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Oil in Ice - JIP

Report no.: 19

Meso-Scale Weathering of Oil as a Function of Ice Conditions. Oil Properties, Dispersibility and In Situ Burnability of Weathered Oil as a Function of Time.

Per Johan Brandvik, Janne Lise Myrhaug Resby, Per Snorre Daling, Frode Leirvik and Janne Fritt-Rasmussen

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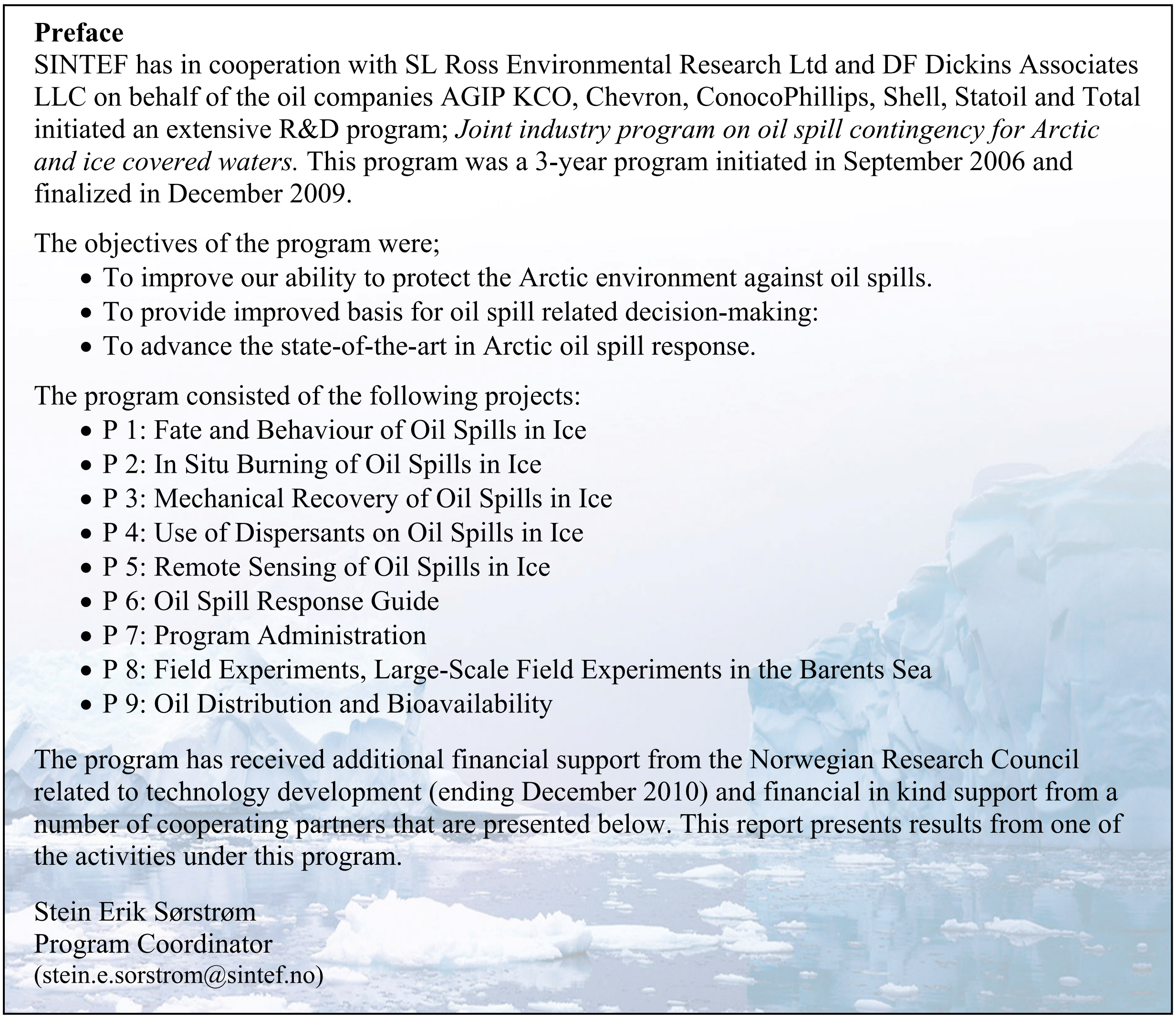

Preface

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.

Stein Erik Sørstrøm
Program Coordinator
(stein.e.sorstrom@sintef.no)

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SINTEF REPORT

SINTEF Materials and Chemistry

Address: NO-7465 Trondheim, NORWAY
Location: Brattørkaia 17B, 4. etg.
Telephone: +47 4000 3730
Fax: +47 930 70730

Enterprise No.: NO 948 007 029 MVA

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AUTHOR(S)

Per Johan Brandvik, Janne Lise Myrhaug Resby, Per Snorre Daling, Frode Leirvik and Janne Fritt-Rasmussen

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ABSTRACT

Meso-scale weathering experiments have been performed with five different oil types: Statfjord (paraffinic), Troll (naphtenic), Grane (asphaltenic), Norne (Waxy) and Kobbe (light oil). The selected oils span a large variation with respect to oil properties which ensures that the results from this study can be interpolated and used for other oil types. This is of special importance since this data will be used to improve the SINTEF oil weathering model's capability to predict oil weathering in ice.

The meso-scale experiments (20 L of oil) have been performed with different ice conditions (0, 30, 50 70 and 90% ice coverage) for two oils (Statfjord and Troll) and with three ice coverages (0, 50 and 90%) for the other three. Similar experiments (0, 50, 90%) have been performed on a larger scale (200 L) at SINTEF's field station in Svea, Svalbard.

Oil properties (evaporation, emulsification, natural dispersion, flash point, pour point, etc.) have been monitored as a function of time and ice conditions. Special attention has been put on the dispersibility and of the in situ burnability of the oil as a function of the ice condition and weathering degree, and has been done for dispersibility (MNS test and the SINTEF FET test) and in situ burnability (Lab burning cell) on the same samples which have been used for monitoring oil properties.

This study shows that oil weathering processes such as evaporation and emulsification can be reduced for an oil spill in ice, thus extending the operational window for both the use of dispersants and in situ burning. The ability to predict these operational windows for an oil spill in ice will be significantly improved when this is implemented into the SINTEF OWM. This improvement is performed in another task in this JIP, but their algorithms are developed based on the data analysis and trends presented in this report.

KEYWORDS	ENGLISH	NORWEGIAN
GROUP 1	Oil spill	Oljesøl
GROUP 2	Weathering	Forvitring
SELECTED BY AUTHOR	Dispersant	Dispergeringsmiddel
	In situ burning	Brenning
	Arctic	Arktis

TABLE OF CONTENTS PAGE

1 Introduction 10
  1.1 Oil weathering 10
  1.2 Dispersants 11
  1.3 In situ burning 11

2 Objectives 13
  2.1 P1 Oil weathering 13
  2.2 P4 Dispersibility testing 13
  2.3 P2 In situ burning 13

3 Background Fate and behaviour of oil spills in ice 14
  3.1 The behaviour of oil spills in open water 14
    3.1.1 Evaporation 15
    3.1.2 Water-in-oil (w/o) emulsion 15
    3.1.3 Oil-in-water (o/w) dispersion 17
  3.2 The behaviour of an oil spill in ice 17

4 Experimental 19
  4.1 Selected oils for testing 19
    4.1.1 Description of oil types 20
  4.2 Physical and chemical analysis 21
  4.3 Meso-scale weathering laboratory testing 22
    4.3.1 Description of the meso-scale flume 22
    4.3.2 Oil weathering in the meso-scale flume 22
    4.3.3 Sampling of surface oil 23
    4.3.4 Collection of water samples 24
    4.3.5 Preparation of ice 24
    4.3.6 Ice, wave and current conditions 24
  4.4 Meso-scale weathering Svea, Svalbard 25
    4.4.1 Field oil sampling and analysis 25
    4.4.2 Ice conditions used in meso-scale testing 27
    4.4.3 Laboratory chemical dispersibility testing 27
  4.5 Laboratory burning cell 29
    4.5.1 Preparation 29
    4.5.2 Ignition 29
    4.5.3 Collection of residue for quantification 29
    4.5.4 Calculating burning effectiveness 30
    4.5.5 Fieldwork Svalbard - meso-scale burning of weathered oil 30
    4.5.6 Fieldwork Svalbard - laboratory scale burning of weathered oil 31

5 Results and Discussions 33
  5.1 Physical and chemical properties of oils tested in flume experiments 33
  5.2 Meso-scale weathering 34
    5.2.1 Paraffinic oil: Statfjord – SeaLab 34
    5.2.2 Napthenic oil: Troll B – SeaLab 36
    5.2.3 Napthenic oil: Troll B – field work Svea, Svalbard 39
    5.2.4 Asphaltenic oil: Grane – SeaLab 41
    5.2.5 Waxy oil: Norne – SeaLab 43
    5.2.6 Light oil: Kobbe – SeaLab 45
    5.2.7 All oils - water content in emulsions versus ice coverage 47
    5.2.8 All oils - viscosity versus ice coverage 49
    5.2.9 All oils – evaporation versus ice coverage 51

Dispersibility testing.......53
5.2.10 Selection of dispersants for further testing.......53
5.2.11 Dispersibility tests on the napthenic oil, Troll B.......56
5.2.12 Dispersibility tests on the paraffinic oil, Statfjord.......62
5.2.13 Dispersibility tests on the asphaltenic oil, Grane.......64
5.2.14 Dispersibility tests on the waxy oil, Norne.......68
5.2.15 Dispersibility tests on the light oil, Kobbe.......71
5.2.16 All oils - dispersibility versus viscosity and weathering time.......74
5.3 In situ burning.......77
5.3.1 Meso-scale SeaLab: Napthenic oil, Troll B.......77
5.3.2 Meso-scale Svalbard: Napthenic oil, Troll B.......78
5.3.3 Meso-scale SeaLab: Paraffinic oil, Statfjord.......79
5.3.4 Meso-scale SeaLab: Asphaltenic oil, Grane.......80
5.3.5 Meso-scale SeaLab: Waxy oil, Norne.......81
5.3.6 Meso-scale SeaLab: Light oil, Kobbe.......82
5.3.7 All oils – burning effectiveness (BE%-Corrected) versus ice coverage.......83
6 Conclusions.......85
6.1 Meso-scale weathering.......85
6.2 Dispersibility testing.......86
6.3 In situ burning.......87
7 References.......88
Appendix A: Tables – Weathering properties.......91
Appendix B: Tables - Dispersibility testing.......101
Appendix C: Tables – In situ burning.......108

LIST OF FIGURES PAGE

Figure 3.1: The weathering processes that take place when oil is spilled on the sea surface. 14
Figure 3.2: Weathering processes relative importance over time. 14
Figure 3.3: A picture taken with a microscope of the water droplet size in a w/o emulsion after (A) 1 hour and (B) 24 hours in a rotating cylinder. 16
Figure 3.4: Stabilisation of the interfacial layer between the water and oil in a w/o emulsion by wax and asphaltenes. 16
Figure 4.1: An illustration of different crude oil properties, based on weathering studies performed at SINTEF. 19
Figure 4.2: A schematic drawing of the meso-scale flume. 22
Figure 4.3: Overview of the meso-scale basin cut out in the first-year fjord in Svea, Svalbard. The tent was used to control the air temperature and ice conditions. 25
Figure 4.4: An overview showing the layout of the flume and the relationship between the weathering flume at the connected channel to the basin used for in situ burning experiments. After the weathering period, the channel was opened and the oil was led to the in situ burning basin. 26
Figure 4.5 A close-up of the wave generator and the current propellers used for controlling circulation. See prior figure for an overview. 26
Figure 4.6: IFP test apparatus 27
Figure 4.7: MNS test apparatus 28
Figure 4.8: FET test 28
Figure 4.9: The new burning unit during initial testing. Left: SINTEF engineer Frode Leirvik, who is responsible for the construction. Right: Janne Fritt-Rasmussen, a PhD student (Denmark Technical University/University Centre at Svalbard - UNIS) who has done most of the ISB work. 29
Figure 4.10: In situ burning of weathered oil. The system consists of a burning basin connected to the weathering basin with a channel (see earlier figure) in operation. 31
Figure 4.11: Collection of residue. After cooling, the residues were easy to remove/collect with 3M adsorption pads. Quantitative collection of residues was important for determining burning efficiency. 31
Figure 4.12: The core unit of the laboratory burning cell operated in “field mode”. Only the cell itself, the butane igniter, the cooling unit (pump, coolant and thermos), and the flame temperature unit/logger were operated in the field. 32
Figure 5.1: Statfjord crude - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure. 34
Figure 5.2: Statfjord crude - Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume. 35
Figure 5.3: Statfjord crude - Evaporative loss as a function of weathering time in the meso-scale flume. 35
Figure 5.4: Troll crude - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure. 36
Figure 5.5: Troll B crude - Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume. 37
Figure 5.6: Troll B crude - Evaporative loss as a function of weathering time in the meso-scale flume. 37

Figure 5.7: Troll B - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure. 39
Figure 5.8: Troll B – Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume. 39
Figure 5.9: Troll B - The evaporative loss as a function of weathering time in the meso-scale flume. 40
Figure 5.10: Grane crude - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure. 41
Figure 5.11: Grane crude - Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume. 41
Figure 5.12: Grane crude - The evaporative loss as a function of weathering time in the meso-scale flume. 42
Figure 5.13: Norne crude - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure. 43
Figure 5.14: Norne crude – Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume. 43
Figure 5.15: Norne crude - The evaporative loss as a function of weathering time in the meso-scale flume. 44
Figure 5.16: Kobbe light crude - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure. 45
Figure 5.17: Kobbe light crude - Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume. 45
Figure 5.18: Kobbe light crude - The evaporative loss as a function of weathering time in the meso-scale flume. 46
Figure 5.19: Water content and halftimes (T½) for all oil types at 0%, 50% and 90% ice coverage as a function of weathering time in the meso-scale flume. 47
Figure 5.20: Viscosity for all oil types at 0%, 50% and 90% ice coverage as a function of weathering time from the meso-scale flume. 49
Figure 5.21: The evaporative loss for all oil types at 0%, 50% and 90% ice coverage as a function of weathering time in the meso-scale flume. 51
Figure 5.22: The effectiveness of various dispersants on the Troll B crude oil at 0°C. 54
Figure 5.23: Viscosity of the tested dispersants as a function of temperature. 55
Figure 5.24: Dispersibility in MNS of Troll B Crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion 57
Figure 5.25: Dispersibility in MNS of Troll B Crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. weathering time 57
Figure 5.26: Dispersibility in field effectiveness test (FET) of Troll B Crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion and dispersibility limits (good, reduced dispersibility and not dispersible) as defined in previous standard dispersibility studies on a different Troll B crude oil batch. 58
Figure 5.27: In situ dispersibility of Troll B crude oil in flume experiments with varying ice coverage, energy (waves) and weathering. 59
Figure 5.28: Mass balance in flume experiment performed with Troll B crude oil at -1.8°C, with no ice and application of Corexit 9500 at the end of the experiment. 59

Figure 5.29: Mass balance in a flume experiment performed with Troll B crude oil at -1.8°C, with 30 % ice coverage and application of Corexit 9500 at the end of the experiment. 60
Figure 5.30: Mass balance in flume experiment performed with Troll B crude oil at -1.8°C, with 50 % ice coverage and application of Corexit 9500 at end of experiment. 60
Figure 5.31: Mass balance in flume experiment performed with Troll B crude oil at -1.8°C, with 70 % ice coverage and application of Corexit 9500 at the end of the experiment. 61
Figure 5.32: Mass balance in flume experiment performed with Troll B crude oil at -1.8°C, with 90 % ice coverage and application of Corexit 9500 at the end of the experiment. 61
Figure 5.33: Dispersibility in MNS of Statfjord crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion. 62
Figure 5.34: Dispersibility in MNS of Statfjord crude oil weathered from 15 minutes to 3 days in flume experiments with varying ice coverage vs. weathering time. 63
Figure 5.35: Dispersibility in field effectiveness test (FET) of Statfjord crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion and dispersibility limits (good, reduced dispersibility and not dispersible) defined in previous standard dispersibility studies on a different batch of Statfjord crude oil. 63
Figure 5.36: In situ dispersibility of Statfjord crude oil in flume experiments with varying ice coverage, energy(waves) and weathering. 64
Figure 5.37: Dispersibility in MNS of Grane crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion. 65
Figure 5.38: Dispersibility in MNS of Grane crude oil weathered from 15 minutes to 3 days in flume experiments with varying ice coverage vs. weathering time. 66
Figure 5.39: Dispersibility in field effectiveness test (FET) of Grane crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion and dispersibility limits (good, reduced dispersibility and not dispersible) defined in previous standard dispersibility studies on a different batch of Grane crude oil. 66
Figure 5.40: In situ dispersibility of Grane crude oil in flume experiments with varying ice coverage, energy(waves) and weathering. 67
Figure 5.41: Dispersibility in MNS of Norne crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion. 68
Figure 5.42: Dispersibility in MNS of Norne crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. weathering time. 69
Figure 5.43: Dispersibility in field effectiveness test (FET) of Norne crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion and dispersibility limits (good, reduced dispersibility and not dispersible) defined in previous standard dispersibility studies on a different batch of Norne crude oil. 69
Figure 5.44: In situ dispersibility of Norne crude oil in flume experiments with varying ice coverage, energy (waves) and weathering. 70
Figure 5.45: Dispersibility in MNS of Kobbe crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion. 71

Figure 5.46: Dispersibility in MNS of Kobbe crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. weathering time.............. 72
Figure 5.47: Dispersibility in field effectiveness test (FET) of Kobbe crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion and dispersibility limits (good, reduced dispersibility and not dispersible) defined in previous standard dispersibility studies on a different batch of Kobbe crude oil. 72
Figure 5.48: In situ dispersibility of Kobbe crude oil in flume experiments with varying ice coverage, energy (waves) and weathering.. 73
Figure 5.49: Dispersibility for all oil types at 0%, 50% and 90% ice coverage, as measured on weathered samples from flume experiments versus emulsion viscosity... 75
Figure 5.50: Dispersibility for all oil types at 0%, 50% and 90% ice coverage, as measured on weathered samples from flume experiments versus weathering time.. 76
Figure 5.51: Troll B crude – Burning efficiency as a function of weathering time in the meso-scale flume. Numbers on the graphs are calculated as the upper limits for “ignitability”. 77
Figure 5.52: Troll B crude – Burning efficiency as a function of weathering time in the meso-scale flume during the field work performed in April 2008 on Svalbard. The numbers on the graphs are calculated as the upper limit for “ignitability” (hours). 78
Figure 5.53: Statfjord crude – Burning efficiency as a function of weathering time in the meso-scale flume. The numbers on the graphs are calculated as the upper limit for “ignitability” (hours).. 79
Figure 5.54: Grane crude – Burning efficiency as a function of weathering time in the meso-scale flume. Numbers on the graphs are calculated as the upper limit for “ignitability”. 80
Figure 5.55: Norne crude – Burning efficiency as a function of weathering time in the meso-scale flume. The numbers on the graphs are calculated as the upper limit for “ignitability” (hours).. 81
Figure 5.56: Kobbe – Burning efficiency as a function of weathering time in the meso-scale flume. The numbers on the graphs are calculated the upper limit for “ignitability” (hours). 82
Figure 5.57: Burning efficiency for all oil types at 0% (A), 50% (B) and 90% ice coverage (C). BE%-Corrected as a function of weathering time in the meso-scale flume. 83
Figure 5.58: Ignitability for all oil types at 50% ice coverage. Ignitability is as a function of weathering time in the meso-scale flume.. 84

LIST OF TABLES PAGE

Table 1.1: Status on fate and weathering of oil in arctic conditions. From the initial state-of-the-art report in the oil-in-ice JIP (Brandvik et al., 2007) 12
Table 4.1: Physical/chemical properties, units and methods 21
Table 4.2: Meso-scale ice scenarios 24
Table 4.3: Meso-Scale Settings. 24
Table 5.1: The physical and chemical properties of oils tested in the Oil-in- Ice Programme. 33
Table 5.2: Effectiveness of in situ dispersion of the Troll B crude in the meso-scale flume at the end of each experiment. 58
Table 5.3 Effectiveness of in situ dispersion of the Statfjord crude in the meso-scale flume at the end of each experiment. 64
Table 5.4: Effectiveness of in situ dispersion of the Grane crude in the meso-scale flume at the end of each experiment. 67
Table 5.5 : Effectiveness of in situ dispersion of the Norne crude in the meso-scale flume at the end of each experiment. 70
Table 5.6 : Effectiveness of in situ dispersion of the Kobbe crude in the meso-scale flume at the end of each experiment. 73

1 Introduction

Work performed in three related projects within the oil-in-ice JIP are included in this report. These projects are:

1. Meso-scale weathering experiments performed in Task 1.3 meso-scale experiments performed at SeaLab in Trondheim and Task 1.4 meso-scale field experiments performed in Svea, Svalbard.
2. Dispersant experiments performed in Task 4 (activities 4.12 and 4.13).
3. Testing of in-situ burning properties performed in Task 2.1, mapping of burning properties versus oil weathering.

This study has been an integrated part of a Joint Industry Program to develop and advance the knowledge, methods and technology for oil spill response in Arctic and ice-covered waters (Oil in ice JIP). The research program started in 2006, experiments were finalized in 2009 and final scientific reports issued in 2010. The JIP summary report (Sørstrøm et al., 2010) gives an overview of the total program and all the technical reports.

1.1 Oil weathering

Operationally important weathering processes for oil spill operations such as water uptake, emulsion stability and viscosity vary with oil type. Normally, they increase relatively quickly with increased weathering time in open water. In ice-infested water, several studies have indicated that this increase over time (e.g. water content) can be changed depending on ice type, ice coverage and energy conditions in the ice. Today, there is only a little available knowledge concerning this for a limited number of oil types and ice regimes through lab and field experiments performed in the US and Norway.

