of the ocean on top of a layer of salty water. The boundary between these two layers is called the halocline.

Some liquid brine droplets become trapped in pockets between the ice crystals. The brine does not freeze because of its high salinity. These brine droplets are of high salinity, but the ice around them is not and the ice has a bulk salinity of typically 10 psu for new ice. Over time, the brine drains out, leaving air pockets, and the salinity of the sea ice decreases down to typically 2 to 3 psu for multiyear ice. The bulk salinity of ice is related to its age and thickness. The relevance of ice of permeability was identified in early studies of oil pollution in the Arctic (Wolfe and Hoult, 1974; Martin,1979 and Milne at al 1977).
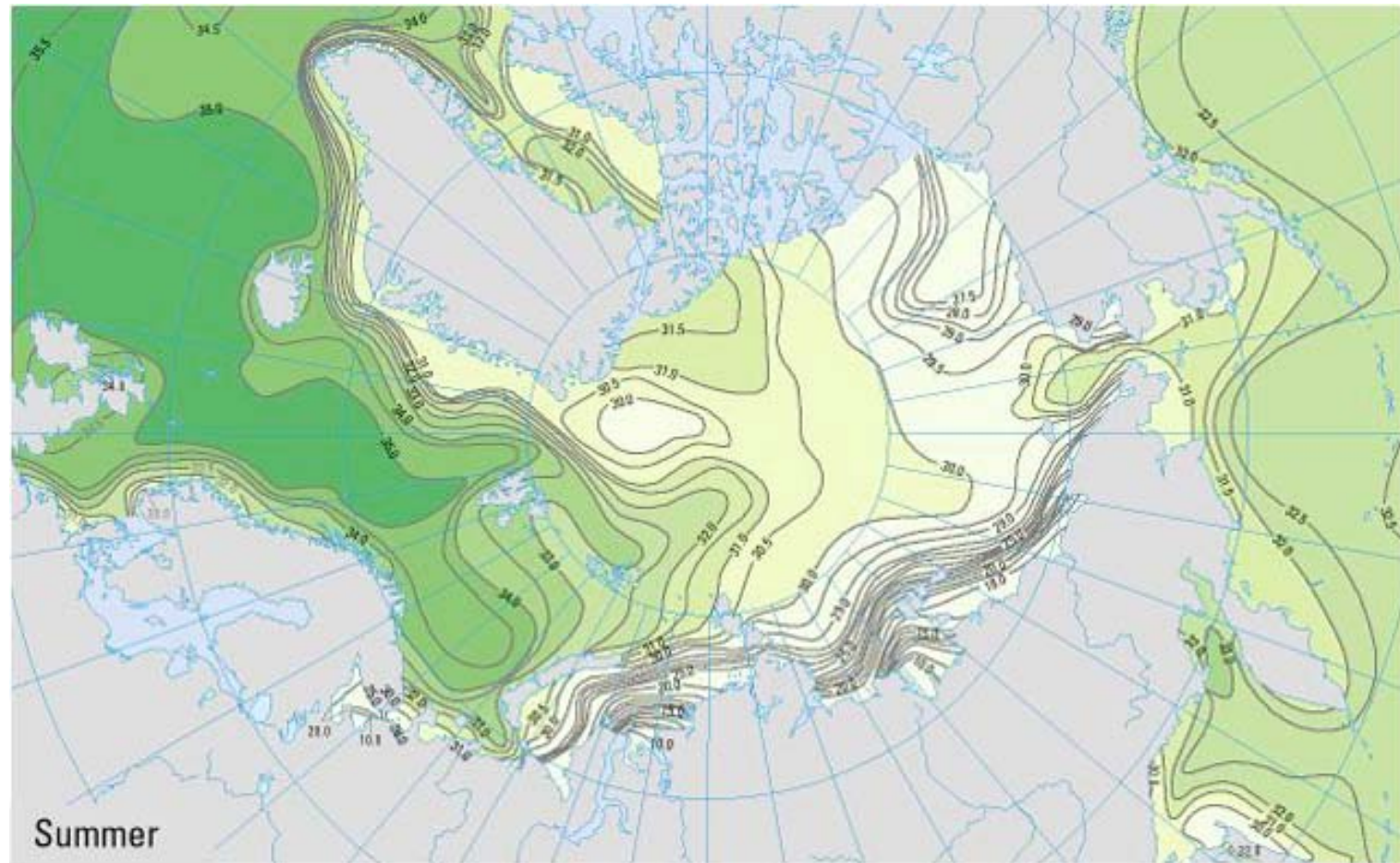
Figure 5.   Salinity of surface water in the Arctic in summer, Philippe Rekacewicz Sources : USSR Ministry of Defence 1980.
Published in: AMAP Assessment Report : Arctic Pollution Issues. Arctic Monitoring and Assessment Programme (AMAP), Oslo, Norway, 1998.