In 2004, MMS initiated a three-year research project which focused on the fundamental weathering processes of oil in ice (spreading, evaporation, migration, etc.). The main contractor on this project is MAR Inc. in cooperation with S.L. Ross Environmental Research Ltd. and DF Dickins Associates, Ltd., all based in the US. This programme includes small-scale laboratory testing and large-scale experiments in MMS' Ohmset facility. This project delivered its final report in 2008 and offers an important contribution in understanding the fate of oil in snow and ice (MMS 2008).

Another recent programme was performed by the University Centre on Svalbard (UNIS) and SINTEF on Svalbard regarding oil weathering with various ice conditions (Brandvik and Faksness, 2009) and the distribution of water soluble components from encapsulated ice (Faksness and Brandvik 2008). This project will supply weathering data for one oil type (Statfjord) and leakage rates for five different oil types to be used for the calibration of the SINTEF Oil Weathering Model OWM). This programme was funded by the Norwegian Research Council, and Liv-Guri Faksness' PhD dissertation in January 2008 marked the end of this programme.

Compared to the in-depth knowledge which exists regarding the fate and behaviour of oil spills in open water and temperate conditions, our knowledge regarding Arctic oil spills is limited. The status on the fate and weathering of oil in arctic conditions is summarised in *Table 1.1* (from Brandvik et al., 2006). There is a need for international protocol, and laboratory and field experiments to collect physical and chemical measurements of oil weathering and use these to validate and enhance oil weathering algorithms for oil weathering models. The objective should be to collect basic research data on evaporation, dispersion, spreading, and other weathering parameters in the marginal ice zone. This data should then be used to enhance and modify or develop new algorithms of oil weathering in and on ice.

1.2 Dispersants

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

The viscosity of the dispersant at low temperatures will be of particular importance, for instance, during application by a helicopter bucket at low temperatures. There were also other dispersant experiments conducted between 2001-2004 using low water temperatures with the presence of ice that were performed by MMS in the Ohmsett facility to test dispersibility at low temperatures and under low energy conditions (J.V. Mullin, 2004).

A review of studies on oil spill dispersant effectiveness in Arctic conditions has been given by Lewis and Daling (2007).

1.3 In situ burning

There are limitations for in situ burning when the surface oil slick starts to weather. The light components evaporate (increasing flash point) and the water is emulsified into the oil as small droplets. Both these processes complicate ignition and lower burning effectiveness. Different percentages of evaporative loss (20-30%) and water uptake rates (25-50%) are reported in the literature as “rule of thumbs” for defining the window of opportunity for in situ burning. Ignitability is however not dependent on how much of the light components are evaporated, but on the flash point of the remaining residue. Two different emulsified crude oils with the same water content can also show very different ignitability characteristics due to their chemical composition and emulsion stability (Buist et al., 1999). Further research is needed to overcome this limitation in order to more precisely define the window of opportunity for in situ burning.

In addition to the properties of the weathered oil, also more operational factors like oil film thickness, type of igniter, wind and wave conditions will influence ignitability and burning effectiveness of an oil spill (Buist et al., 2003).

Table 1.1: Status on fate and weathering of oil in arctic conditions. From the initial state-of-the-art report in the oil-in-ice JIP (Brandvik et al., 2007)

Parameter	**In open water**	**In ice with increasing ice coverage**	**Conclusion**
Spreading	Spreading due to diffusion, gravity, inertial force, viscosity and interfacial tension. Spreading normally from thick to thin oil films, dependent on oil.	Spreading in ice is dependent on ice types and ice coverage. Increasing oil film thickness with increasing ice coverage. Limited knowledge of oil-ice interaction.	Drift, spreading and distribution of oil in sea ice are mainly dependent on ice conditions. Limited knowledge of oil-ice interaction.
Drift	Oil drift due to wind and currents.	Current assumption is that if ice coverage is less than 30%, the drifting of oil will be independent of the ice. At an ice coverage larger than 60-70 %, the oil will mainly drift with the ice. Limited knowledge of oil-ice interaction.	
Evaporation	Evaporation is rapid and high due to thin oil films. Field and laboratory data available for a wide range of oil types.	Evaporation is a surface phenomenon and increasing oil film thickness due to confinement in ice reduces both the rate and degree of evaporation. Reduced evaporation due to a diffusion barrier of precipitated wax (skin) at low temperatures is also observed.	The knowledge of different weathering processes and properties of oil in open water is very good. Field and laboratory data is available for a wide range of oil types. Numerical models with good predicting ability available, e.g. the SINTEF OWM. To provide reliable predictions of the weathering properties of oil in ice, more basic knowledge and a deeper understanding of these processes are needed. At present, field and laboratory data are only available for a few oil types Reliable predictions (forecasts) are also dependent on the ability to predict the dynamics of sea ice conditions.
Natural dispersion	Natural dispersion dependent on oil type and sea state. Field and laboratory data available for a wide range of oil types.	The rate of natural dispersion will decrease by increasing ice coverage and could be very low due to a reduced energy condition in the ice.	
Emulsification	Emulsification will primarily take place in the presence of breaking waves. Field and laboratory data available for a wide range of oil types.	The presence of ice will reduce wave activity and the emulsification will usually decrease by increasing ice coverage. Ice-ice interaction is reported to induce emulsification.	
Water uptake rate	Rapid water uptake, dependent on oil type. Field and laboratory data available for a wide range of oil types.	Water uptake rate will probably decrease with increasing ice coverage due to wave damping effects and will be slow in dense sea ice.	
Leakage of water soluble components (WAF)	Amount and type of components dependent on oil type. Field and laboratory data available for a wide range of oil types.	Only limited lab and field experiments performed by SINTEF and UNIS in 2003-2005.	
Stability of emulsion	Stability of emulsion dependent on oil type. Stability increases with increasing weathering degree. Field and laboratory data available for a wide range of oil types.	Stability of emulsion dependent on oil type.	
Viscosity	Increasing viscosity due to increasing water uptake and evaporation. Field and laboratory data available for a wide range of oil types.	The viscosity will increase with increasing water uptake and evaporation as in the open sea, but the increase will be slower due to slower evaporation and water uptake.	

2 Objectives

The individual objectives for the three different projects within the oil-in-Ice JIP are given below:

2.1 P1 Oil weathering

The main objective with this has been to generate new knowledge on the behaviour of oil spills in ice covering a wide range of oil types. This data was used to develop new and improved algorithms which describe oil weathering for selected oil-in-ice scenarios. These algorithms have been implemented into the SINTEF oil weathering model in order to give more accurate predictions of oil weathering in ice needed for contingency planning.

2.2 P4 Dispersibility testing

The overall objective of the dispersant application testing has been to establish better criteria for where and when to use dispersants in ice-covered areas. The purpose of the specific laboratory dispersant testing was:

- To perform an effectiveness screening of relevant dispersant concentrates on weathered emulsion under low temperature and varying salinities in order to select a robust test dispersant for the oil-in-ice weathering testing in the meso-scale flume at SINTEF.
- To study the dispersant effectiveness as a function of oil type, weathering and ice concentration in order define the limiting factors for dispersant use. This will establish a more precise “window of opportunity” for the operational use of dispersants under various spill situations in ice-covered waters.

2.3 P2 In situ burning

The objectives for this study have been to map the ignitability and burning effectiveness of oil spills as a function of weathering, using a wide range of oil types. This knowledge has been used to implement new algorithms into the SINTEF oil weathering model in order to better predict the window of opportunity for in situ burning.

3 Background Fate and behaviour of oil spills in ice

This chapter contains a brief overview of the weathering processes of marine oil spills in open water and ice.

3.1 The behaviour of oil spills in open water

When a crude oil is spilled at sea a number of natural processes take place which change the volume and chemical properties of the oil. These natural processes are evaporation, water-in-oil (w/o) emulsification, oil-in-water (o/w) dispersion, the release of oil components into the water column, spreading, sedimentation, oxidation and biodegradation. A common term for all of these natural processes is weathering. The relative contribution of each process varies during the duration of the spill. Figure 3.1 illustrates the various weathering processes and Figure 3.2 shows their relative importance over time.

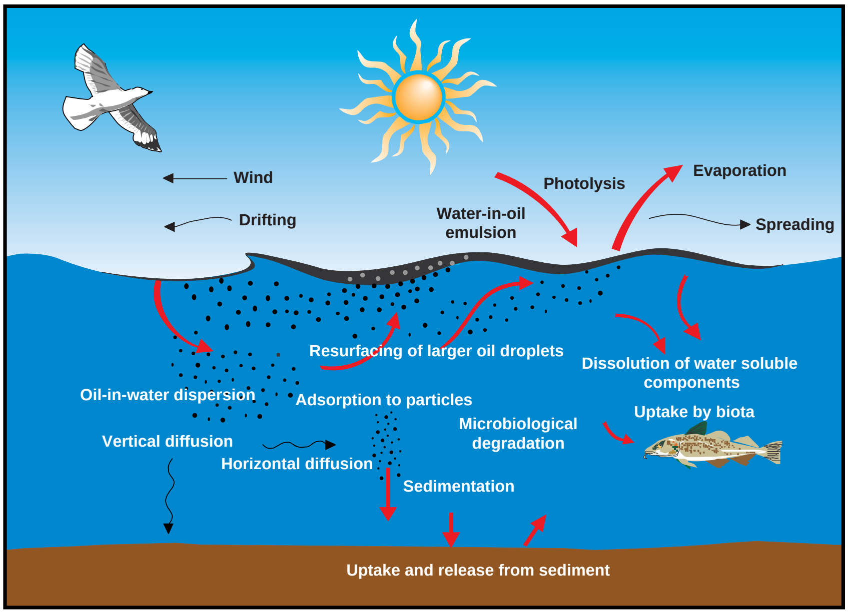

Figure 3.1: The weathering processes that take place when oil is spilled on the sea surface.

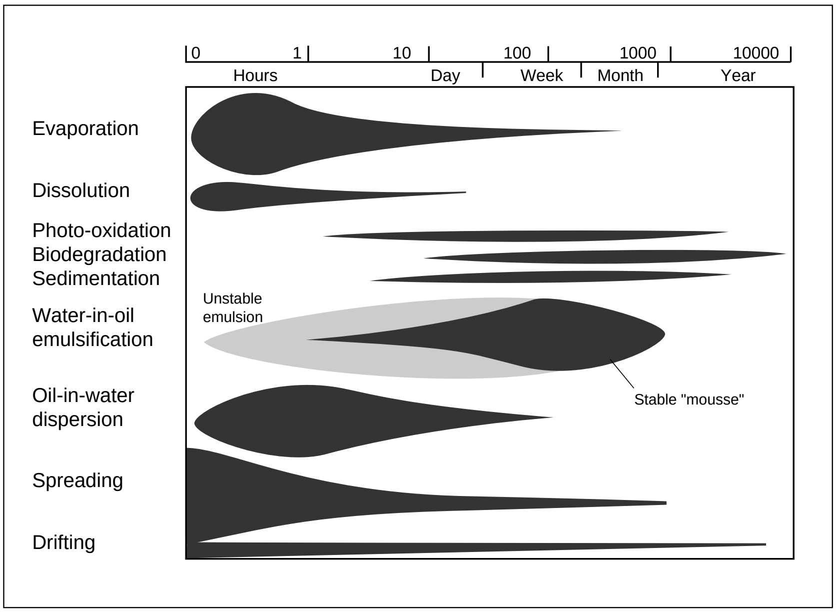

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Figure 3.2: Weathering processes relative importance over time.

The weathering of oil depends on the oil type (chemical and physical properties), the weather conditions (wind, waves, temperature and sunlight) and the properties of the seawater (salinity, temperature, bacteria flora, etc.).

3.1.1 Evaporation

Evaporation is one of the natural processes that help in removing spilled oil from the sea surface. The evaporation process starts immediately after the oil is spilled and the evaporation rate decreases exponentially throughout the duration of the oil spill.

The amount which is evaporated depends on the chemical composition of the oil in addition to the prevailing weather conditions, the sea temperature and the oil film thickness.

The rate of evaporation will vary for different oil types. Light refinery products (e.g. gasoline and kerosene) may completely evaporate after a few hours/days on the sea surface. Condensates and lighter crude oils can lose 50% or more of their original volume during the first days after an oil spill.

The most significant difference caused by evaporation is the loss of volatile and semi-volatile compounds which increase the relative amounts of higher molecular weight compounds. The chemical and physical properties of the remaining oil change, for example, the density, viscosity, and pour point, and the relative wax and asphaltene content will increase with increased evaporation.

3.1.2 Water-in-oil (w/o) emulsion

Emulsification is the weathering process that contributes to keeping the oil on the sea surface. A w/o emulsion has a higher viscosity than the parent crude oil, and the emulsification process will therefore retard natural dispersion process. This will increase the life time of the surface oil and could increase possibilities for stranding. The volume increase caused by emulsification (a water content of 75%, quadruples the total volume) and the viscosity increase are also additional challenges for responders.

The minimum criteria for the formation of w/o emulsions is the presence of breaking waves (i.e. a wind speed of 5 m/s), although a slow water uptake can also take place during calmer weather.

Surface active compounds present in crude oil will promote the formation of w/o emulsions and contribute to stabilising the emulsion. These components contain both hydrophilic and hydrophobic groups.

The maximum water uptake will vary for different crude oils. Tests performed at SINTEF have shown that the maximum water uptake is fairly independent of the prevailing weather conditions as long as the lower energy barrier for the formation of w/o emulsions is exceeded; however, the rate largely depends on the weather conditions. In the laboratory, the $t_{1/2}$-value, which is the time in hours it takes before the oil has taken up half of its maximum water content, is determined.

The rate of formation of the w/o emulsion varies for different oil types since it is dependent on the chemical composition of the oil. For instance, a large amount of wax will increase the rate of formation. Another important factor which influences the rate of formation is the prevailing weather conditions, and wind speed (and waves) influences significantly on the the rate of formation.

The stability of the w/o emulsion depends on the water droplet size in the emulsion. The largest droplets may coalescence and settle out of the w/o emulsion. Larger water droplets may be reduced in size by the flexing, stretching and compressing motion of a slick due to wave action. After a period of time, the emulsion may only contain small water droplets with a diameter of 1 to 10 µm.

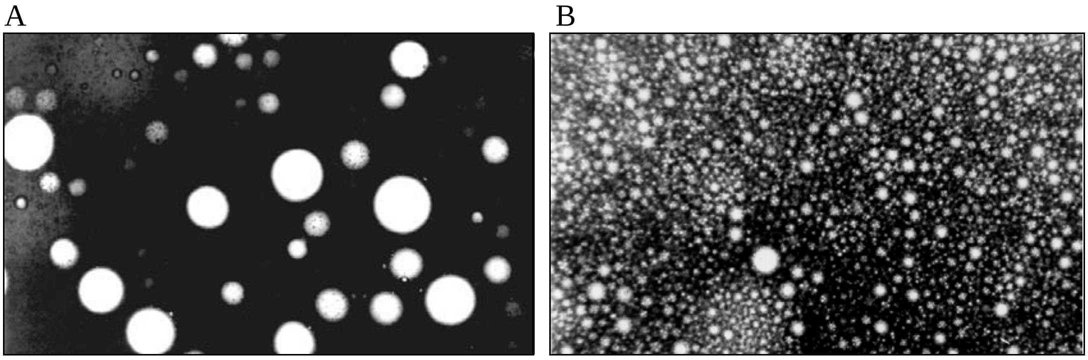

Figure 3.3: A picture taken with a microscope of the water droplet size in a w/o emulsion after (A) 1 hour and (B) 24 hours in a rotating cylinder.

Another factor that influences w/o emulsion’s stability is the amount of surface-active components present in the parent oil. Resins and asphaltenes have hydrophobic and hydrophilic properties and will concentrate at the interface between the water and oil, thereby forming a layer which stabilises the water droplets. The hydrophobic properties can lead to the concentration of wax along the water droplets which further stabilises the interfacial “skin” layer. The interfacial layer between the oil and water forms a physical barrier that hinders coalescence and will stabilise the w/o emulsion by hindering the fusion of water droplets. The stabilisation of the water droplets by asphaltenes, and by asphaltenes and wax, is shown in Figure 3.4.

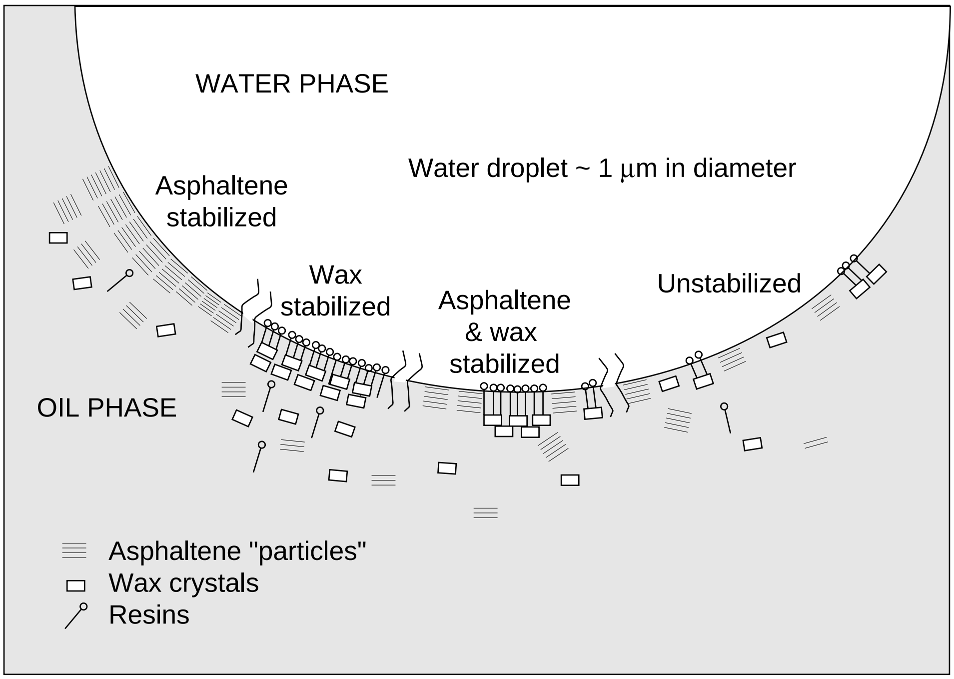

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Figure 3.4: Stabilisation of the interfacial layer between the water and oil in a w/o emulsion by wax and asphaltenes.

Oils that contain a large amount of wax and little asphaltenes can form w/o emulsions that may appear to be stable. These w/o emulsions appear to be stabilised by the continual phase's rheological strength (viscosity and elasticity). This strength is due to the wax structure formed by participated wax. Wax stabilised emulsions are characterised by large water droplets and are fairly stable when stored, though they may break when stress is applied and/or when the emulsion is heated to 40-50°C.

3.1.3 Oil-in-water (o/w) dispersion

Natural o/w dispersion will take place if there is sufficient energy on the sea surface, i.e. if there are breaking waves present. The waves will break the slick into droplets with a typical diameter between 1 to1000 μm which are mixed into the water mass. The largest oil droplets will resurface and form a sheen behind the oil.

In addition to weather conditions, the dispersion rate depends to a large extent on oil type and can be one of the main processes which determine the life expectancy of an oil slick on the sea surface. The natural o/w dispersion will gradually decrease since evaporation of the lighter compounds will increase the viscosity of the remaining oil.

The purpose of applying chemical dispersion agents is to increase the natural o/w dispersion rate. When effective chemical dispersion is achieved, small oil droplets are formed with a diameter of 5 to 50 μm. The dispersion agent reduces the interfacial tension between the water and oil, and promotes dispersion.

3.2 The behaviour of an oil spill in ice

The complexity of an oil spill in ice is much larger than a similar oil spill in open water. The difference in oil distribution in scenarios with thick, solid multiple-year and fresh first-year ice is large. Also, an oil spill in a freezing autumn situation or a thawing spring scenario represents different challenges in predicting the fate and behaviour of oil. Studying weathering properties (evaporative loss, water uptake, viscosity, pour point, etc.) in this JIP, we have selected to focus on the large quantities of oil usually gathered in the leads between the ice sheets (see figure 3.1).

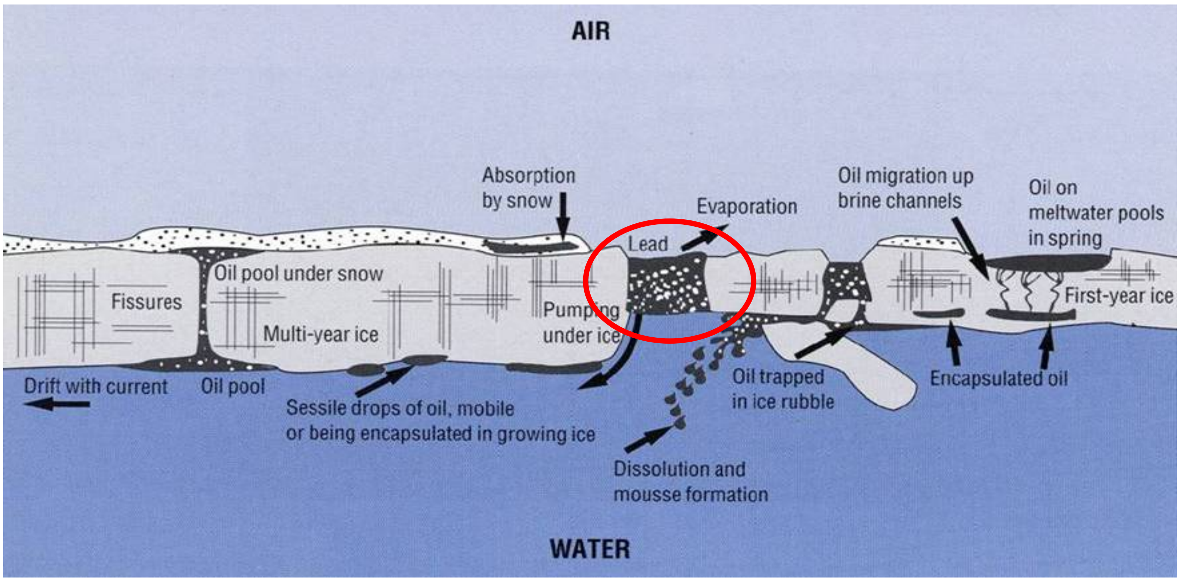

Figure 3.1: An illustration of the complex distribution of oil in different oil-in-ice scenarios. *(AMAP, 1998).*

The rate of the weathering process is usually reduced in an oil spill in ice due to the usually calm conditions, high oil film thickness and low temperatures. A comparison between an experimental oil spill in open water (Haltenbanken 1989) and in broken ice (Barents Sea 1993) is presented in Figure 3.2. There is a large difference in the water uptake between these two scenarios, and this has large operational consequences in regard to spill volume, viscosities, influence area and life expectancy.