During the winter season, dense shelf water is formed in the continental Beaufort Sea and eastern Chukchi Sea by brine rejection accompanied by a large amount of ice production in the coastal open water and polynya where the density of the underlying water increased rapidly. CTD moorings in the Barrow Canyon in 1991-1992 showed that salinity reached minimum in fall and maximum in summer for all the stations (Weingartner et al., 1998). Data from the Beaufort Sea showed fresh surface water of 27 psu in August compared to 31 psu in April, which indicates a saline injection during the winter freezing season.

When the sea ice begins to melt during the summer, small freshwater ponds (called melt ponds) form on the top layer of the ice and this freshwater travels through the cracks and holes in the ice, washing out the remaining brine. This lowers the bulk salinity of the ice to very low values. Melting of the ice releases low-salinity water, or even fresh water.

Freshwater (or low salinity water) from melting ice is less dense than seawater. The density of surface seawater depends on the temperature and salinity (and pressure). Seawater with a salinity of 35 psu at 0ºC has a density of 1028 kg/m^3 and freshwater has a density of 999.8 kg/m^3. Melt water from the ice will mix with the underlying water, but for the short period while the ice is melting the very upper layer of water at the sea surface will be of lower salinity than the underlying water. The depth and salinity of the low salinity water layer varies with location.

The south-east Bering Sea shelf is a relatively shallow but extremely wide region that is seasonally covered with ice. Salinities at the edge of the melting ice were measured to be of the order of 31.2-31.4 psu, increased with depth to about 32.0 psu on the bottom, and passed through a halocline at ~10-20 metres (Alexander and Niebauer, 1981).

Other measurements made in the Eastern Bering shelf (Stabeno et al., 1998) indicated that freshwater from ice melt reduced the salinity of the underlying water by ~0.5 psu. Although the reduced salinity provided a positive flux of buoyancy, it was not sufficient to prevent mixing. Wind (acting on ice or directly on water) and tidal stirring resulted in near-isothermal conditions in shallow water. Over the deeper outer shelf, winds provided the mixing energy to create a shallow (~30-m) mixed layer.

2 Testing oil spill dispersants in "arctic conditions"

Only a very limited number of experiments have been conducted with dispersants in real ice conditions and the results – like any results obtained with dispersants at sea – need careful interpretation.

There have been several studies using wave tank test methods.

The testing oil spill dispersants in simulated cold conditions has been undertaken by several research groups, but with different combinations of:

- low temperature;
- absence or presence of ice;
- and water salinity

It is not always possible to assess the individual contribution of a variation in each of these three factors.

2.1 Laboratory tests

Testing of dispersants in a range of different laboratory-scale test methods is an established way of assessing the relative performance of different dispersants or investigating the relative effect of pertinent variables, such as degree of oil weathering (evaporative loss and water-in-oil emulsification). It is accepted than no laboratory-scale test method is an accurate simulation of the mixing and dilution conditions that occur at dispersion of oil at sea. Nevertheless, the methods are relatively simple, inexpensive and it is relatively easy to conduct large studies requiring many tests with alterations of significant variable.

Most laboratory test methods have used low water temperature, close to 0°C, as the only simulation of 'Arctic' conditions, while others have used the addition of ice to the test method and a few have studied the effect of salinity.

> Wells and Harris, 1979 evaluated the effect of salinity on dispersant effectiveness using the MNS (Mackay / Nadeau / Steelman) test method. The dispersants tested (Corexit 9527, Oilsperse 43, BP 1100X, Drew OSE 71 and Corexit 8666) were of lower effectiveness in freshwater 0 psu than at 29 – 31 psu.

> Mackay et al., 1980, using a prototype MNS test method found that the presence of ice caused a reduction in dispersant effectiveness because the presence of ice caused total damping of the air-induced waves.

> Cox and Schlutz, 1981, using a test method with an oscillating hoop, found no reduction in dispersant effectiveness with up to 50% ice cover in the test apparatus.

> Byford at al., 1983 used a 25 litre wave tank to study the effect of the presence of ice to the water. These studies were initiated as part of a BP / PetroCanada project to develop an oil spill dispersant for use in the Beaufort Sea. The wave action was created by a paddle wave-maker attached to a rotating cam. In general, the presence of ice caused higher dispersant effectiveness. The waves in the tank were damped by the presence of the ice, but the 'pumping' action of the ice (ice moving up and down in the water as the waves passed) seemed to add increased mixing action and thus caused increased dispersant effectiveness.

The addition of pieces of ice in the WSL test method would not simulate ice conditions at sea since a breaking wave is broadly simulated by the end-over-end mixing action - adding ice to the oil / water mixture would create a much more intense mixing action. The effect of salinity was studied using the WSL test method and dispersant effectiveness was lower at 0 psu than at 33 psu for most dispersants.

Lehtinen and Vesala. 1984 tested three dispersants on REBCO (Russian Export Blend Crude Oil) in the MNS (Mackay Nadeau Steelman) apparatus under simulated Baltic Sea conditions (4°, 12° and 15°C and salinities of 3, 7 and 12 psu). No ice was used in these tests. They concluded that the dispersants differed in effectiveness.

Payne et al., 1985 tested four dispersants using the EPA test protocol with Prudhoe Bay crude oil at two temperatures (1°C and 10°C) and three water salinities (0, 18 and 33 psu) and found that there were wide variations in effectiveness. No ice was used in these tests.

Belk et al., 1989, used the WSL method to show that oil spill dispersants that are effective in freshwater could be formulated.

Daling, et. Al 1991: As a part of the research program "Oil Spill Response in Northern and Arctic waters (ONA), testing of dispersants effectiveness and leaching of surfactants at arctic conditions were studied. This dispersibility studies were both bench-scale laboratory tests (using WSL, MNS and IFP-test methods) and dispersibility testing of oils weathered in melting pools on ice. Totally, 13 different dispersants available at that time were tested under different arctic conditions (more than laboratory 250 tests).

Fingas and others 1991 studied the role of salinity on the effectiveness of three dispersants on three types of crude oil using the Swirling Flask Test (SFT) method. These tests showed an increase in dispersion with an increase in salinity from 0 to 45 psu. A decline in dispersion was observed at salinities greater than 45 psu. The use of the SFT method produced effectiveness values of 5 to 15% for Alaska North Slope (ANS) crude oil at salinities of about 20 psu and temperatures of about 10°C. Higher energy tests such as the MNS, and EXDET show much higher values, but at higher temperatures and salinities

DIWO Report 18 (Brandvik et al., 1993) defined Arctic conditions "*in this context as low temperature (0°) and seawater salinity between 5 psu and 35 psu*" This distinguished these conditions from typical North Sea conditions of 6°C to 13°C and 33 psu salinity. The main conclusion was that many dispersants that exhibit high effectiveness in normal salinity water show reduced performance in low salinity water.