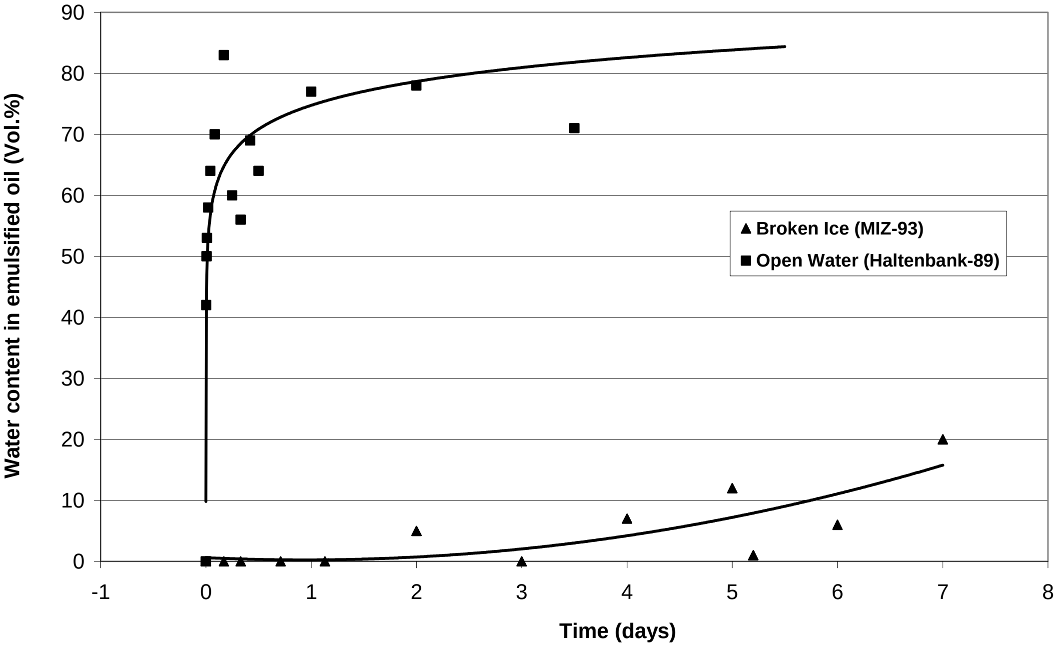

Figure 3.2: Water uptake (volume %) *in a surface oil slick as a function of time for both open water and broken ice large-scale experiment (Haltenbanken 1989 and Barents Sea 1993).*

4 Experimental

This section contains a description of the oils used and descriptions of the experimental work performed in this study.

4.1 Selected oils for testing

To ensure that a maximum amount of information could be drawn out of all the laboratory and field tests that have been performed, a selection of five different oil types with varying composition and weathering properties has been tested to span the necessary, important oil weathering properties which influence the behaviour of oil and response methods in ice-covered areas.

The selection of oils has been done among oils previously characterised at SINTEF with respect to weathering properties and dispersibility. Based on such weathering studies, oils can be visually placed in a "map" based on their behaviour when spilled at sea in addition to their chemical composition (Figure 4.1).

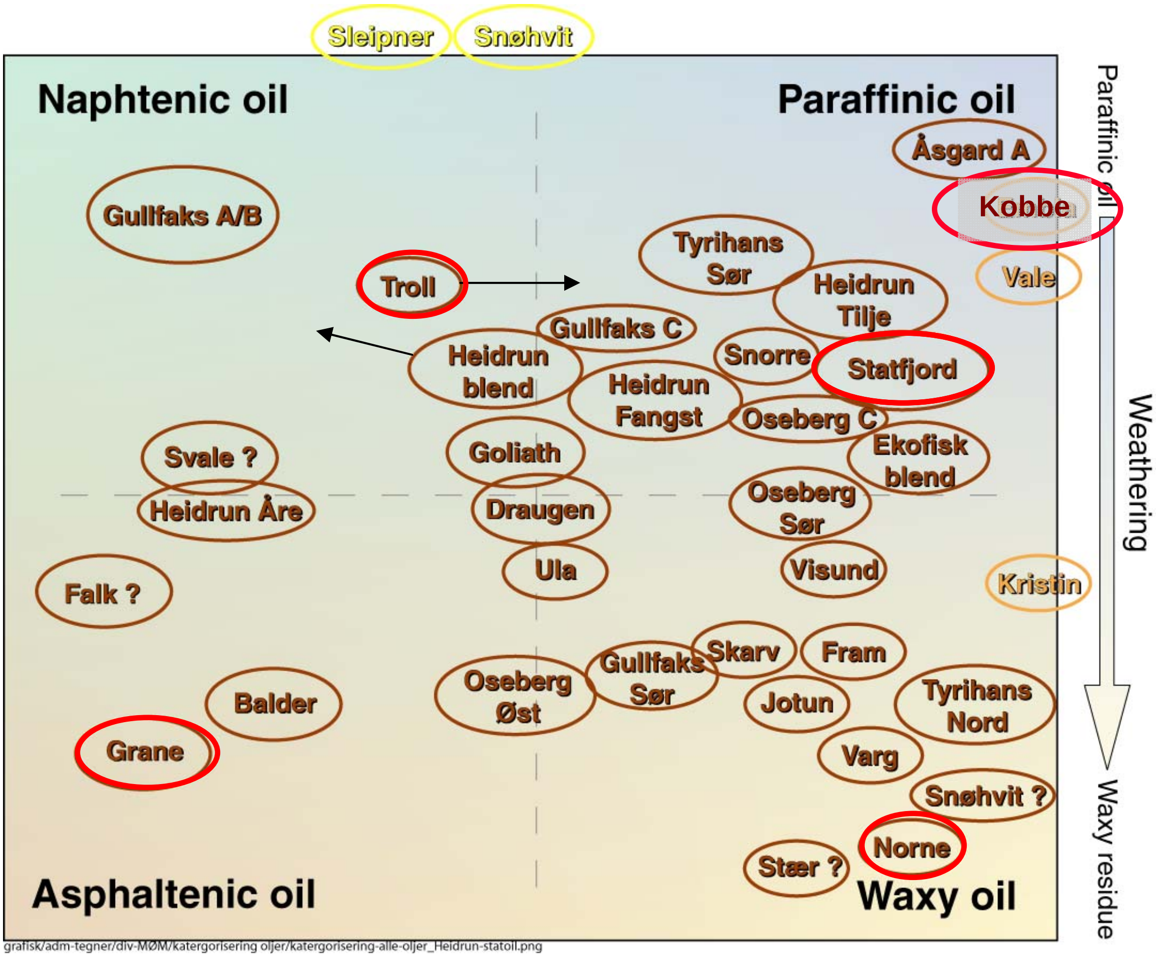

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Figure 4.1: An illustration of different crude oil properties, based on weathering studies performed at SINTEF.

In addition to a span in oil properties, the possible oil types that are likely to be spilled and the availability of these oil types was considered in the project design as well. Based on weathering properties, possibility of spill and availability, five different oils have been chosen for weathering and dispersibility testing from among five different crude oil categories:

- Paraffinic crude oil: Rich in paraffins and saturated components.
- Waxy crude oil: Rich in waxes (higher saturated components > C20), high pour point.
- Naphtenic crude oil: Biodegraded, rich in saturated cyclic components, branched alkanes and often aromatic components.
- Asphaltenic crude oil: Rich in polar resins and asphaltenes, high density.
- Light crude oil: Contains mostly light components, but also some heavier components (waxes/asphaltenes). Light oils can form w/o emulsions, unlike condensates.

4.1.1 Description of oil types

Based on the characterisation map (***Figure 4.1***) from earlier weathering studies performed at SINTEF, the five oils listed below where selected for testing in the JIP. The physical and chemical properties of these oils are provided in
Table ***5.1***.

These five oils represent a broad selection of oil types and should represent a large number of oils worldwide. These oils were used for both meso-scale weathering studies and dispersant testing at the SINTEF SeaLab. In addition, Statfjord, Grane and Troll B were also used for meso-scale field testing at the SINTEF field research station at Svea, Svalbard. A final field verification was performed in 2009 (weathering, in situ burning and the use of dispersants), and 20 m^3 of Troll B was used for this purpose.

Paraffinic crude oil: Statfjord crude oil (SINTEF no: 2008-0047).
This oil has been used for a large variety of projects at SINTEF's field research station at Svea, Svalbard and functions much like standard reference oil. Eighty barrels was already stocked at Svea from previous testing.

Asphaltenic oil: Grane crude oil (SINTEF no: 2007-1060).
Large quantities of this oil were available at the Sture terminal.

Naphtenic crude oil: Troll B (SINTEF no: 2007-0287).
A special arrangement was made by Statoil at the Mongstad oil refinery to obtain access to pure Troll B.

Waxy crude oil: Norne (SINTEF no: 2007-0260).
The Norne Blend is produced at the Norne field, and the oil is available from the Mongstad refinery. Later analysis showed that this blend mainly consisted of pure Norne crude, which has a very high wax content.

Light crude oil: Kobbe (SINTEF no: 2006-1061).
Kobbe is a Norwegian Arctic oil and the from the planned Goliat field in the Barents Sea. Sufficient quantities were available from an earlier test production.

Further information regarding these oil types are available from the following weathering studies (Strøm-Kristiansen et al., 1995, Kristiansen et al., 1997, Moldestad et al., 2001 and leirvik, F., 2005).

4.2 Physical and chemical analysis

The analytical methods used to determine the physical and chemical properties of the oils are described in this section.

Table 4.1: Physical/chemical properties, units and methods

Property	**Unit**	**Method**
Viscosity of weathered oil	cP (or mPas) at shear rate 10 or 100 s^{-1} at 3-6 ºC	Daling et al. (2003)
Water content of w/o-emulsion	Volume %	Daling et al. (2003)
Density of water free oil	g/ml at 15.5 ºC	ASTM D4052-91
Chemical dispersibility of weathered oil	Weight %	Concawe (1988)
Evaporative loss	Weight %	Daling et al. (2003)
Flash point of water free oil	ºC	ASTM D93-90
Pour point of water free oil	ºC	ASTM D97-87

4.3 Meso-scale weathering laboratory testing

In an oil spill situation at sea, the weathering processes will occur simultaneously and affect each other. It is thus of great importance that the oils are weathered under realistic conditions when studying the oil's behaviour when spilled on the sea surface.

A meso-scale flume basin (Singsaas et al., 1992) located at SINTEF is routinely used to simultaneously study the weathering processes under controlled conditions. A schematic drawing of the meso-scale flume basin is given in Figure 3. A new flume with updated instrumentation was built in 2006 at the SINTEF SeaLab.

4.3.1 Description of the meso-scale flume

Approximately 4.8 m^3 of seawater is circulated in the 10 metre long flume, and the flume is located in a temperature controlled room (0°C – 20°C). Two fans placed in a covered wind tunnel allow for control of the wind speed. The wind is calibrated to simulate an evaporation rate corresponding to a wind speed of 5-10 m/s at the sea surface. A schematic drawing of the flume is given in **Figure 4.2**.

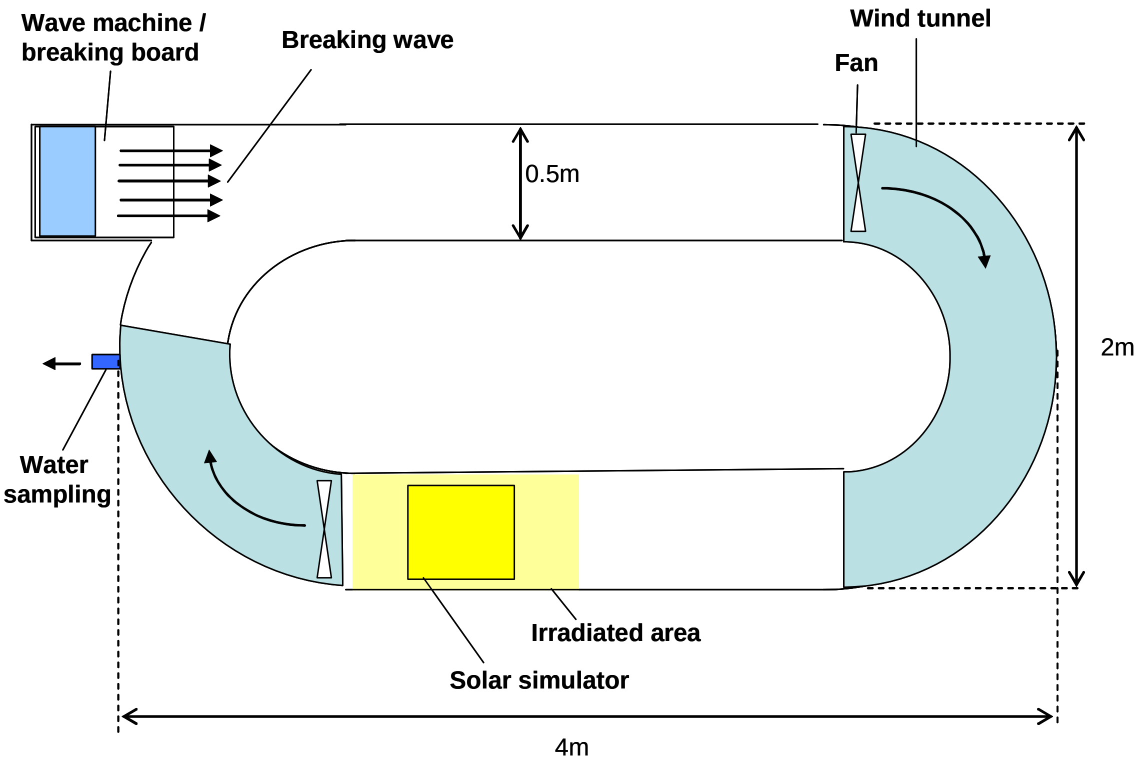

Figure 4.2: A schematic drawing of the meso-scale flume.

4.3.2 Oil weathering in the meso-scale flume

The oil sample (9 L) was carefully released on the water surface. The oil was weathered for a total of three to seven days in the flume. Samples of the surface oil were taken frequently in the first hours of the experiment and thereafter only once a day. Water samples are taken at a few times during the weathering part (days 1-3) and more frequently during the dispersant application part of the experiment.

The physical properties determined for all the emulsion samples during the experiment were:

- evaporative loss
- density
- water content
- viscosity

An analysis was performed on a limited amount of the sampling to detect:

- Emulsion stability
- Oil concentration in the water column (droplets and dissolved components)

The methods for each analysis are described below.

4.3.3 Sampling of surface oil

Samples of the surface oil/emulsion were taken by use of an aluminum tray and transferred to a 0.5 L separating funnel. After settling for 10 minutes in the climate room, the free water was removed. The oil phase was further handled for an analysis of its rheology and water content in emulsion and density. One sample was taken from the water surface.

Evaporative loss

As the light end components of the oil evaporates the density increases. The density of the oil was linearly dependent on the wt% evaporative loss. As the density of the water free residue was known (a method described above), the evaporative loss can be calculated.

Density

The density of the water free sample was measured according to ASTM method D 4052-91 with an Anton Paar DMA 4500 densitometer, and the water was removed as described above under the methodology for the determination of water content.

Water content and stability

The amount of water within the emulsion formed is determined by adding approximately 2000ppm of emulsion breaker to the sample and heating it in a vial. As the emulsion is broken, the height of the water-oil interface and height of the total sample are measured in the vial. The relative amount of water compared to the total sample volume is then calculated.

Rheological measurements

Rheological measurements were performed with a Physica MCR300 rheometer. Viscosity is measured according to the standard methodology described in McDonagh et al, 1995.

Experimental setup for viscosity measurements:

Measurement system : PP50
Gap : 1mm
Shear rate : $1s^{-1}$, $5s^{-1}$, $10s^{-1}$, $50s^{-1}$,$100s^{-1}$,$200s^{-1}$,$500s^{-1}$, and $1000s^{-1}$
All viscosities are reported at $10\ s^{-1}$.

Experimental setup for stress-sweeps:

Measurement system : PP50
Gap : 1mm
Angular velocity : 10rad/s
Stress interval : 0.05-1000 Pa (logarithmic increase)

4.3.4 Collection of water samples

Water samples were taken at a depth of 50 cm through a tap in the basin wall into a Pyrex glass bottle (1 L). The water that was sampled was acidified with some droplets of 10% HCl (pH lower than 2), and the sampling position is shown in **Figure 4.2**. Samples were extracted by liquid-liquid extraction with dichloromethane and quantified by use of a UV/spectrophotometer.

4.3.5 Preparation of ice

The ice was frozen in the plastic crates (40cm x 60cm x 15cm) using 0.5% salinity water. This does not yield a realistic porous first-year ice, but the mechanical strength of this ice is needed for a 3-7 day experiment. Previous testing has shown that a more realistic ice, e.g. frozen in our ice basin, is too porous and weak for the mechanical stress in the meso-scale flume. After a day or two, this ice would be crushed and the flume would have been filled with slush ice, thereby resulting in very little difference among the experiments (e.g. 0, 50 and 90% ice coverage).

4.3.6 Ice, wave and current conditions

Based on initial testing, the following settings were selected for the different ice scenarios simulated in the flume (ice/wave/current).

Table 4.2: Description of the meso-scale ice scenarios

Exp no - description	Ice conditions	Wave height (cm)	Wave conditions	Currents (cm/sec)
1 – 0%	Open water	30	Breaking waves	15
2 – 30%	30	30	Breaking waves	15
3 – 50%	50	20	Non-breaking waves	10
4 – 70%	70	15	Swells	5
5 – 90%	90	10	Swells	5 (under ice)

Table 4.3: Description of the meso-scale settings.

Exp no - description	Number of ice sheets (40x60x15 cm) divided into 4 (20x30)	Wave settings (“amplitude, freq”)	Current propeller (setting, volt AC)
1 – 0%	0	Outer hole, 30	90
2 – 30%	6	Outher hole, 30	90
3 – 50%	9	Hole no 3, 20	130
4 – 70%	13	Hole no 4, 17	130
5 – 90%	17	Hole no 4, 17	90

The wave energy and the creation of a breaking wave in the flume are done by use of an oscillating wave generator (hoop). The type of waves and the settings used are given in the tables above and are based on testing conducted during the initial experiments. The current in the circulating flume is generated by both the wave generator and an underwater propeller. The current and settings are given in the tables shown above and are based on testing during the initial experiments.

4.4 Meso-scale weathering Svea, Svalbard

A circulating flume was used to study the weathering of oil at different ice conditions. The flume dimensions and principal layout are given in **Figure 4.3** to **Figure 4.5**. The depth of the flume was 50 cm and did not cut completely through the fjord ice (total ice thickness 110 cm). Two propellers were used to control circulation, and a wave maker to introduce wave energy.

Compared to related experiments performed in 2005 (Brandvik and Faksness, 2009), the experiments performed in 2007 were larger in scale with 200 litres of oil per experiment. The weathering experiments were coordinated and terminated with in situ burning (ISB) experiments, and the duration of each experiment was from 3-5 days.

4.4.1 Field oil sampling and analysis

A comprehensive sampling programme was carried out during the 3-5 day period that each experiment lasted for. Initially, 200 litres of crude were very gently applied to the surface of the flume. Samples were taken from the emulsified surface oil for a series of physical and chemical analyses. Any surplus of free seawater in the collected sample was immediately drained off using a separation funnel before the sample was homogenised and divided into aliquots for further analysis. The analyses of the physical and chemical properties of the surface emulsified oil were performed in a laboratory container on the ice close to the flume immediately after sampling (see Table 4.1). The two last analyses (pour and flash point) were performed later at the SINTEF laboratories in Trondheim. Details regarding the analysis above are described in Daling et al. (2003).

Figure 4.3: Overview of the meso-scale basin cut out in the first-year fjord in Svea, Svalbard. The tent was used to control the air temperature and ice conditions.

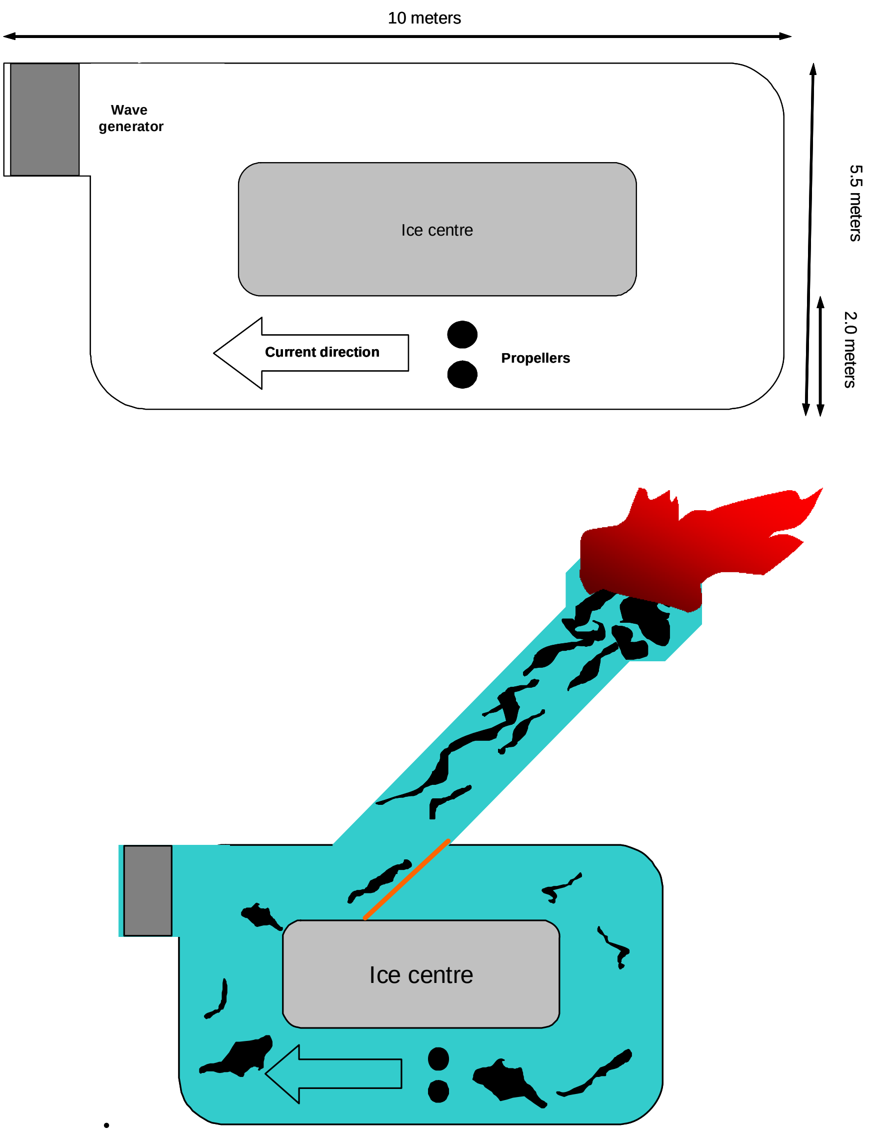

Figure 4.4: An overview showing the layout of the flume and the relationship between the weathering flume at the connected channel to the basin used for in situ burning experiments. After the weathering period, the channel was opened and the oil was led to the in situ burning basin.