However, other studies have shown that dispersants have been formulated to be particularly effective in freshwater (Figure 6).
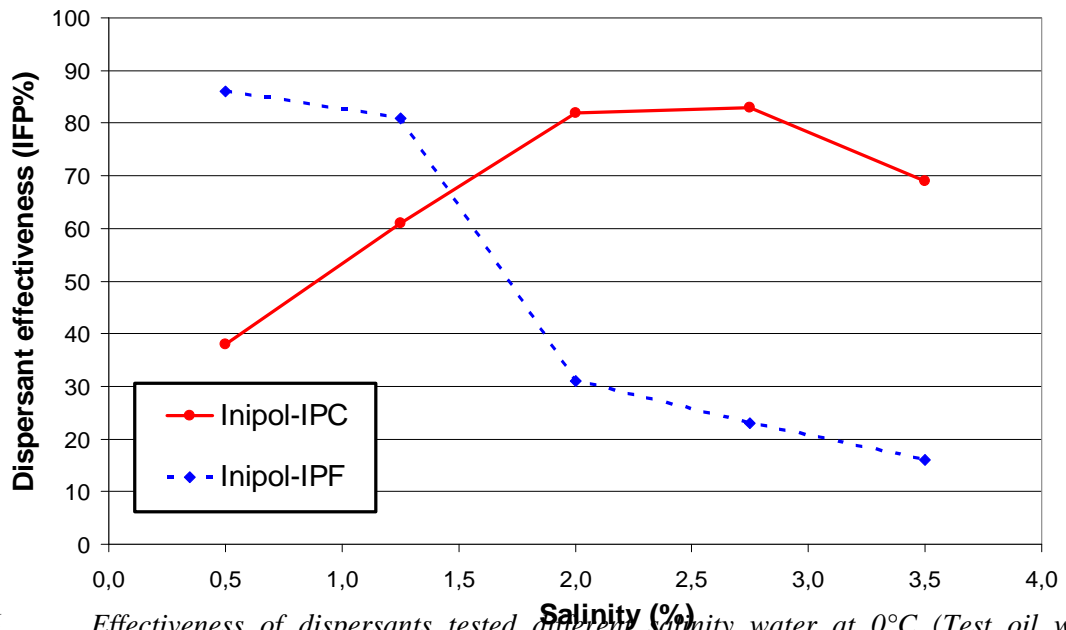
Figure 6.   Effectiveness of dispersants tested different salinity water at 0°C (Test oil was Oseberg Blend 150°C+)

<u>Knudsen and Daling, 1994:</u> Prior the establishment of the new Norwegian regulations for use of dispersants, an extensive evaluation of different laboratory test methods (including the MNS,IFP, ExDet) were performed testing 19 different dispersants under different test conditions (temperature, salinities application strategies: neat/ water diluted etc.). The aim of this study was to come up with recommendations to test-criteria for the new regulations. Figure 7 (below) is an example of the results obtained with different dispersants under various temperatures and salinity.
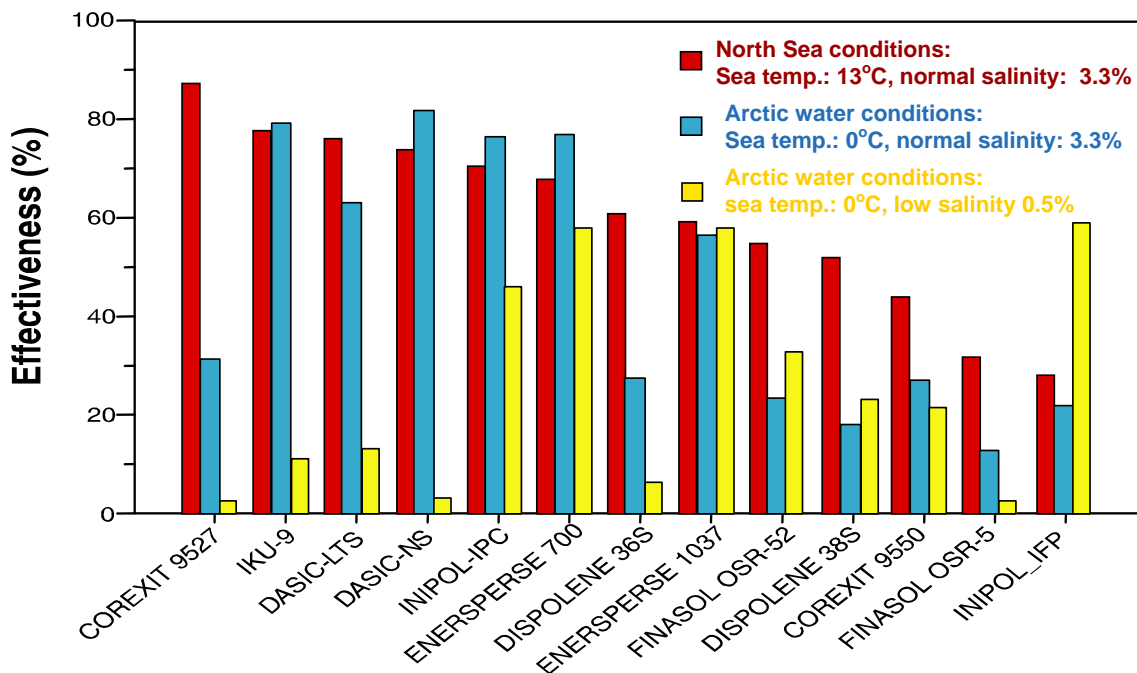