Figure 4.5 A close-up of the wave generator and the current propellers used for controlling circulation. See prior figure for an overview.

4.4.2 Ice conditions used in meso-scale testing

The size of the circulating flume used in Svea is given in Figure 4.4. The waves generated by the wave generator were non-breaking and varied in height from 15 cm (open water and 50% ice) to 10 cm with 90% ice. The circulation time in the flume varied from 1 minute (±20%) for the open water experiment, to 1-3 minutes (increasing with increasing viscosity) for the 50% ice, to no circulation of surface ice/water with the 90% scenario, in which the circulation was blocked by ice.

4.4.3 Laboratory chemical dispersibility testing

There is a multitude of various tests for evaluating the effect of chemical dispersants. The energy input will differ in different tests, and the obtained efficiency will be representative of different wave energies. In the screening of different dispersants, the IFP test was used. In the systematic testing of weathered samples collected from the meso-scale flume, the MNS test was used.

IFP (Institute Francais du Petrole test, Bocard et al., 1984) is a low energy test and is thought to be representative for low wave energies (2-5m/s wind speed). A ring beating up and down in the test vessel at a given frequency gives energy input to the seawater column. The water column is continuously diluted, which gives a more realistic approach to field conditions as compared to other tests. The test is shown in Figure 4.6.

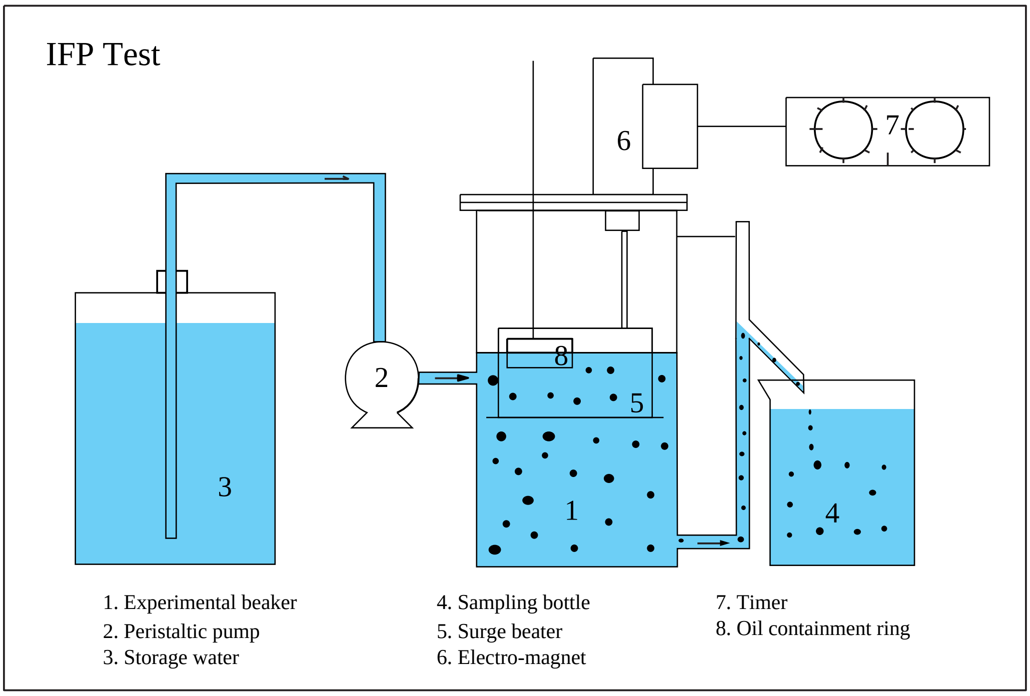

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Figure 4.6: IFP test apparatus

MNS (Mackay and Szeto 1980) has been estimated to correspond to a medium to high sea-state condition. The energy input in this system is applied by streaming air across the oil/water surface, thus producing a circular wave motion. The sample of the oily water is taken under dynamic conditions after a mixing period of 5 min. The test is shown in Figure 4.7.

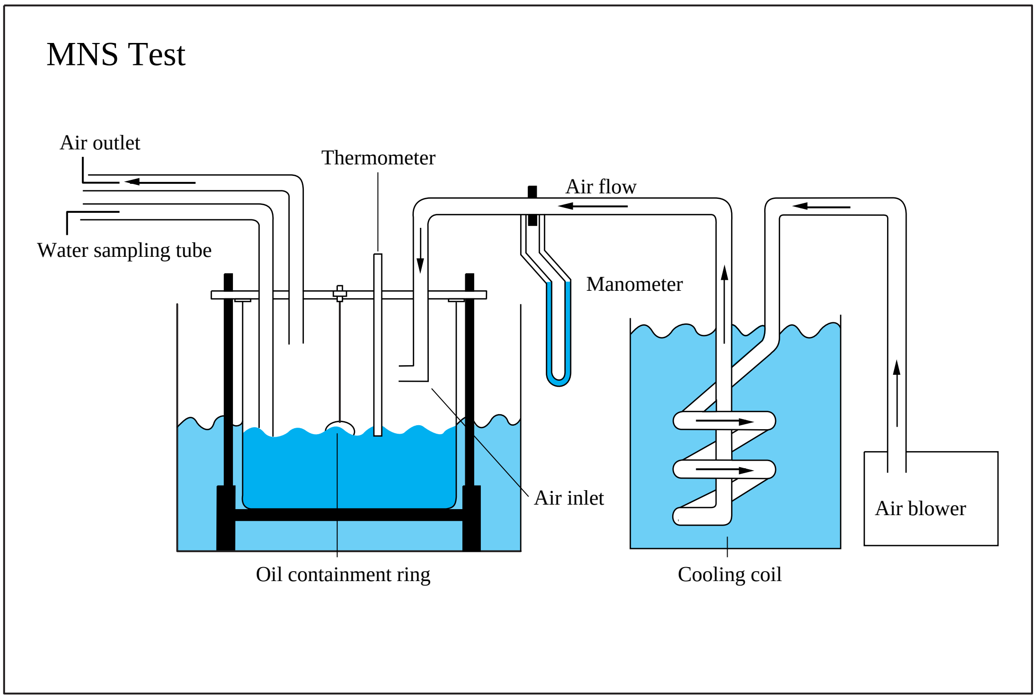

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Figure 4.7: MNS test apparatus

Field Effectiveness Test (FET)

In addition to a standard MNS test, a field effectiveness test is used for checking the dispersibility of the oil/emulsion. This method is described by Fiocco et al. (1999).

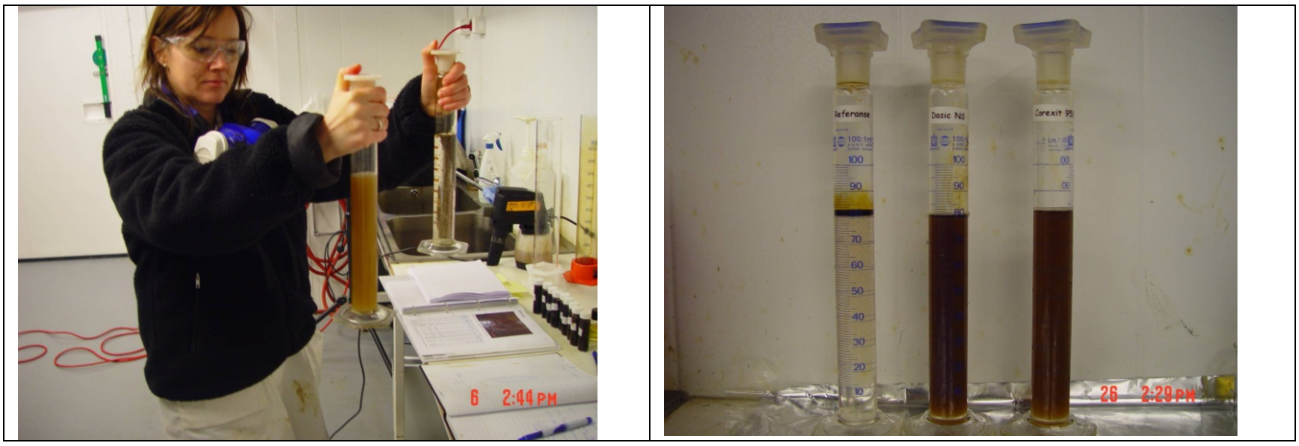

Figure 4.8: Dispersant field effectiveness test - FET test

Simple visual criteria:

1. **Good dispersibility:** A brown dispersion forms immediately when starting tilting. Small oil droplets settle slowly to the surface when standing after tilting.
2. **Reduced dispersibility**: Black dispersion forms during the tilting. Larger droplets settle relatively quickly to the surface when standing.
3. **Not dispersable**: Black, very unstable dispersion forms (large oil droplets, similar to non-treated oil/emulsion).

4.5 Laboratory burning cell

The laboratory burning cell was used to measure the ignitability as a function of weathering and to determine the window of opportunity for using ISB. The results from this small scale laboratory cell (100 mL) have been validated by comparison with field burns from large scale experiments (200-450 L). The burning cell was operated in accordance to a laboratory procedure at SINTEF which was developed during the initial testing, with a short version of this procedure given below. The full laboratory procedure for the operation of the laboratory burning cell is given elsewhere (Brandvik et al., 2010a).

Figure 4.9: The new burning unit during initial testing. Left: SINTEF engineer Frode Leirvik, who is responsible for the construction. Right: Janne Fritt-Rasmussen, a PhD student (Denmark Technical University/University Centre at Svalbard - UNIS) who has done most of the ISB work.

4.5.1 Preparation

1. A fixed amount (approx. 120 g) of fresh oil, evaporated oil or water-in-oil emulsion from the meso-scale flume was added to the water surface in the cell. This corresponds to an oil film thickness of approx. 10 mm.
2. The temperature probes were adjusted (in the water, in the oil layer and in the flame).
3. The temperature logger was turned on.
4. The water flow (through cell outer walls) was adjusted to 500 mL/min.
5. The water temperature was set to 10ºC and controlled.
6. Check exhaust fume filters and fan motor.

4.5.2 Ignition

A propane or butane torch was used as the ignition source. The torch was held at a 30º angle to the oil for 10 seconds. If the oil did not ignite, this procedure was repeated three times. If no ignition was recorded after the third attempt, the oil was declared as “not ignitable”.

4.5.3 Collection of residue for quantification

After the burning stopped, the residue was collected. The residue was collected by adding a circular piece of (pre-weighted) 3M adsorption pad which matched the inner diameter of the burning cell. The warm residue usually soaked into the 3M pad and could easily be removed with the pad after cooling. The amount of water adsorbed to the 3M pad was usually marginal (<10%), and the amount of oil residue left in the cell was also usually marginal (<10%).

After each burn the cell was usually sufficiently cleaned by the removal of residue. However, for more viscous or sticky residues (e.g. from Balder) a more thorough cleaning procedure might be needed. The water level was adjusted dependent on the amount of water in the emulsified samples. This water is usually separated from the emulsion during the experiment and sometimes caused in a rise in the water level.

4.5.4 Calculating burning effectiveness

The burning effectiveness (BE%) was calculated as given below:

$$Burning\ Effectiveness\ (BE\%) = 100 \cdot \left(1 - \left(\frac{mass\ of\ residue}{mass\ of\ initial\ oil}\right)\right) \quad (3.1)$$

- ***Initial oil:*** *Oil applied to the burning cell before ignition.*
- ***Residue:*** *Oil left in burning cell after burning process is finished.*

Since the “mass of initial oil” in Equation 3.1 could contain a different amount of water due to the varying degree of weathering, the absolute number of BE% could vary significantly (between 50 – 90%) for a successful burn. Because the emulsions break and water is separated during a successful burn, the BE% for emulsified samples could be higher than for less weathered samples. To allow for an easier comparison, samples with varying water content and BE% can be corrected for the varying water content (see Equation 3.2).

$$Burning\ Effectiveness\ Corrected\ (BE\% - Corr.) = 100 \cdot \left(\frac{1 - (100 - BE\%)}{(100 - WC\%)}\right) \quad (3.2)$$

- ***WC%:*** *Water content in emulsified samples.*

BE%-Corr is used to present the burning effectiveness when the results are presented in Chapter 4.5 . Nevertheless, the absolute value of both the BE% and BE%-Corr are of less importance since the main use of this laboratory cell is to study the ignitability of the weathered oil as a function of weathering in order to estimate the time window for in situ burning.

The absolute value of BE% is also dependent on the scale of the laboratory equipment. Large-scale burns will usually produce a higher BE% due to the generation of more heat and higher temperatures.

4.5.5 Fieldwork Svalbard - meso-scale burning of weathered oil

The meso-scale verification of ignitability of the weathered oil (300-600 L scale dependent on emulsification) was performed at SINTEF’s field research station on Svalbard. After each weathering experiment, the emulsion was led to the burning chamber (see **Figure 4.10**) by a simple boom arrangement assisted by some shovelling of the surface weathered oil. The film thickness in the 9 m^2 burning chamber varied from 15 to 25 mm, which are realistic for oil spills in broken ice (70 – 90% ice coverage) or for use of fire-resistant booms. The igniter was applied to the middle of the weathered oil and lit by a propane torch. The igniter that was used consisted of gelled crude (1L) added 4% emulsion breaker (Alcopol O 60). If there was not a sufficient amount of flame spreading and the initial burning of the weathered oil started during the burn time of the igniter (10 min), the weathered oil was classified as “not ignitable”. In the cases where the weathered oil ignited, the residue was collected with adsorption pads and gravimetrically quantified (see **Figure 4.11**).

4.5.6 Fieldwork Svalbard - laboratory scale burning of weathered oil

The laboratory burning cell was operated outside the laboratory container, and all samples collected from the flume were tested with the laboratory cell. The same procedure as described earlier (Chapter 4.5.5) was used for the operation of the laboratory burning cell, and the core unit of the burning cell was operated in "field mode". Only the cell itself, the propane igniter, the cooling unit (pump, coolant and thermos), and the flame temperature unit/logger were operated in the field (see **Figure 4.12** for details).

Figure 4.10: In situ burning of weathered oil. The system consists of a burning basin connected to the weathering basin with a channel (see earlier figure) in operation.

Figure 4.11: Collection of residue. After cooling, the residues were easy to remove/collect with 3M adsorption pads. Quantitative collection of residues was important for determining burning effectiveness.

Monitoring coolant temperature during experiments

Figure 4.12: The core unit of the laboratory burning cell operated in “field mode”. Only the cell itself, the butane igniter, the cooling unit (pump, coolant and thermos), and the flame temperature unit/logger were operated in the field.

Details concerning use of the laboratory burning cell at Sea Lab, in Svea and during the large-scale field experiments in May 2009 are given in Brandvik et al., 2010a and Brandvik et al., 2010b.

5 Results and Discussions

The results from the weathering, chemical dispersion and in situ burning experiments are presented in this section. This is done mainly with figures, but a few tables are also used. The data are given as tables in Appendix C.

5.1 Physical and chemical properties of oils tested in flume experiments

The physical and chemical properties of the oils tested in this project are listed in Table ***5.1***. Further details regarding the oils can be found in weathering studies for each oil type (Chapter 4.1).

Table 5.1: The physical and chemical properties of oils tested in the Oil-in- Ice Programme.

SINTEF Id	Oil type	Residue	Density (Kg/m^3)	Evaporative Loss (Vol. %)	Pour point (°C)	Wax (wt. %)	Asphaltenes (wt. %)
2007-0287	Troll B	Fresh	0.900	0	-36	0.9	0.04
		250°C	0.930	25.5	-27		
2007-0260	Norne	Fresh	0.860	0	21	10.8	0.3
		250°C	0.888	28.4	30		
2006-1061	Kobbe	Fresh	0.797	0	-39	3.4	0.03
		250°C	0.875	53.6	21		
2008-0047	Statfjord	Fresh	0.835	0	-6	4.3	0.1
		250°C	0.896	42.4	21		
2007-1060	Grane	Fresh	0.941	0	-24	3.2	1.4
		250°C	0.968	13	-6		

5.2 Meso-scale weathering

The results from the meso-scale testing at the SINTEF SeaLab in Trondheim and at SINTEF's field research station at Svea, Svalbard are presented in this section. First, each oil is individually presented and then a comparison of the various properties for all oils at 0, 50 and 90% ice coverage.

5.2.1 Paraffinic oil: Statfjord – SeaLab

Statfjord crude has a distinct character as a light paraffinic oil with a high paraffin content, a very low content of asphaltenes, and a high evaporative loss due to its high content of light components.

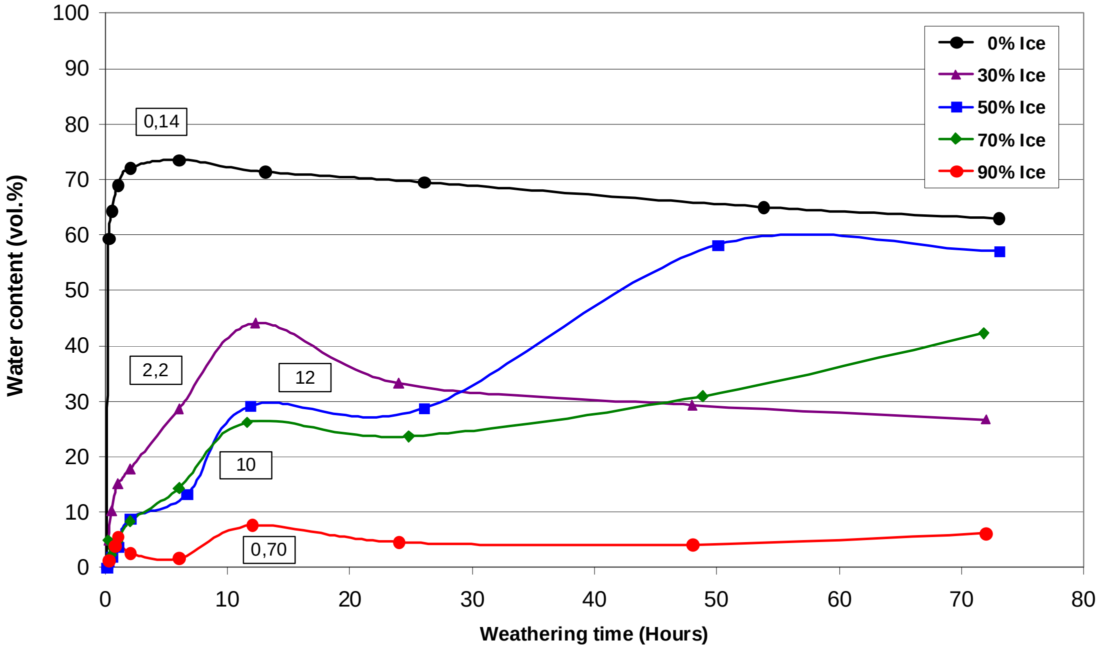

Figure 5.1: Statfjord crude - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure.

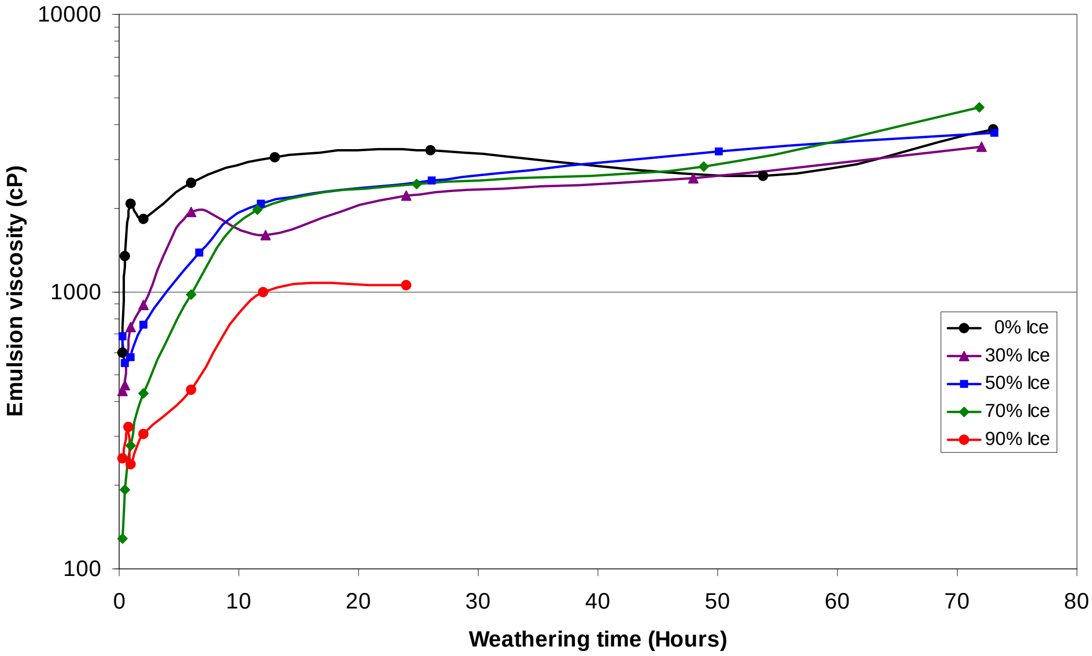

Figure 5.2: Statfjord crude - Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume.