Figure 7.   Effectiveness of dispersants tested in Arctic conditions compared to North Sea conditions (Test oil was Oseberg Blend 150°C+/ 50% w/o-emulsion)

Blondina et al. 1997 & 1999 investigated the effect of water salinity on the effectiveness of two oil dispersants, Corexits 9527 and 9500 using a modified version of the Swirling Flask Test. The dispersants were tested with ten different oils, representing a wide range of physical and chemical properties. Test salinities ranged from 0 to 35 ppt, with temperature held constant at 15°C. Results showed Corexit 9500 to be generally more effective on most of the dispersible oils at most salinities, but performance of both products was significantly affected by salinity. Both dispersants performed best at salinities above 25 ppt, with Corexit 9500 maintaining its effectiveness over a fairly wide range of salinities. Correlations between dispersant effectiveness and various oil physical/chemical properties were highly variable.

George-Ares et al., 2001 reported that the addition of calcium chloride to Corexit 9500 produced a dispersant that is effective in freshwater. The intended use was not for use in Arctic conditions, but in temperate freshwater such as rivers and deltas.

Moles et al, 2001, studied the effectiveness of Corexit 9500 and Corexit 9527 on Alaska North Slope crude oil at various salinities and temperatures representative of conditions found in Southern Alaskan waters with the Swirling Flask Test method. The oil was weathered to different degrees. Tests were conducted at temperatures of 3°, 10°, and 22°C with salinities of 22 and 32 psu. The authors concluded that, at the common temperatures found in the estuaries and marine waters of Alaska, the dispersants were largely ineffective. They also found that there was an interactive effect between temperature and salinity.

The results from the studies listed above have several common themes:

- Some tests are more energetic than others and a higher mixing energy causes a higher degree of dispersion (higher dispersant effectiveness). This is sometimes interpreted to say that some tests simulate low sea states (calm seas) and others simulate higher sea states (rough seas), but evidence to support this is very limited.

- Oil viscosity increases with decreasing temperature. Dispersion is limited by oil viscosity. The dispersibility of oil decreases with decreasing temperature when a limiting oil viscosity is exceeded.

- Most available dispersants are formulated for use in marine waters and are of lower effectiveness in low salinity water. However, new dispersants can be formulated, or existing dispersants can be modified, to be effective in freshwater.

- The presence of ice has been introduced to only a few test methods. In most test methods (for example, the WSL, IFP, SFT test methods) it would completely alter the mixing conditions by adding a lot more agitation as the ice tumbled around in the water under the influence of the imposed mixing action. The evidence from the laboratory scale tank tests is mixed; the presence of ice was found to decrease, not affect or increase dispersant effectiveness.

In common with dispersant testing in other conditions, the greatest differences of opinion come when translating the results obtained in the laboratory-scale tests into expected performance of dispersants on spilled oil at sea.

2.2 Larger scale tank tests

Larger scale wave tank tests have a supposed advantage of increased 'realism'; a closer simulation of mixing conditions at sea, but inevitably suffer from a number of obvious differences from the sea.

Wave tanks are contained systems and there will be shearing action at the walls. Waves are normally generated by a wave-paddle system. This creates waves by moving the bulk of the water, whereas waves at sea are caused by wind stress at the water surface. Nevertheless, wave tanks are the only test system where ice, in various forms, can be added.

Brown and Goodman, 1996, conducted dispersant tests with broken ice, of different types, present in a large outdoor wave basin in winter. This study followed on from earlier work at low temperature without ice present (Brown and Goodman, 1988) that indicated dispersion of crude oil was feasible at 0°C. The water salinity was 30 psu. 'Low wave activity' (8 cm mean height at a frequency of 0.6/second) caused extensive dispersion (90%+) of crude oil treated with dispersant when broken ice was present, but not in a lead created between two ice sheets.

Belore, 2002 describes the testing of Corexit 9500 dispersant on Hibernia crude oil in cold water (0°C and 1°C) conditions in SL Ross's wave tank. The wave conditions were non-breaking waves with an amplitude of 15 cms and a period of 1.5 seconds. No ice was used in these tests. The study indicated that the crude oil could be dispersed until it weathered to a degree when the Pour Point of the oil was +27°C.

SL Ross, 2003 includes testing dispersant testing on Alaska North Slope, Endicott, North Star and Point McIntyre crude oils in the SL Ross wave tank with a water temperature of 0°C to 2°C.