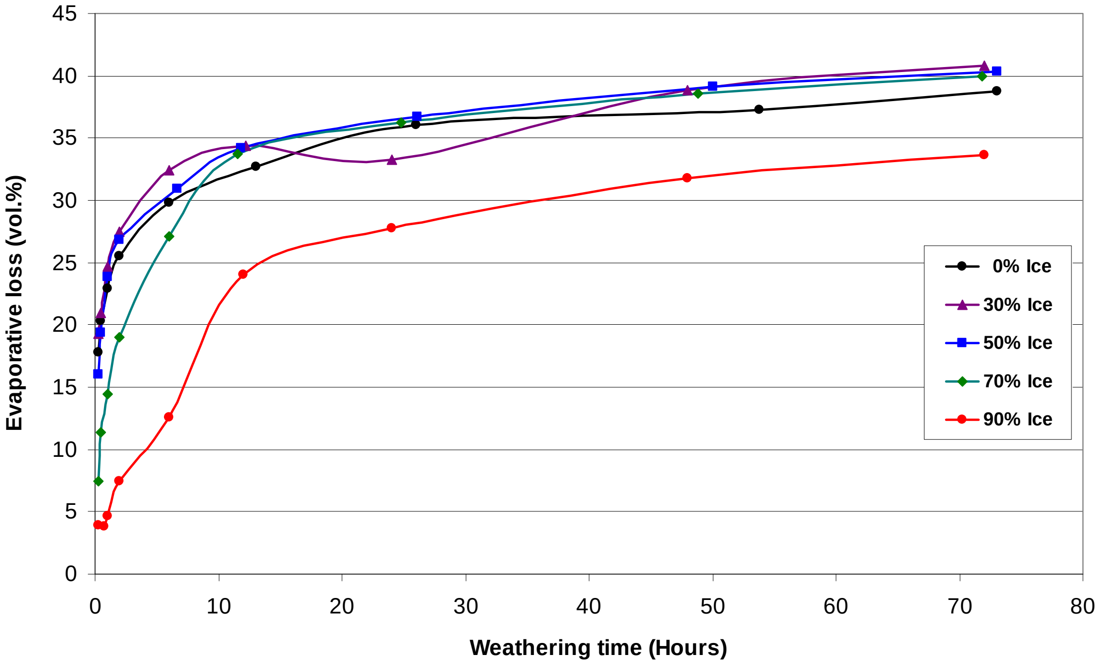

Figure 5.3: Statfjord crude - Evaporative loss as a function of weathering time in the meso-scale flume.

The water uptake rate for Statfjord (**Figure 5.1**,) is very dependent on the ice and energy conditions. The open water or 0% ice experiment has a very rapid and high water uptake (80%), and both the uptake rate and the uptake level decrease in the experiments with an increase in ice coverage. The 30% ice experiment has an unexpectedly low water uptake due to problems with the regulation of air temperature (very low temperature) and the formation of slush ice in the flume. The slush ice has a very clear wave dampening effect, which can be seen on the halftimes (T½) for the water uptake, which are also given in the figure.

This same trend can also be seen for the viscosity of the formed emulsion (**Figure 5.2**) since the viscosity of the emulsified oil is also very dependent on the ice and energy conditions. The open water or 0% ice scenario, which allows the oil to spread freely with breaking waves and high energy, forms emulsions with a high water content, a high stability and a high viscosity. The viscosity is correlated with the water uptake level and shows the same clear decreasing trend as a function of ice and energy conditions as the water uptake. The 30% ice experiment has an unexpectedly low viscosity due to unwanted slush formation as discussed above.

Since evaporation is a surface phenomenon, it should ideally be a direct function of ice coverage (Figure 5.3). 0% ice and free surface spreading should give maximum evaporation, while increasing ice coverage and restricted spreading should reduce evaporation accordingly. This is complicated by emulsification that creates thicker oil layers (80% water is equal to a five times thicker oil layer), thus reducing evaporative loss. This is also dependent on how evenly the oil spreads out, and if it forms “lumps” during emulsification. In some cases, the movement of the ice sheets can help to break up “lumps” and increase evaporation. For the light Statfjord, the evaporative loss for the more energetic scenarios are rather equal (0% and 50% ice), while the high ice coverage experiment (90% ice) is significantly lower than the others (Figure 5.3). This is probably due to oil film thickening which is caused by emulsification that is working towards the film thickening caused by the increased ice concentration. The only scenario with a significantly reduced evaporative loss is the 90% ice experiment which is due to a reduced spreading and thick oil films.

5.2.2 Napthenic oil: Troll B – SeaLab

Troll B is a naphenic crude high in napthenic components (cyclic and branched saturated hydrocarbons). This is caused by micro organisms that have degraded the linear hydrocarbons, yielding a very low paraffinic content and a relatively high content of napthenic components.

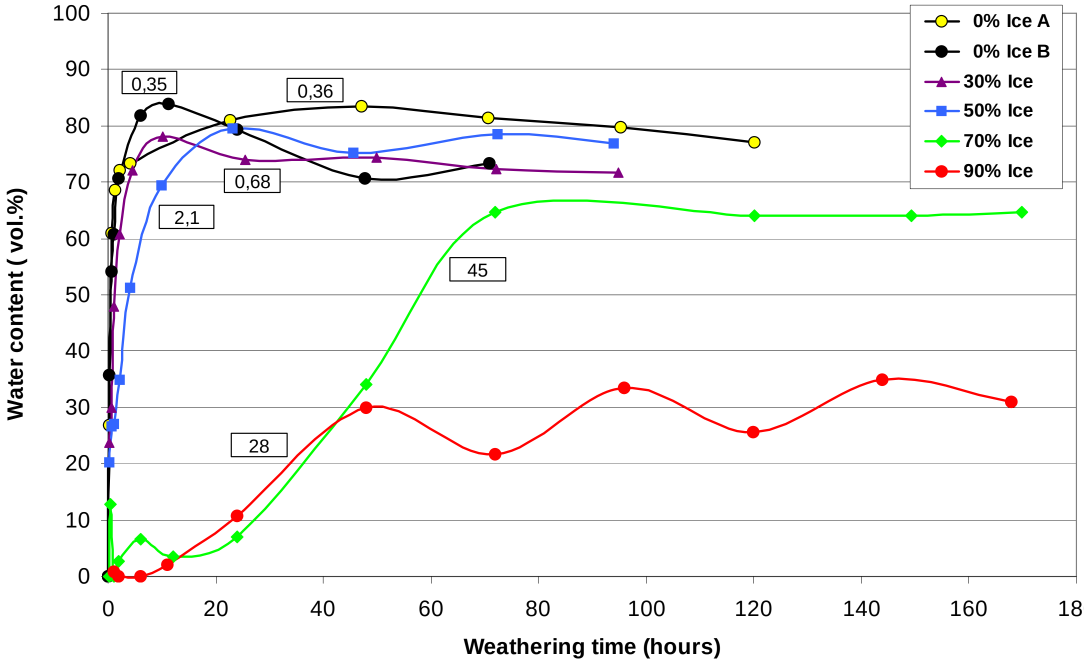

Figure 5.4: Troll crude - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure.

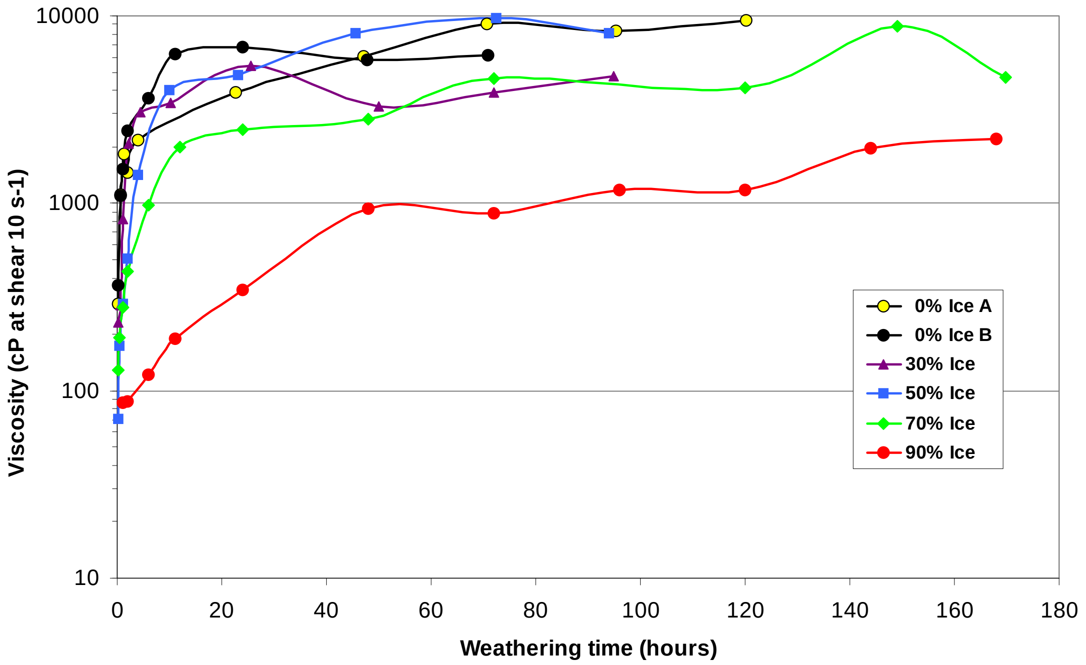

Figure 5.5: Troll B crude - Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume.

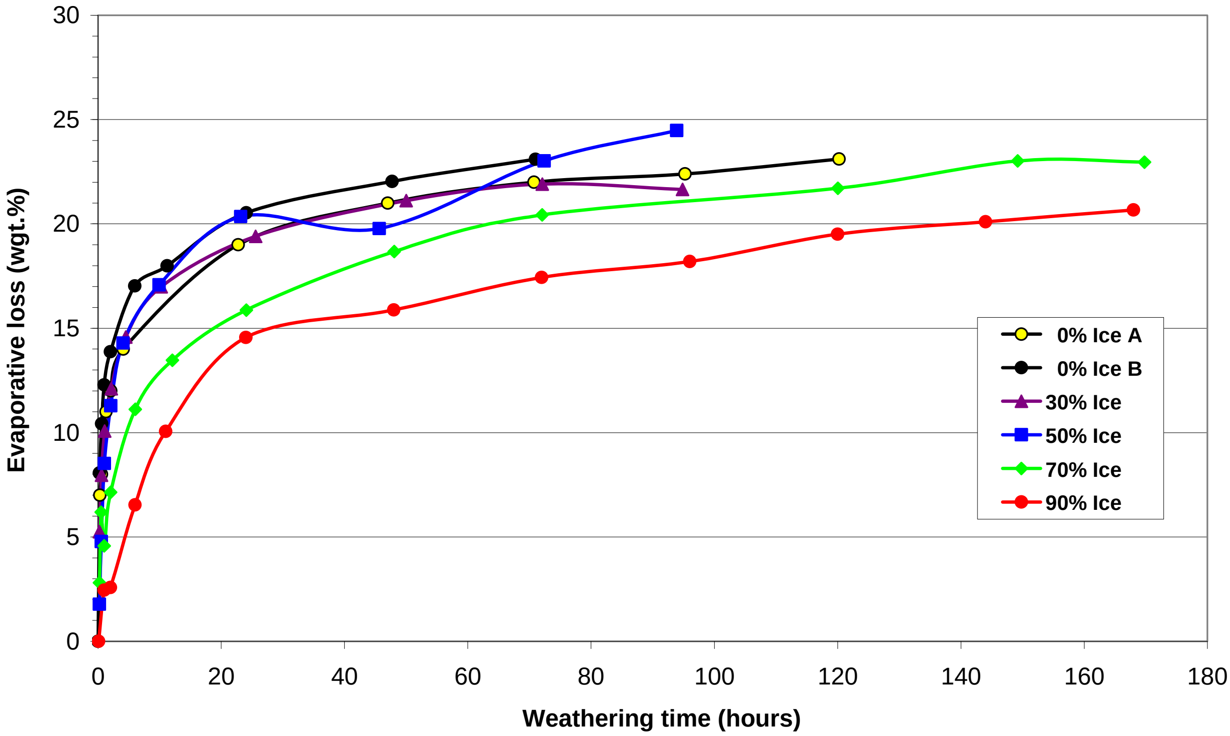

Figure 5.6: Troll B crude - Evaporative loss as a function of weathering time in the meso-scale flume.

The napthenic Troll B has a more balanced blend of emulsion stabilising components (waxes, resins and asphaltenes) compared to Statfjord and forms more stable water-in-oil emulsions. This can be seen in **Figure 5.4**, where the level of water uptake is not so different from the experiments with the lowest ice coverage (0-50% ice). This indicates that emulsification is not so sensitive to the varying energy input (ice conditions). Due to the higher content of natural surface active components (surfactants, also see **Figure 3.4**), the water droplets are more easily stabilised in the emulsion. However, the difference in water uptake level is significantly lower for the 70% ice and 90% ice experiment, and the uptake rate (T½) corresponds well with increasing ice coverage. Two replicate experiments were performed with Troll B to estimate the variations in weathering behaviour (0% Ice A and B). The differences between these two replicates are representative of the experimental uncertainty of the meso-scale system.

Additionally, the emulsions formed with Troll B are more stable and have a higher viscosity compared to the emulsions formed by the paraffinic Statfjord (**Figure 5.5**). However, we also observe that the viscosity of the emulsified oil is very dependent on the ice and energy conditions. The viscosity is correlated with the water uptake level and shows the same decreasing trend as a function of ice and energy conditions as the water uptake.

Troll B has a very low pour point due to its low wax content (naphenic character). For this reason, the emulsion formed is free of wax lumps and does not show any tendency to solidify, and adsorption to the walls in the flume is also low. This minimises effects other than the effect of thickness, and we can see a clearer relationship between evaporation and ice coverage in **Figure 5.6**. Higher ice concentrations give higher oil thickness and reduced evaporation.

5.2.3 Napthenic oil: Troll B – field work Svea, Svalbard

In addition to the meso-scale experiments performed at SINTEF SeaLab, experiments were performed in a larger scale (200 versus 20 litres) at SINTEF's field research station in Svea, Svalbard. The main objective with this additional testing of one oil type was to verify the findings from the large number of meso-scale tests performed at SeaLab.

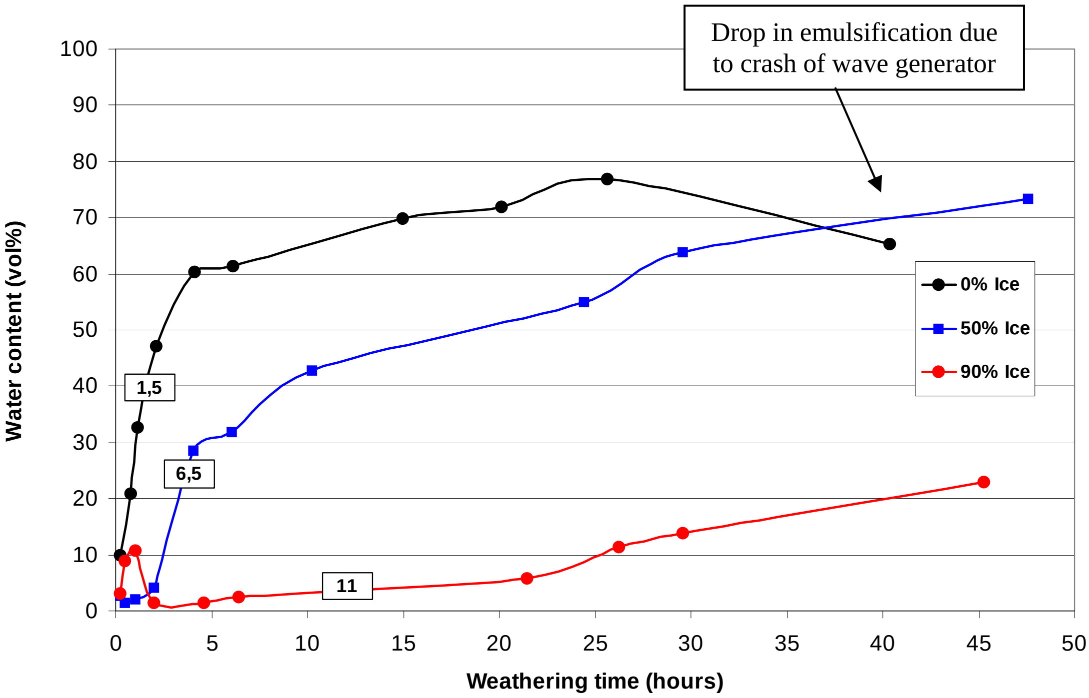

Figure 5.7: Troll B - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure.

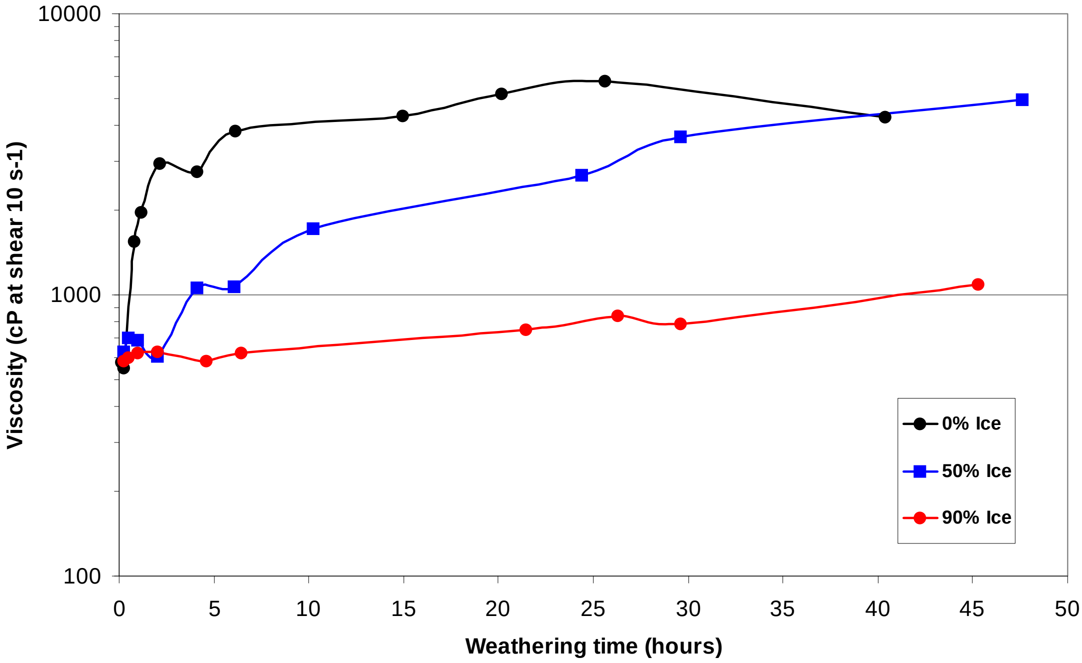

Figure 5.8: Troll B – Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume.

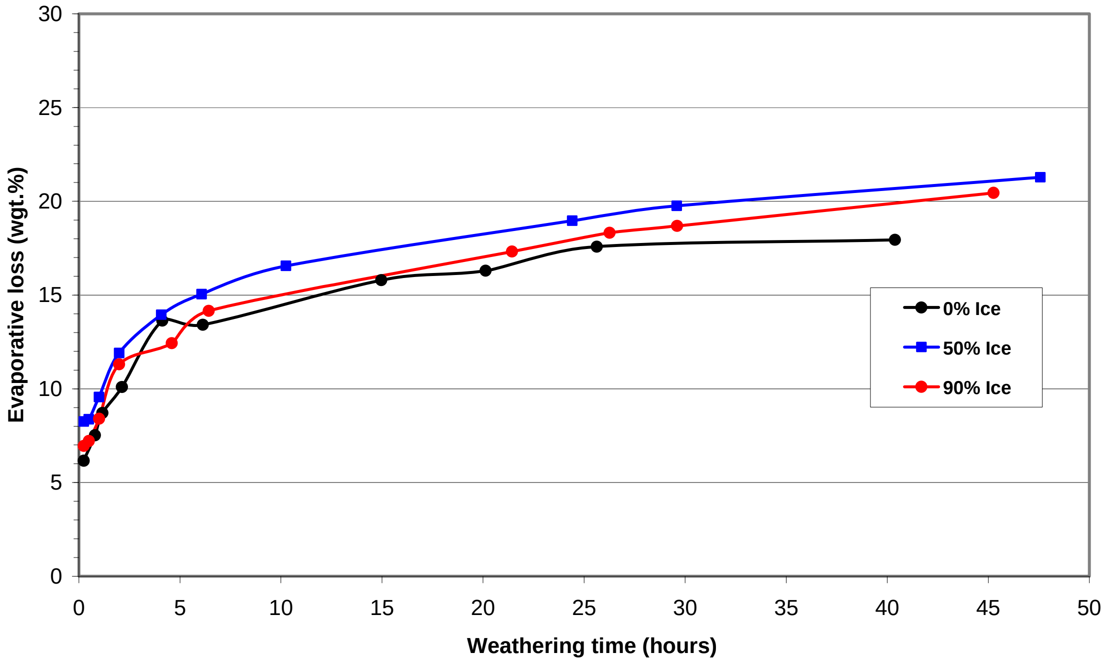

Figure 5.9: Troll B - The evaporative loss as a function of weathering time in the meso-scale flume.