2.3 Testing at OHMSETT (Oil and Hazardous Materials Simulated Environment Test Tank

OHMSETT is a 10, 000 tonne normal salinity salt water test tank located near Atlantic Highlands, New Jersey.

There has been a sequence of tests conducted at OHMSETT) by S L Ross Environmental Research (Belore, 2002 & 2003, SL Ross 2000, 2001, 2002, 2003 & 2006 and Owens and Belore, 2004) to investigate the effect of dispersants on various crude oils in cold water conditions.

The early tests (SL Ross 2000, 2001, 2002) were conducted at low temperatures, around 0°C, at normal salinity and without ice. The average wave amplitude ranged between 16.5 and 22.5 cms and wave period ranging from 1.7 to 1.9 seconds. The results indicated that these crude oils could be dispersed to a high degree (82% to 99%) in cold water conditions.

SL Ross, 2003 describes dispersant testing in cold conditions (-0.4°C to -1.8°C water temperature and -7.4°C to +2.8°C air temperature) on Alaska North Slope, Endicott, North Star and Point McIntyre crude oils. The waves were 15 to 22 cm in amplitude with a frequency of 1.8 to 2.2 seconds.

SL Ross, 2006 describes the procedures used; the results obtained and conclude that Alaska North Slope, Endicott, North Star and Point McIntyre crude oils can be almost totally dispersed by Corexit 9527, up to a certain degree of weathering, in cold water. These results confirmed the earlier findings at OHMSETT (SL Ross, 2003).

Owens and Belore, 2004

Tests on the effectiveness of chemical dispersants for oil spills in brash ice were conducted at OHMSETT. Ice fields were simulated within three-meter diameter circular booms by varying proportions of ice blocks 30 cm and 60 cm square and small ice fragments created by breaking up ice blocks with an axe. Nominal ice concentrations were 0/10, 4/10 and 8/10. Corexit 9527 dispersant was applied to Alaska North Slope, Hibernia and Chayvo crude oils in these ice fields. Dispersion was observed for waves with 17 cm average height and a 5.5 second period and with waves with 33 cm average height and 4 second period. The energy levels produced by these waves were considerably lower than those typically used in open water dispersant testing.

A total of eighteen unique tests were completed in brash ice and open water conditions with various combinations of oil type, dispersant-to-oil ratios (DOR), and ice type and concentration. The tests used either 100% blocks of ice, 100% fragments of ice, 50% blocks with 50% fragments or no ice at all. Ice was placed in the containment areas to simulate 0/10 (0%), 4/10 (40%), and 8/10 (80%) ice coverage. The crude oils used were Hibernia, Alaska North Slope (ANS) and Chayvo crude oils (fresh and weathered).

The test results indicated that chemical dispersants can be effective in brash ice conditions. Increased brash ice cover increased the amount of mixing energy and led to increased dispersion. Higher ice concentration tests (8/10 cover for all ice types tested) consistently led to better dispersion. 4/10 ice cover tests required higher wave energies to achieve visible dispersion. In a test where no ice was present, application of dispersant did not lead to the same rapid dispersion observed in the tests with ice. If waves similar to those used in these tests were to propagate through brash ice, then the energy delivered should be sufficient to facilitate chemical dispersion.

3 Discussion

As is often the case with dispersant testing, the main question about the results obtained in the studies described in Section 3 is: How accurately do the conditions simulate the actual conditions that will prevail in "Arctic' conditions?

'Arctic' conditions can be considered to be a combination of low sea and air temperature, in some cases lower than normal salinity and the presence of ice.

- The effect of low sea and air temperatures causing an increase in the viscosity of the spilled oil can be simulated accurately by conducting the tests at the appropriately low temperature. The effect of low temperatures on the rate and extent of oil weathering is known in principle, although not in detail. Previous studies conducted in the MIZ (Marginal Ice Zone) of the Barents Sea in 1993 indicate that the time "window of opportunity" for dispersant use can be much longer in Arctic conditions because the reduced rates of evaporation and water –in-oil emulsification lead to a much slower increase in viscosity towards a limiting value.

- The effect of lower than normal salinity can be simulated with accuracy by conducting the test with water of the appropriate salinity.

  - The bulk salinity of the upper mixed layer (30 to 50 metres depth and above the halocline) of Arctic seas is known with a high degree of accuracy and is only slightly lower than open ocean salinity.

  - The salinities of the seas in the proximity of river estuaries with a seasonal high output of freshwater are also known, but are highly localised and seasonally variable.

  - The bulk salinities of enclosed and semi-enclosed seas with high freshwater inflows are also known.

- The effects of the presence of ice on the top surface water layer are the source of the main unknowns in the dispersant testing that have been undertaken so far.

3.1 Effect of ice on wave energy

Waves are the driving force for the dispersion of dispersant-treated spilled oil. Wave conditions at sea can be broadly related to the wind speed. Other factors, such as fetch and "wind-with-current" or "wind-against-current" modify the wave conditions by altering the spectrum of waves, but these effects on dispersion are generally thought to be minor.

The presence of ice modifies the waves at sea. Short wavelength waves, the wave action that causes dispersion of oil, are produced by the effects of the wind over the waves. Ice damps out these shorter wavelength waves. The slightly out of phase movement of ice on the sea surface takes energy out of the sea. This leaves only the longer wavelength swell component. The wave-damping effect varies with the form of the ice. The tank tests that have been conducted have used non-breaking, low amplitude waves with relatively small waves of low frequency. Dispersion of the dispersant-treated oil was caused by the differential motion of the ice at the water surface (no dispersion occurred in the absence of ice under the same wave conditions). However, it has not yet been established whether the

wave conditions used in these tests are typical or representative of wave conditions at sea with ice present.

3.2 Effect of ice on water salinity

Ice is of lower salinity than the seawater on which it floats; first year ice has a salinity of around 10 psu, while multi-year ice has a salinity of 3 psu or less. During ice melt conditions low-salinity water will be released from the ice as it melts. If the melting is on the top surface of the ice and caused by solar radiation, pools of low salinity melt-water will be formed. This may run down the sides of the ice as further ice melting occurs.

Low salinity water will be introduced at the oil / water interface if spilled oil is present and this is precisely where the surfactants in dispersants act to cause dispersion. It is not known whether this is a significant effect in most circumstances. The role of bulk low salinity water in seas near river estuaries has been established, but the effect of low salinity in the 'micro-scale'; the very upper water surface layer where dispersants function, is unknown. It is therefore recommended (prior the series of planned meso-scale weathering and dispersibility testing of different oils under different ice conditions/ coverage in flume at SeaLab P1 and P4), to design a specific study of the sea-water salinity under a simulated spring thawing conditions were performed. The purpose is to look on the potential for a possible salinity gradient in the water column of the flume during the weathering experiments with different ice and energy /turbulence conditions.

4 Conclusions and recommendations

The testing oil spill dispersants in simulated cold conditions has been undertaken by several research groups, but with different combinations of:

- low temperature;
- absence or presence of ice;
- water salinity

It is not always possible to assess the individual contribution of a variation in each of these three factors.

- The primary effect of low temperature is to increase spilled oil viscosity, compared to higher temperature conditions. This increased oil viscosity causes reduced dispersant effectiveness when a limiting oil viscosity is exceeded. However, the rate of oil weathering is suppressed by cold conditions and the presence of ice and the time "window of opportunity" for dispersant use can be longer in Arctic conditions than in more temperate conditions.

- The main effect of the presence of ice seems to be to add agitation at the oil / water interface by the slightly out of phase movement of the ice, relative to the water. This seems to indicate that dispersion can occur when ice is present in wave conditions (small amplitude, low frequency) that would not cause dispersion in ice-free conditions. This effect has been observed in wave tank tests at several different scales. However, it has not yet been established whether the wave conditions used in these wave-tank tests are typical or representative of wave conditions at sea with ice present.

- Most commercially available dispersants exhibit lower effectiveness in low salinity water than in normal, open ocean salinity of 33 psu. Some dispersants have been formulated to be particularly effective in low salinity water and others can be modified to be so. Low salinity waters occur in enclosed or semi-enclosed seas (Baltic, Caspian and Black Seas, for example) and seasonally and locally in areas of other seas near river estuaries. Melting ice may also cause temporary and localised low salinity conditions in the very upper layers of water where dispersants function.

It is recommended that a specific study, using the new meso-scale flume at SINTEF, be carried out to study the effects of sea ice on dispersibility.

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