The main difference between the experiments performed at SeaLab (20 litres) and on a larger scale in Svea (200 litres) is the water uptake rate for the experiment performed at 50% ice. Both the water uptake rate (T½: 2.1h versus 6.5h) and the emulsion viscosity (8000 vs. 5000 cP) show that the experiments at SeaLab have a more rapid water uptake and form more viscous emulsions at 50% ice compared to the experiments at Svea. This indicates that the energy input (wave generation) at 50% ice has been somewhat lower in Svea compared to SeaLab. This is probably caused by slightly lower waves during the Svea experiments compared to the experiments performed at Sea Lab. Different water depths and basin sizes in the two experiments also influence on wave size and type.

For the two other experiments performed in Svea, open water or 0% ice and 90% ice, the correspondence between the small- and large-scale experiments was much better.

5.2.4 Asphaltenic oil: Grane – SeaLab

The asphaltenic crude Grane is rather heavy compared to most other Norwegian crudes, which is probably due to degradation in the reservoir by micro organisms. It has a high content of asphaltenes and a low content of lights components, which gives the oil a high content of natural surfactants and the highest density of all the test oils.

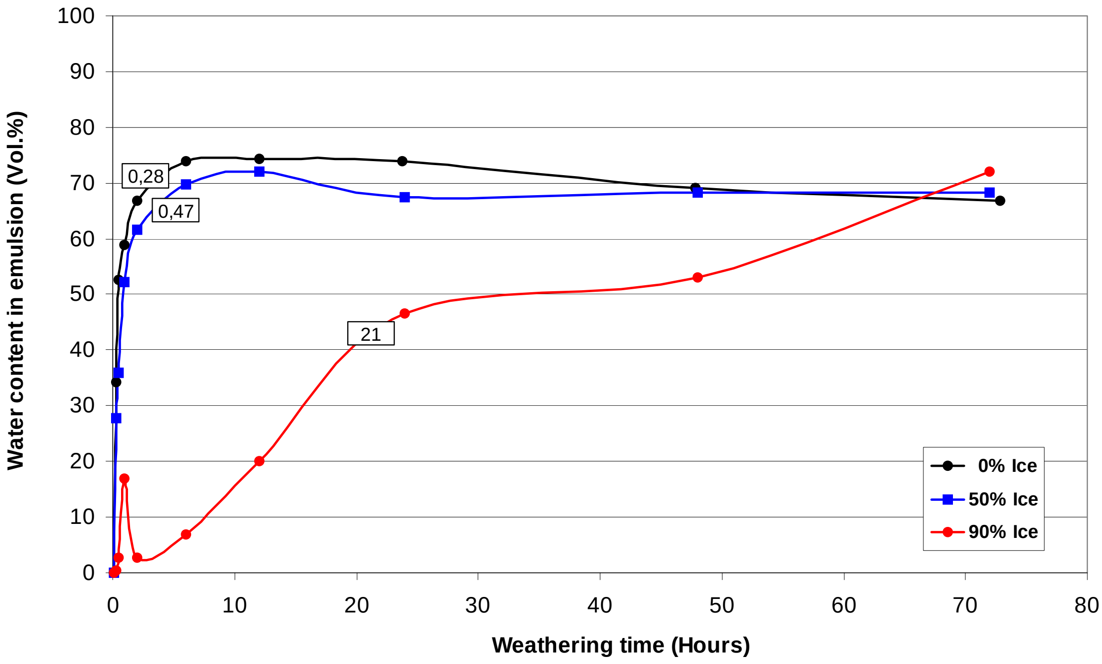

Figure 5.10: Grane crude - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure.

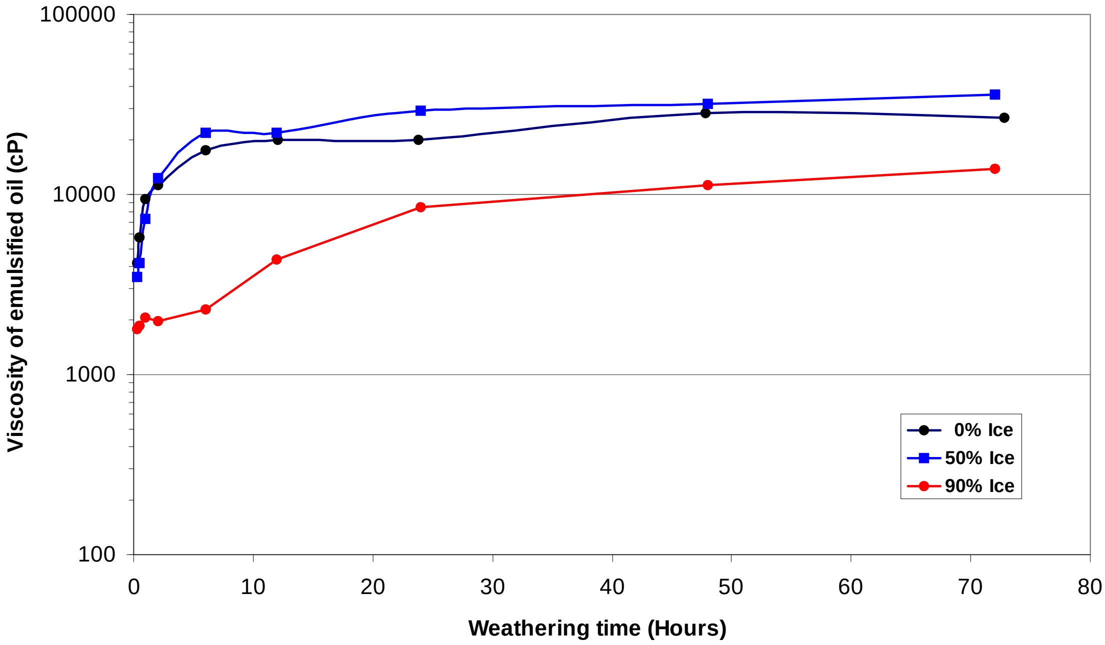

Figure 5.11: Grane crude - Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume.

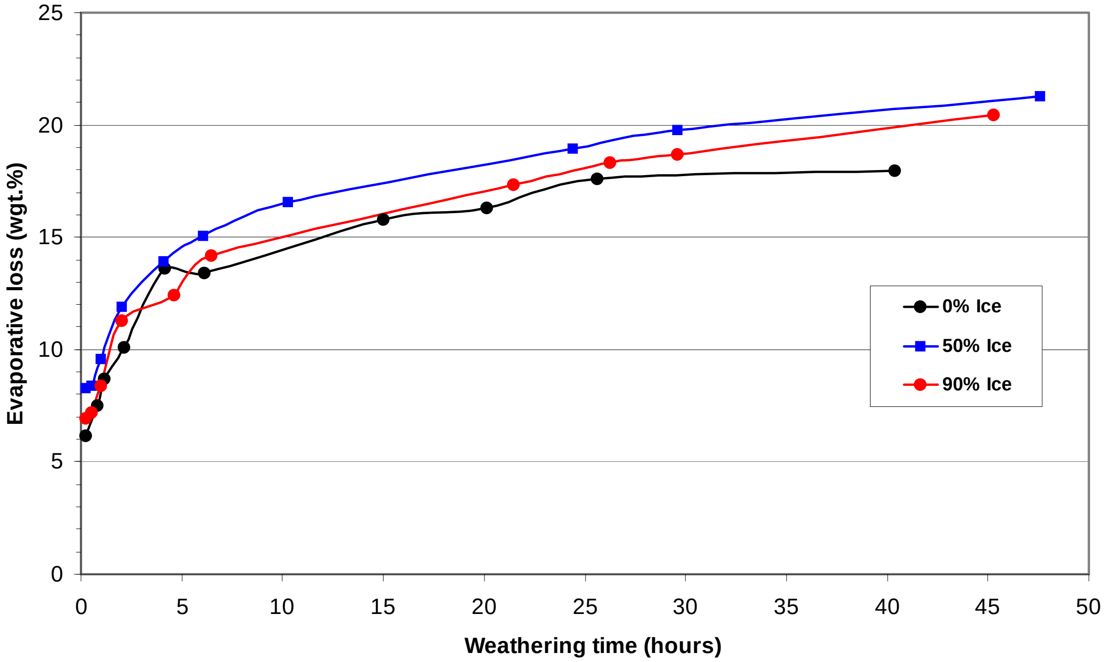

Figure 5.12: Grane crude - The evaporative loss as a function of weathering time in the meso-scale flume.

The asphaltenic Grane has a very rapid water uptake and forms very stable emulsions due to the high content of emulsion stabilising components (waxes, resins and asphaltenes). This can be seen in **Figure 5.10**, where the water uptake for Grane is not so different for the three experiments performed (70% maximum water uptake). This indicates that the emulsification is not so dependent on the ice and energy conditions for this oil type. Due to the higher content of natural surfactants, the water droplets are more easily stabilised in the emulsion (**Figure 3.4**). The water uptake for the low energy 90% is slower, but ends in a total water uptake of 70%.

In addition, the emulsions formed with the heavy Grane are much more stable and have the highest measured viscosity among all the test oils (10000-20000 cP at a shear rate of 10 s^{-1}, see **Figure 5.11**). Also in these experiments, the viscosities are correlated with the water uptake rates, and very stable emulsions with a high viscosity are formed even at 90% ice (> 10000 cP).

The rapid emulsification of the Grane crude creates thick layers or patches of emulsion in the meso-scale flume. This high film thickness could reduce the evaporation which is a surface phenomenon. This is probably the reason for the slightly lower evaporative loss from the 0% ice experiment compared to the 50% ice experiment (**Figure 5.12**). With the flume filled with 50% ice, interaction with the ice will probably prevent the establishment of large thick patches of emulsified oil. However, evaporation in the 90% ice experiment is significantly lower due to the total entrapment of the oil between the ice floes which produces thicker layers.

5.2.5 Waxy oil: Norne – SeaLab

Norne is a typical waxy crude oil, with a very high pour point which gives the fresh oil a semi-solid behaviour at a low temperature for the experiments (-1.8°C). The oil has to be heated to be applied to the water surface when initiating the experiment.

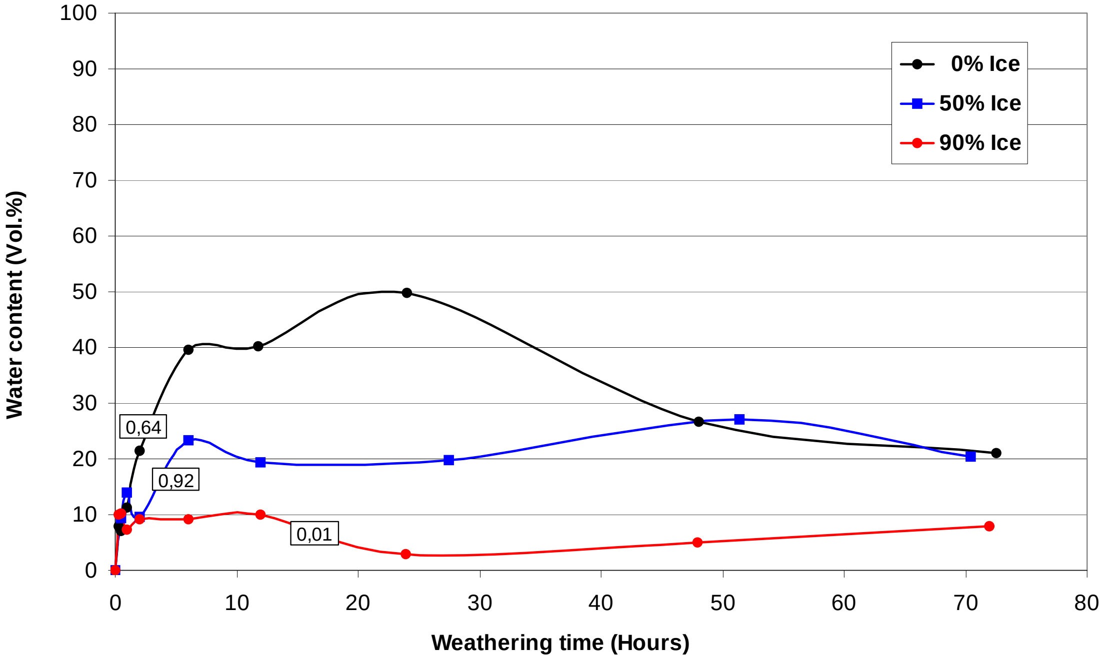

Figure 5.13: Norne crude - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure.

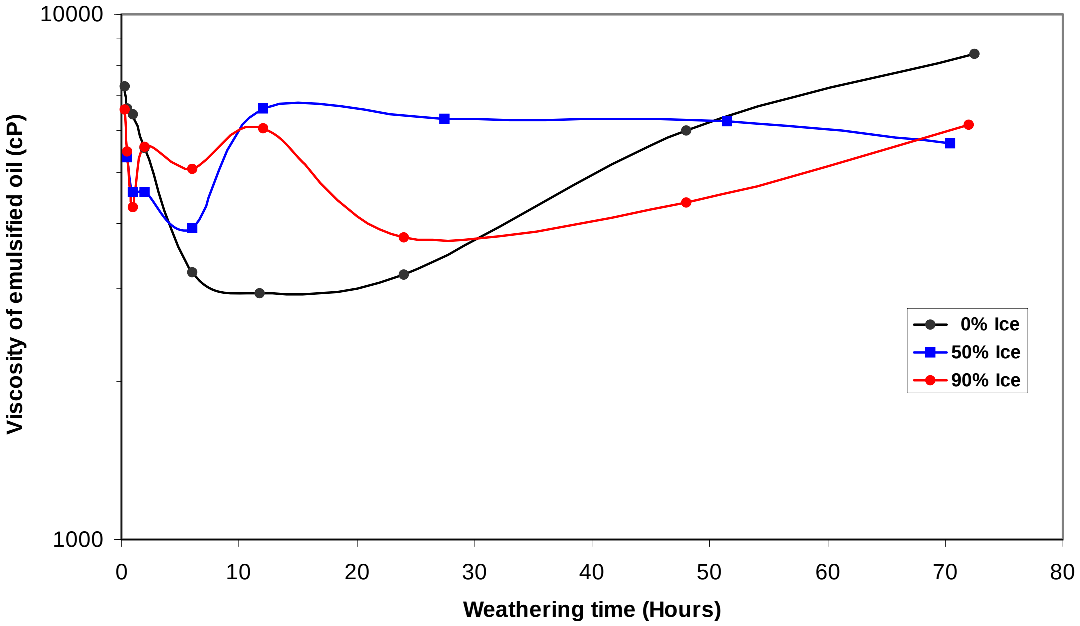

Figure 5.14: Norne crude – Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume.

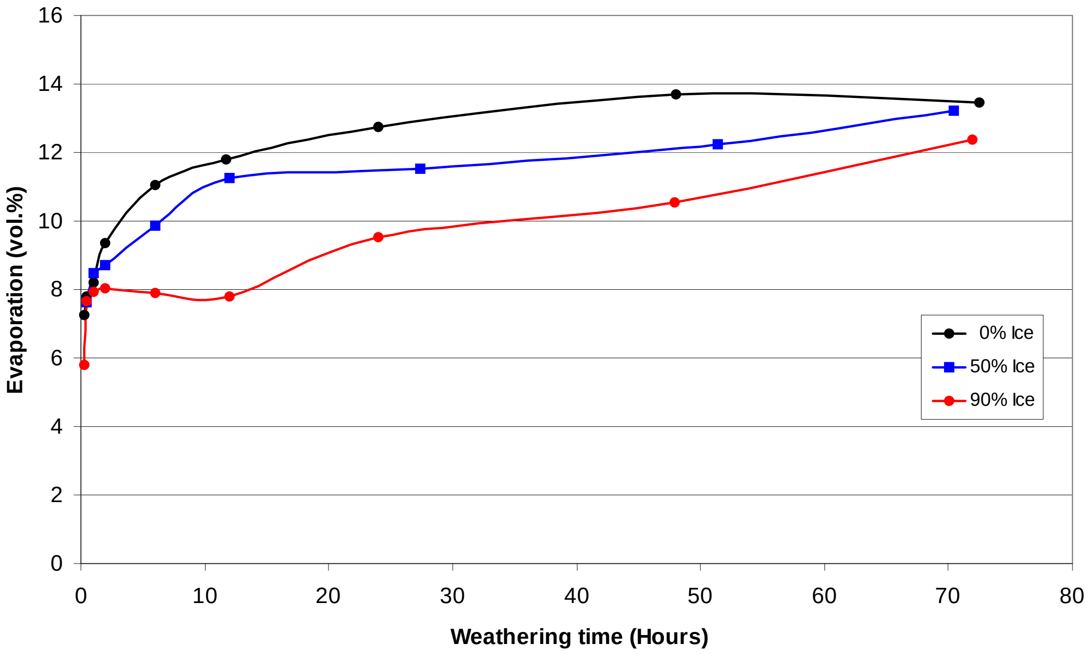

Figure 5.15: Norne crude - The evaporative loss as a function of weathering time in the meso-scale flume.

The main components stabilising the water-in-oil emulsions for Norne crude are the wax compounds. Similar to the paraffinic Statfjord, this makes the water uptake highly dependent on the energy conditions. This can be seen from **Figure 5.13** where the difference in both uptake rate and maximum water uptake is dependent on the ice/energy conditions. The highest and fastest water uptake is seen in the open water experiment (0% ice), and the lowest and slowest water uptake is seen in the experiment with the highest ice coverage and the lowest energy (90% ice).

The viscosity of weathered oil is usually correlated with the water content, and increasing viscosity is normally the consequence of emulsification. This trend of viscosity is not seen in the waxy crude Norne. In **Figure 5.14**, the open water experiment (0% ice) shows a decreasing viscosity when the oil emulsifies. Due to the high pour point of the fresh crude and the low temperature (-1.8°C) used in the experiments, the viscosity actually decreases as the oil emulsifies. These slushy, unstable emulsions have a low viscosity compared to the initial water free and semi-solid oil. When the oil starts to emulsify the waxes are used to stabilise the water droplets by accumulating on the water droplets. This accumulation reduces the effective concentration of waxes in the oil and the oil’s pour point. The increasing number of water droplets in the oil will also disturb the formation of larger and continuous wax lattices which are needed to solidify the oil.

For the waxy crude Norne, the relationship between ice coverage and evaporative loss is as expected (see **Figure 5.15**). Higher ice coverage gives less spreading, a higher film thickness and a reduced evaporative loss. The open water experiment (0% ice) has the highest evaporative loss, while the highest ice coverage (90% ice) has the lowest evaporative loss.

5.2.6 Light oil: Kobbe – SeaLab

The light oil Kobbe has a low content of heavy components such as waxes and asphaltenes which are important for the stabilisation of water-in-oil emulsions. However, it contains a sufficient amount of such stabilising components to form stable emulsions.

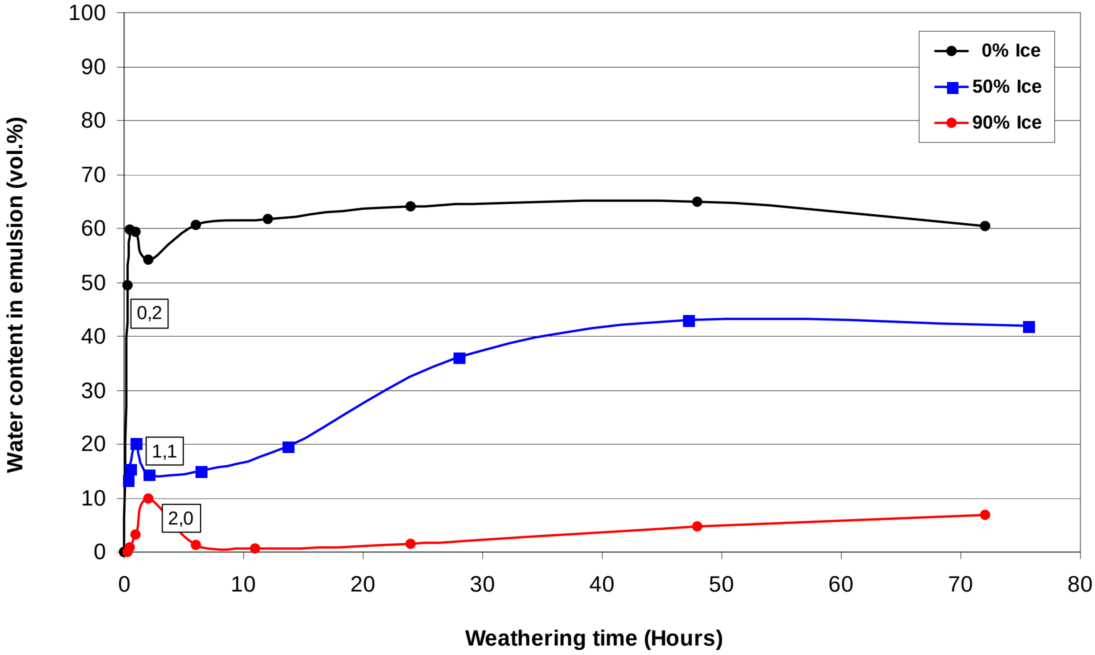

Figure 5.16: Kobbe light crude - The water content in the emulsified oil as a function of weathering time in the meso-scale flume. The halftimes (T½) for the water uptake are also given in the figure.

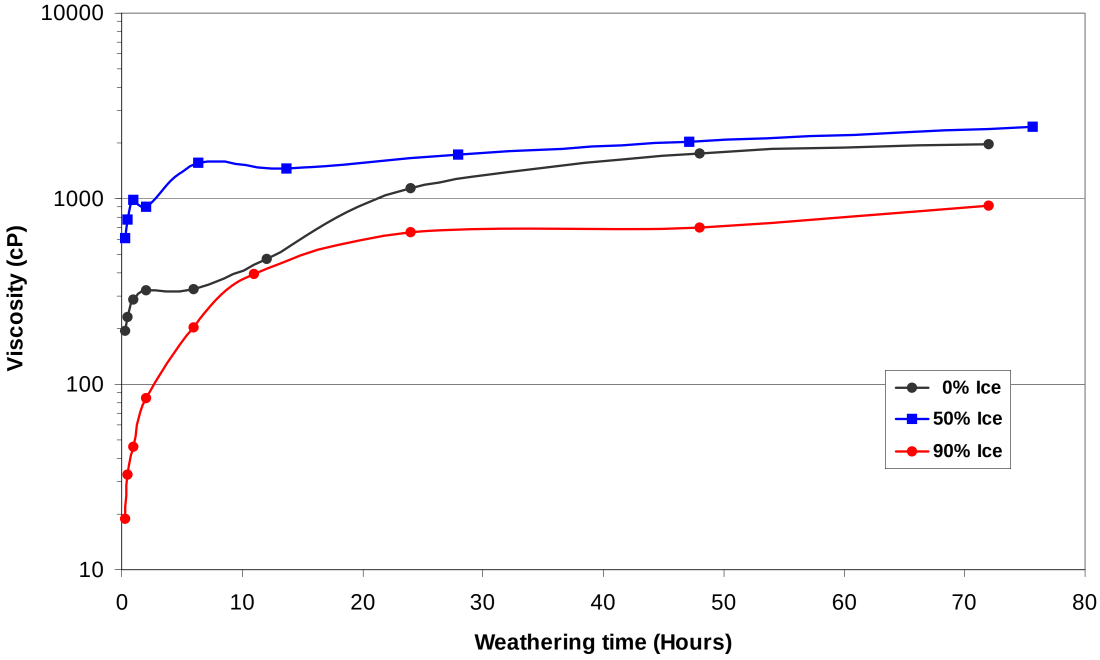

Figure 5.17: Kobbe light crude - Viscosity (cP at shear rate 10 1/s) for the emulsified oil as a function of weathering time in the meso-scale flume.

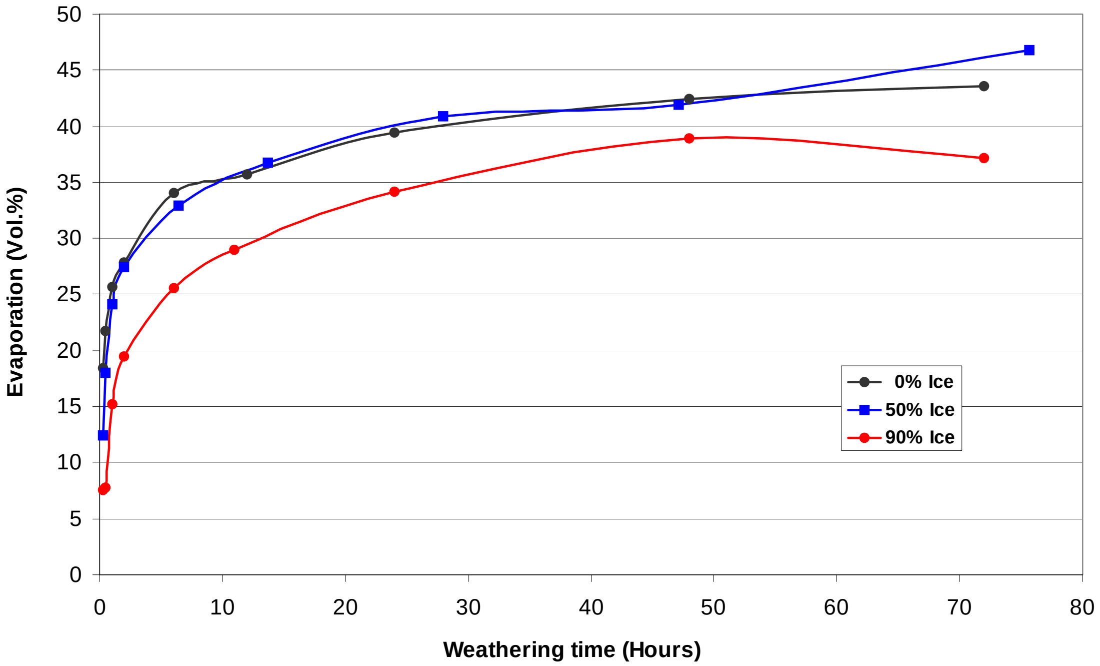

Figure 5.18: Kobbe light crude - The evaporative loss as a function of weathering time in the meso-scale flume.

As in other oil types that lack a broad composition of emulsion stabilising components (waxes, resins and asphaltenes), e.g. Statfjord and Norne, the water uptake of Kobbe is greatly dependent on the ice/energy conditions. **Figure 5.16** shows a large difference in water uptake as a function of ice/energy conditions. Nevertheless, the maximum water uptake is only 65%, which is among the lowest for the oil tested, and is due to the low content of natural surfactants.

The emulsions formed by the light oil Kobbe have a very low viscosity, but the viscosity correlates well with the water uptake. The experiments with high water contents also have a high viscosity (see **Figure 5.16** and **Figure 5.17**).

The evaporative loss of the light Kobbe is high, up to 45% for the open water (0% ice) and 50% ice and lower for the 90% ice experiment at 38%.

This oil has earlier been tested in the meso-scale basin at SINTEF at 5°C as a part of a weathering study. At this temperature the Kobbe oil formed very unstable emulsions and had a high degree of natural dispersion. Not much was left on the surface in the meso-scale basin after 24 hour (Leirvik et al., 2007). This shows that environmental temperature is very important for the fate of the light oil Kobbe.

5.2.7 All oils - water content in emulsions versus ice coverage

The figures below compare the water content for all five oil types with 0, 50 and 90% ice.

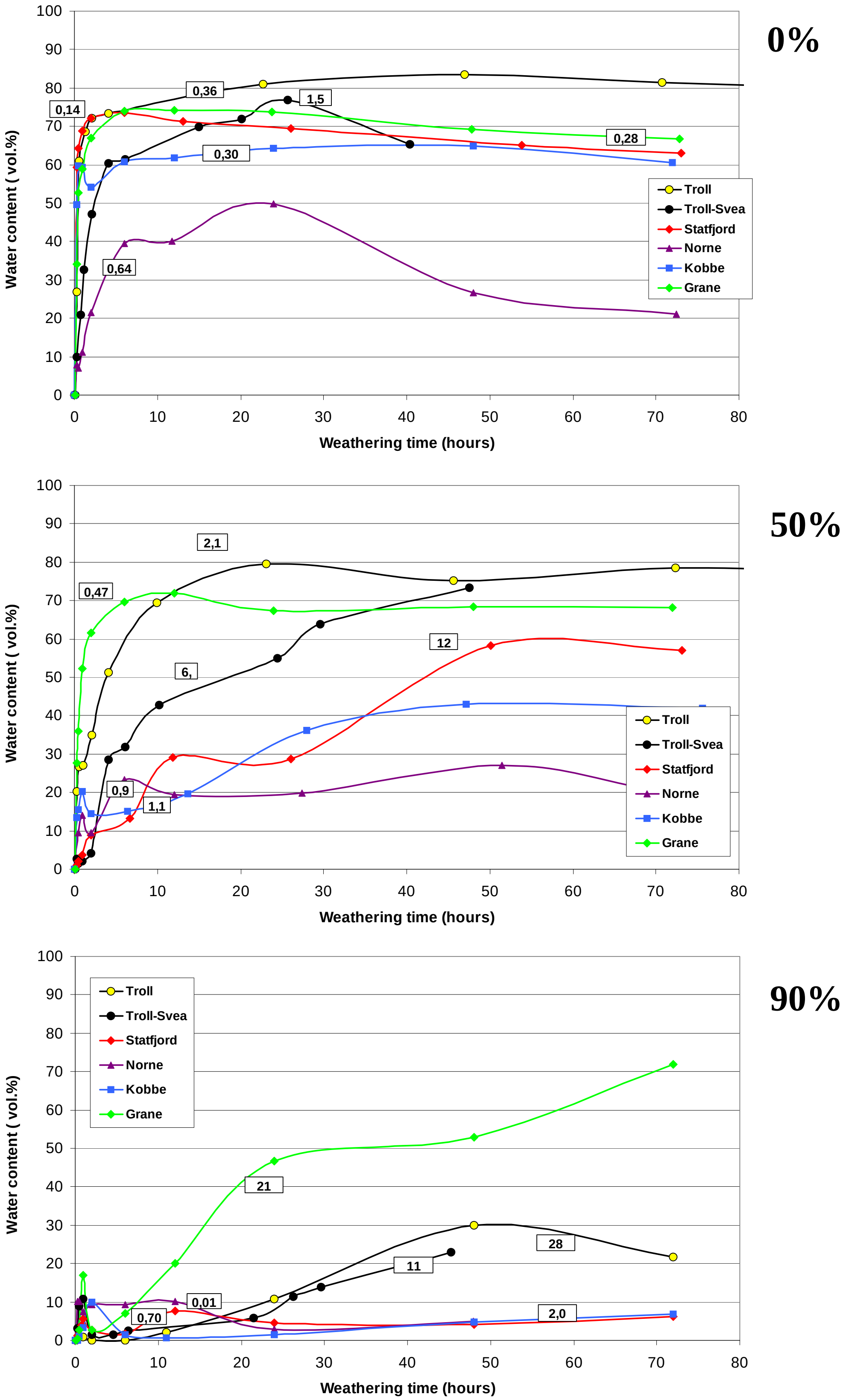

Figure 5.19: Water content and halftimes (T½) for all oil types at 0%, 50% and 90% ice coverage as a function of weathering time in the meso-scale flume.

The main impression from Figure 5.19 is the general reduction in both water uptake rate and level as a function of energy and ice conditions. In the open water experiments (0% ice), the water uptakes are generally rapid and high compared to the experiments performed at 50% and 90% ice. At a high ice coverage and low energy (90% ice), the oils generally have a slow and low water uptake due to the low energy present at these experiments.

Comparing the water uptake for the five different oils, we can observe differences which reflect their chemical composition and ice and energy conditions. The two oils forming the most stable emulsions (Troll and Grane) have the most rapid and highest water content, especially at medium and high ice coverage. These oil types demand less energy to form emulsions due to their high content of emulsion stabilising components (waxes, resins and asphaltenes).

Other oils such as, naphtenic Statfjord or light oil Kobbe which rely more on waxes alone to stabilise emulsions, are more dependent on energy input (waves) to form emulsions. When the content of emulsion stabilising components is low, the interfacial tension between oil and water is higher and higer energy is needed to create small droplets.

This knowledge is important for responders since varying water uptake will increase the volume of the pollutant and increase viscosity and expected life time at sea (see next chapter). The easiest way for the responders to utilize this knowledge, would be to use the new model of the SINTEF Oil Weathering model to predict water uptake for oil spills in ice.

5.2.8 All oils - viscosity versus ice coverage

The figures below compare the emulsion viscosity for all five oil types at 0, 50 and 90% ice.

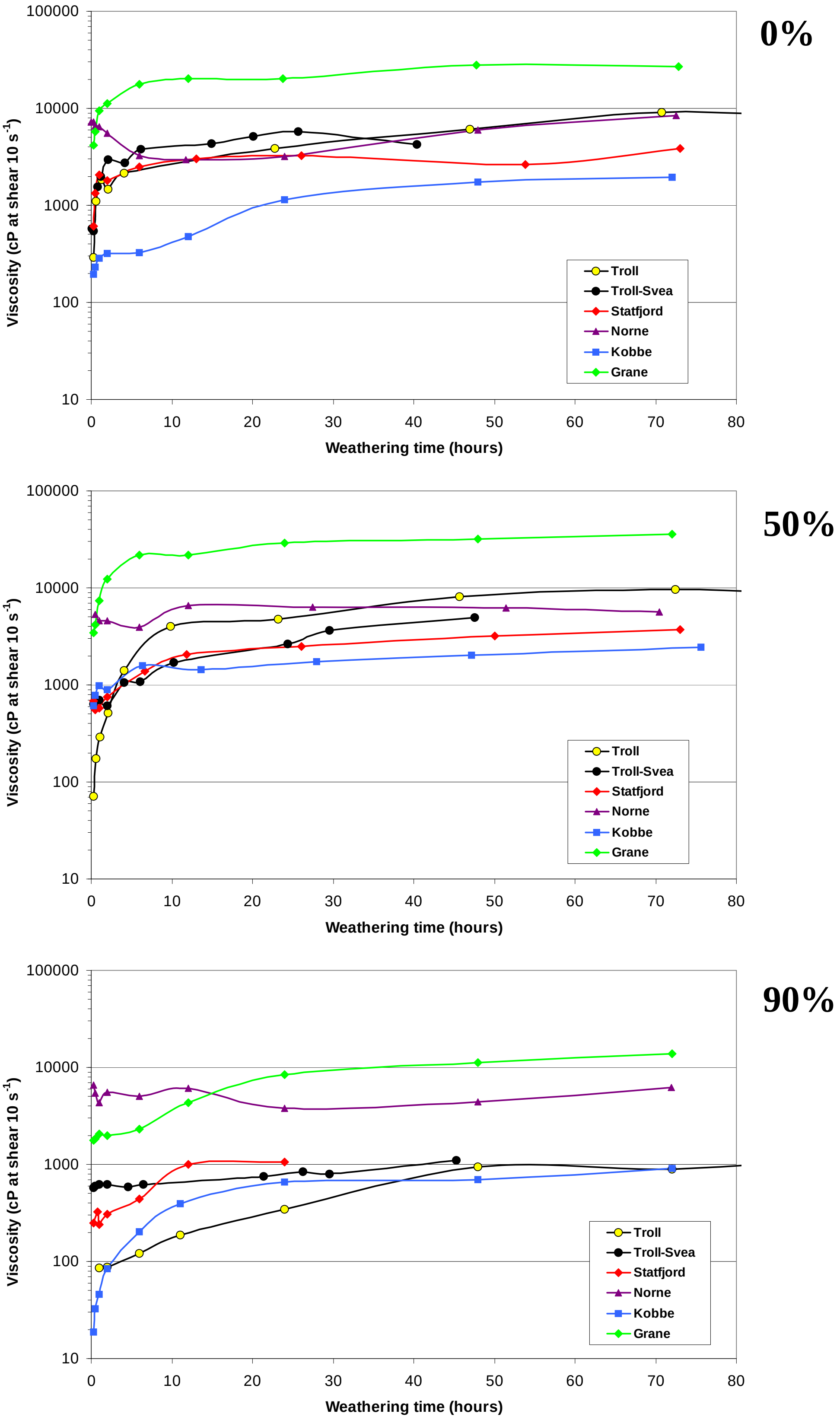

Figure 5.20: Viscosity for all oil types at 0%, 50% and 90% ice coverage as a function of weathering time from the meso-scale flume.

The viscosity of the five different oils used in the meso-scale experiments is very different and ranges from 20 000 to 2 000 cP depending on their chemical composition. The asphaltenic Grane has a high content and favourable mix of natural surfactants (waxes, resins and asphaltenes) and forms very stable emulsions with a high viscosity (10 000 – 20 000 cP). At the other end of the scale is the light oil Kobbe, which has a very low content of natural surfactants and forms unstable emulsions with a low viscosity (800 – 2 000 cP).

This knowledge is important for responders since the expected life time at sea are increased with increased emulsion viscosity. Also seletion of skimmer type and estimated performance will be influenced by emulsion viscosity.

The easiest way for the responders to utilize this knowledge, would be to use the new version of the SINTEF Oil Weathering model to predict viscosity for oil spills in ice.

5.2.9 All oils – evaporation versus ice coverage

The figures below compare the evaporative loss for all five oil types at 0, 50 and 90% ice.

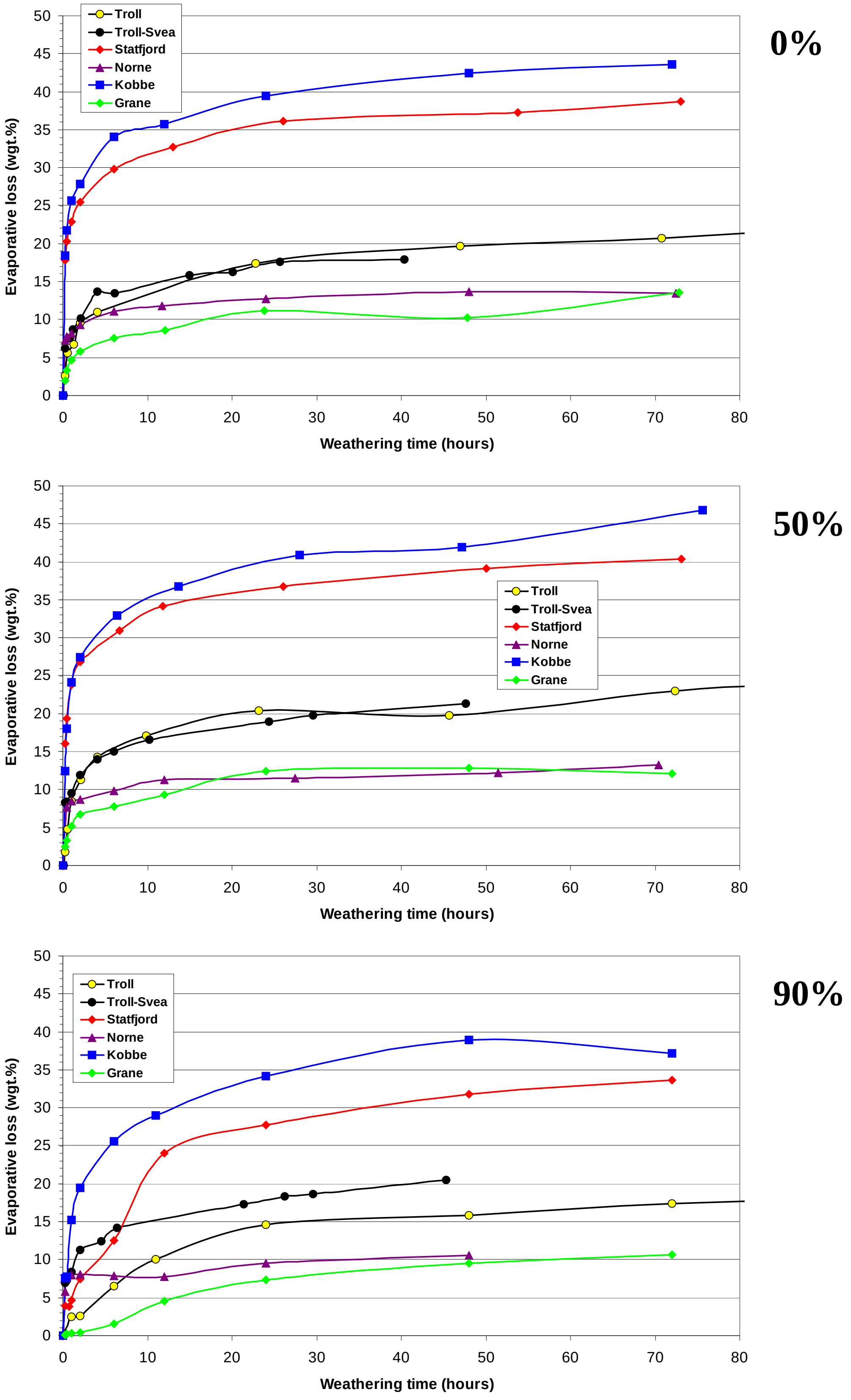

Figure 5.21: The evaporative loss for all oil types at 0%, 50% and 90% ice coverage as a function of weathering time in the meso-scale flume.

The difference in evaporative loss among the five different oils used in the study usually reflects their varying content of light components. The light oil Kobbe has an evaporative loss of 47%, followed by Statfjord with 40%, Troll with 23% and then Grane and Norne which are both at 12%, with all the numbers coming from the experiments with 50% ice. The only exception from this general dependency on the content of light components is the waxy Norne. Its evaporative loss of only 12% is low, given that an evaporative loss 10% higher would have been more in accordance with the boiling point curve for Norne and the experimental conditions (temperature, film thickness, etc.). This reduced evaporative loss is probably caused by the oil solidifying into thick lumps.

This knowledge is important for responders since evaporative loss remove pollutant from the sea surface. The easiest way for the responders to utilize this knowledge, would be to use the new version of the SINTEF Oil Weathering model to predict evaporation for oil spills in ice.

Dispersibility testing

The dispersibility testing performed in the oil-in-ice JIP includes the following:

- An effectiveness screening of relevant modern dispersant concentrates on weathered emulsion under low temperature and varying salinities in order to select a robust test dispersant for the oil-in-ice weathering testing in the meso-scale flume at SINTEF SeaLab.
- A study of the dispersibility of five different oil types as a function of weathering in ice at different ice conditions (0%, 30%, 50%, 70% and 90% ice coverage).

Results from the screening study are shown in the next chapter.

5.2.10 Selection of dispersants for further testing

An effectiveness screening of different dispersants using the IFP dilution test were performed to select dispersants for further testing in the flume. Prior the laboratory testing, an extensive search among dispersant manufacturers and hearing within the reference group was performed. Based on this, following 6 dispersant products were selected out for the study::

• Corexit 9500:	The most available disapersant in stock in thwe US, customized for highly weathered oils (produced in USA)
• Dasic NS:	The most available disapersant in stock in Norway, customized for North Sea crude oils (produced in UK)
• Dasic FW :	Customized for use in low-salinity/ brackish water (produced in UK)
• Gamlen 4000 OD:	The most available disapersant in stock in Europe (prod.d in France)
• Finasol OSR-62:	New dispersant formulation (Produced in France)
• Enersperse 1037	Product that earlier has show high performance under various salinities (not presently commercial available)

The tests were performed at a dispersant to oil ratio (DOR = 1: 25) and at four different salinities (35, 20, 10 and 3 ppt).

The results from the testing are shown in Figure 5.22**.**

All dispersants except for Finasol OSR-62 showed a significant reduction in effectiveness with decreasing salinity. In open water, the salinity of sea water is 35 ppt, but in ice-covered waters salinities in surface layers could vary due to ice melting and runoff from rivers in the spring.

Dasic NS can document a relatively high performance on most crude oils produced in the North Sea, which is the primary reason that the Norwegian Clean Seas Association (NOFO) has stockpiled this dispersant in Norway (ca. 620 m^3). Corexit 9500 is the primary dispersant being stockpiled in the US.

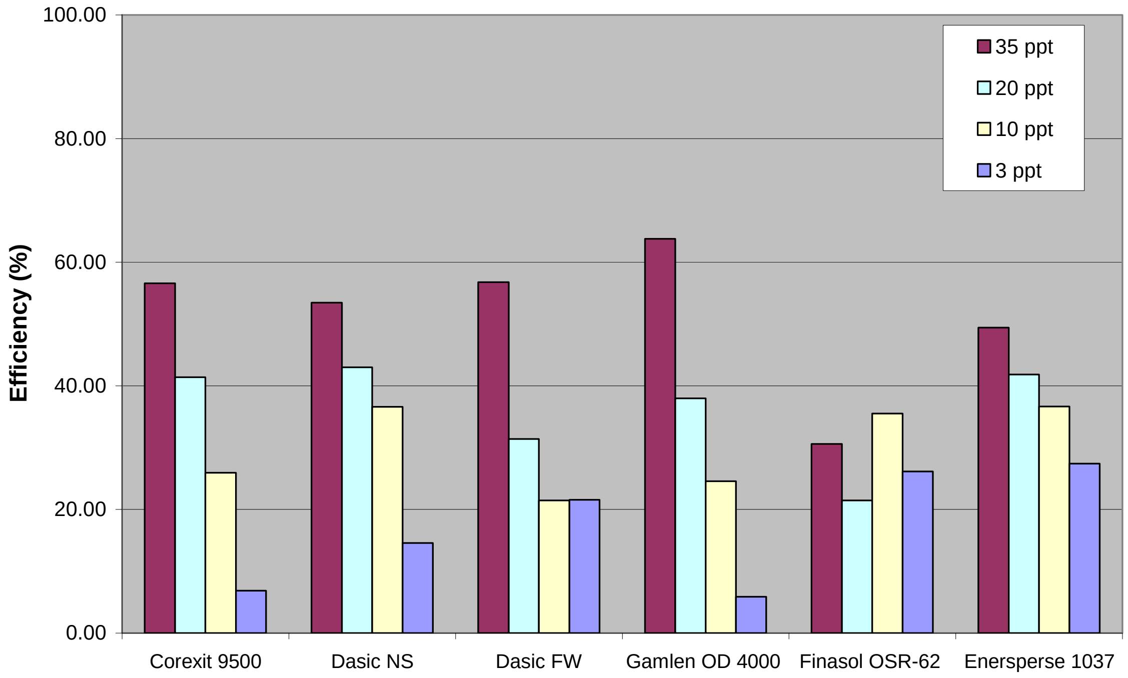

Figure 5.22: The effectiveness of various dispersants on the Troll B crude oil at 0°C.

At a salinity of 3.5 ppt, both Dasic NS and Corexit 9500 are among the four dispersants that show the highest effectiveness on Troll B crude oil and show a very similar performance. Both dispersants show a rapid decrease in effectiveness with decreasing salinity.

The physical properties of the dispersant can limit the functionality of some dispersant application systems at low temperatures. The viscosity of the tested dispersants is presented below in Figure 5.23.

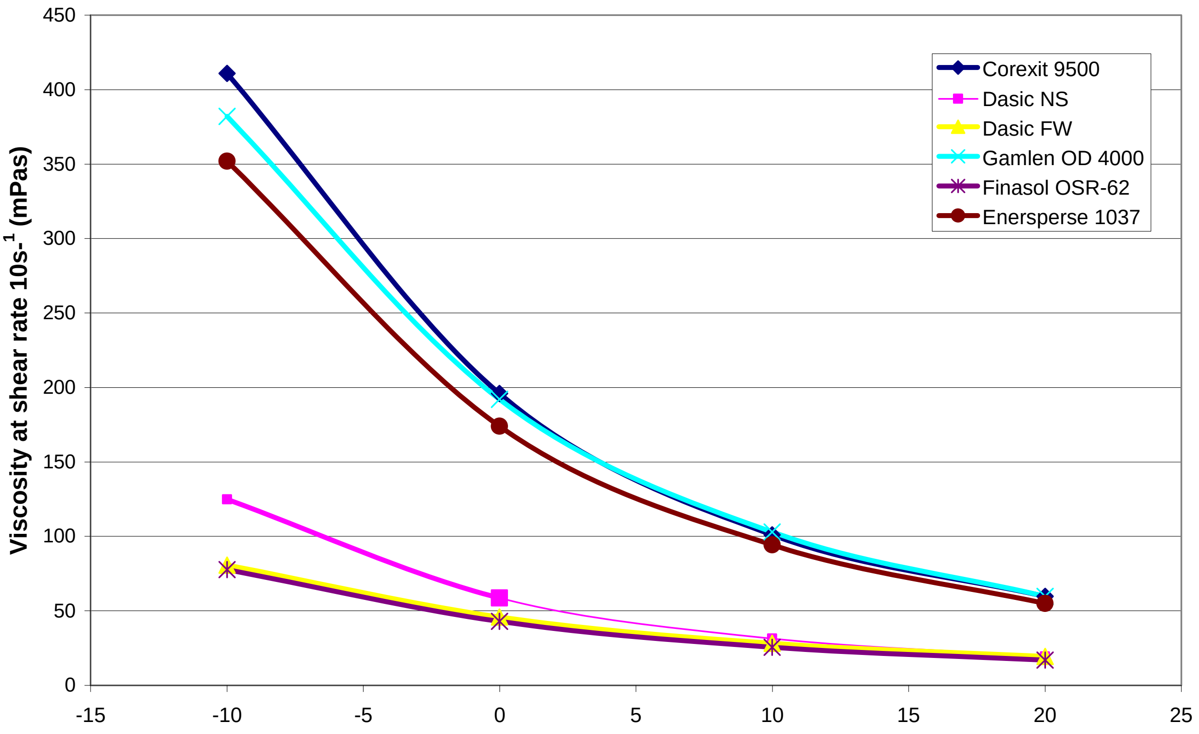

Figure 5.23: Viscosity of the tested dispersants as a function of temperature.

As shown in Figure 5.23 above, the viscosity profiles for Dasic NS and Corexit 9500 are very different. The high viscosity of Corexit 9500 (approx. 200 cP or mPas at 0ºC) could influence both spray pattern and capacity if the dispersant reservoir and pump are not kept insulated/heated during operation.

Prior to the planned start of the series of meso-scale weathering and dispersibility testing of different oils under different ice conditions/coverage, some specific seawater salinity measurements under simulated spring thawing conditions in a flume at SINTEF were taken (see technical memo by Daling and Brandvik, March, 2007). The purpose of this was to look at 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. This ice thawing study showed that only under totally static conditions in the flume could a significant reduction of salinity in the top 10-15 cm (in the same thickness area as the initial ice thickness) be built up, which was easily broken again under very gentle “swell” movements in the flume. Based on the results obtained from this study, it was not expected that any gradient of salinity would be generated during the planned meso-scale flume experiments, even with the lowest turbulence setting conditions selected with the highest ice conditions. It was therefore suggested to use a high performance “marine” dispersant, and Corexit 9500 was selected for further dispersant testing in this study.

5.2.11 Dispersibility tests on the napthenic oil, Troll B

Due to its napthenic character, Troll crude and its residue show a very low pour point (Table 5.1). Consequently, the Troll emulsions show a low elastic character (i.e. will not solidify due to its low wax content and a very low pour-point, see table 5.1) with viscosities less than 9.000 cP, even for the most weathered emulsion (see, e.g. Figure 5.5), which is important to take into account when discussing dispersibility results.

Figure 5.24 and 5.25 summarise all the MNS test results from all five experiments with Troll B crude. Based on previous standard weathering and dispersibility studies with Troll crude under simulated North Sea conditions (Strøm-Kristiansen et al. 1995 and Leirvik, 2005), the dispersibility borders/limits have been defined as:

- Good dispersibility: < 3000 cP
- Reduced dispersibility: 3000-7000 cP
- Not dispersable: < 7000 cP

These specific borders for the Troll crude are based on another dispersant (Dasic NS), but also seem to fit fairly well for the dispersibility studies with ice present. Figure 5.24 shows that only the 3-day weathered sample from the 50% ice experiment which obtained a viscosity of ca. 8000 cP gives a low effectiveness (< 20%) with the MNS test. Emulsion samples in the area of 3000-7000 cP show a slight reduction in effectiveness that also fits well with previous studies undertaken in North Sea conditions. Based on these studies, the viscosity border for “not dispersible” for Troll crude using Corexit 9500 can be extended up to 10000 cP.

Figure 5.26 show also that there is a good correlation between FET testing and previous tests defines the dispersibility borders obtained.

Figure 5.27 summarises the *in situ* dispersant treatment at the termination of each experiment (see Figure 5.28 - Figure 5.32), showing that a maximum dispersibility was obtained with the 70% ice experiment. In this experiment, the viscosity of the emulsion ended at 4690 cP after seven days of weathering, which is a “good dispersible” emulsion when combined with the energy setting in the 70% experiment that generated sufficient energy to fulfil the dispersion process. For the low ice coverage experiments, some lower effectiveness was obtained by use of the *in situ* dispersant treatment (see, e.g. mass-balance figures 5.28 -5.30), likely due to high viscosity (see Table 5.2). In the 90% ice coverage experiment, an effectiveness of only 60% is likely, due to the very low turbulence conditions (only a slight swell). However, the more energetic MNS and the FET test show booth high dispersant effectiveness at the termination of the 90%-experiment.

This is in good agreement with the experiences and findings from the FEX 2009 trials (Daling et al., 2010) where the use of artificial turbulence by, e.g. vessel thrusters /water jet systems fulfilled the dispersion process of the Troll crude weathered for 6 days in high ice conditions.

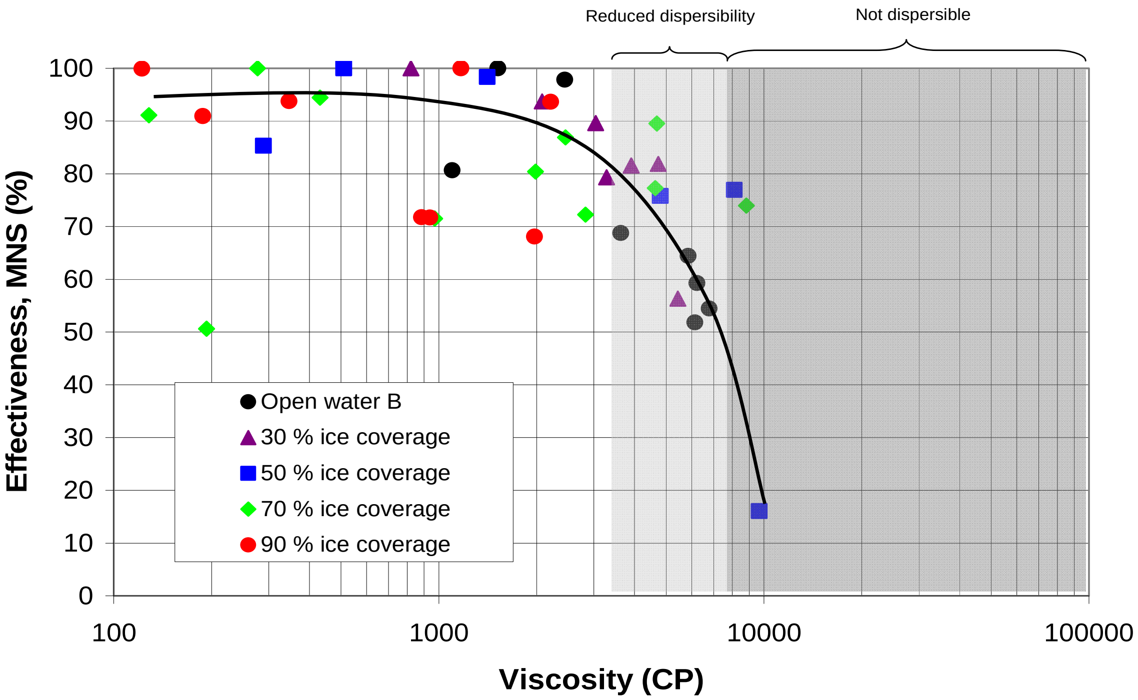

Figure 5.24: *Dispersibility in MNS of Troll B Crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion .*

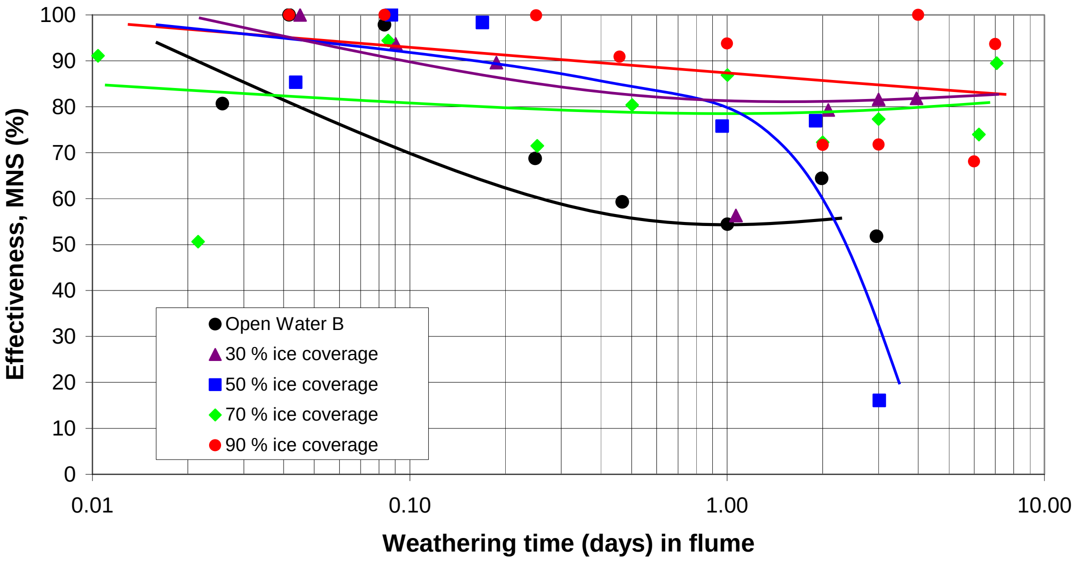

Figure 5.25: *Dispersibility in MNS of Troll B Crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. weathering time .*

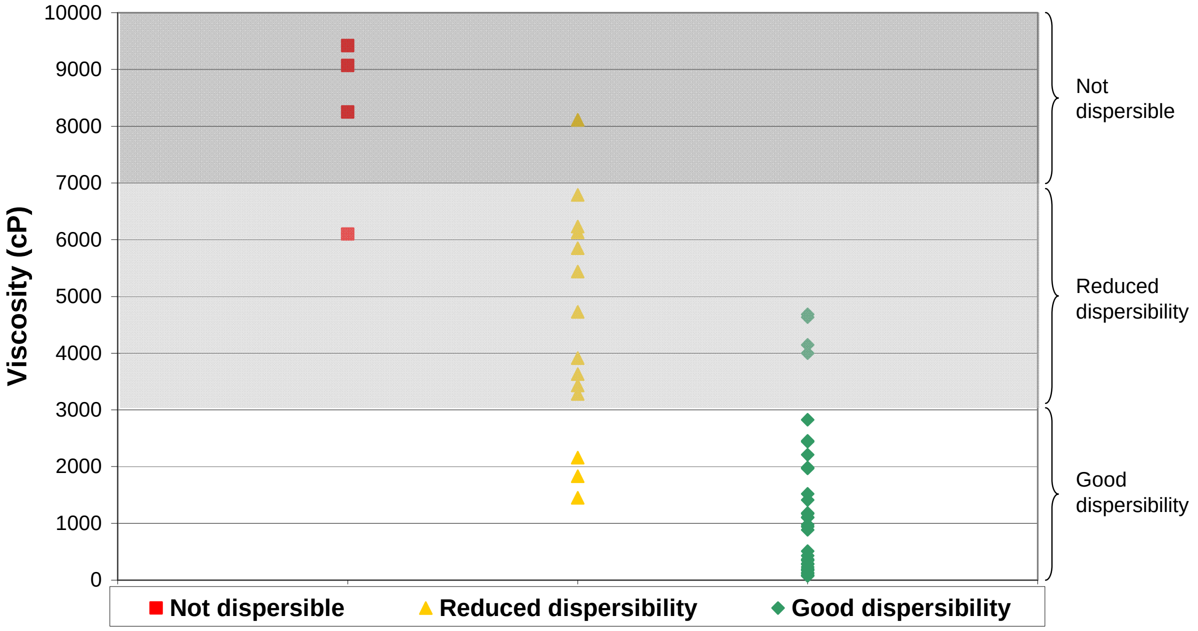

Figure 5.26: Dispersibility in field effectiveness test (FET) of Troll B Crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion and dispersibility limits (good, reduced dispersibility and not dispersible) as defined in previous standard dispersibility studies on a different Troll B crude oil batch.

Table 5.2: Effectiveness of in situ dispersion of the Troll B crude in the meso-scale flume at the end of each experiment.

Oil	**Ice coverage**	**Effectiveness of in situ dispersion (%)**	**MNS (%)**	**FET Cate-gory**	**Weathering (days)**	**Viscosity of emulsion at application of dispersant**
Troll B	Open water	32	52	Red	3	6130
	30%	63	82	Red	4	4730
	50%	78	16	Red	4	8050
	70%	100	90	Good	7	4690
	90%	59	94	Good	7	2200

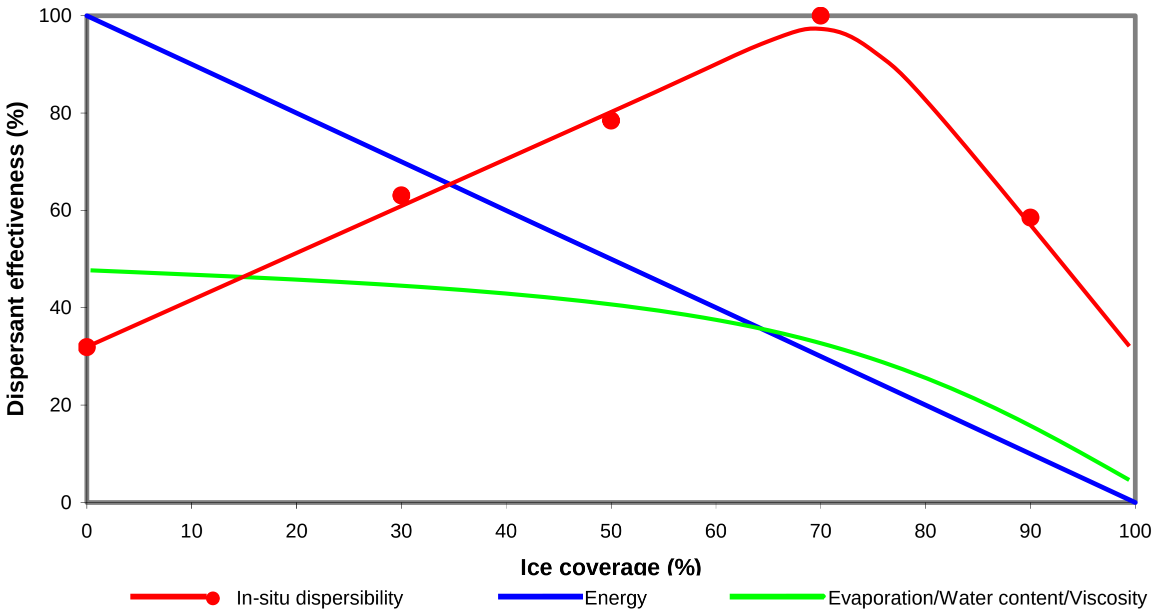

Figure 5.27: In situ dispersibility of Troll B crude oil in flume experiments with varying ice coverage, energy (waves) and weathering.

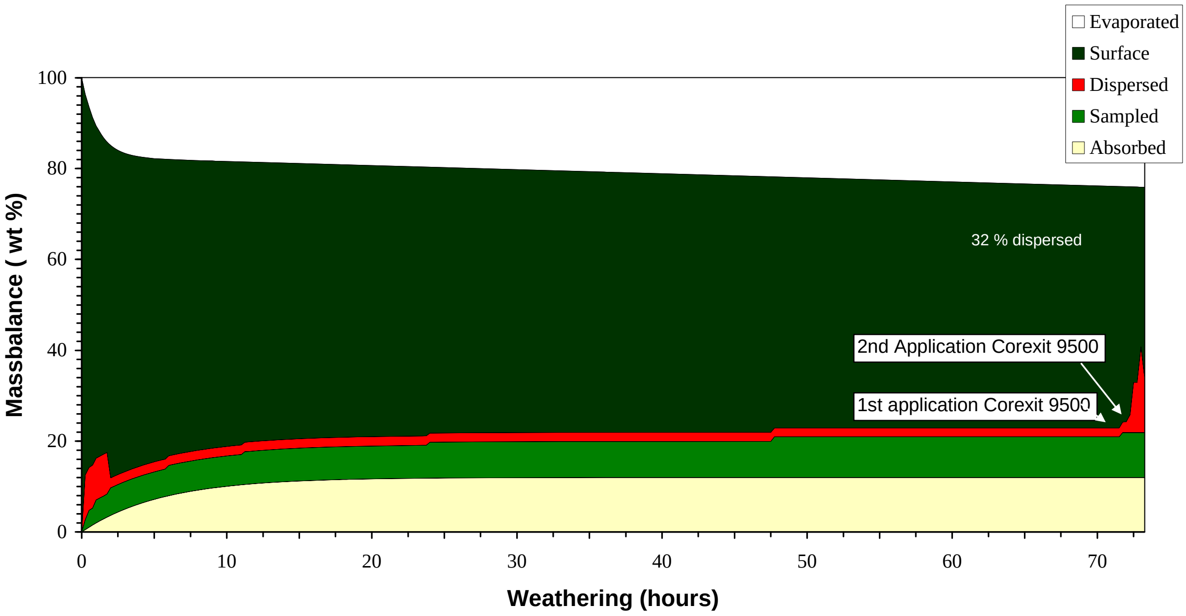

Figure 5.28: Mass balance in flume experiment performed with Troll B crude oil at -1.8°C, with no ice and application of Corexit 9500 at the end of the experiment.

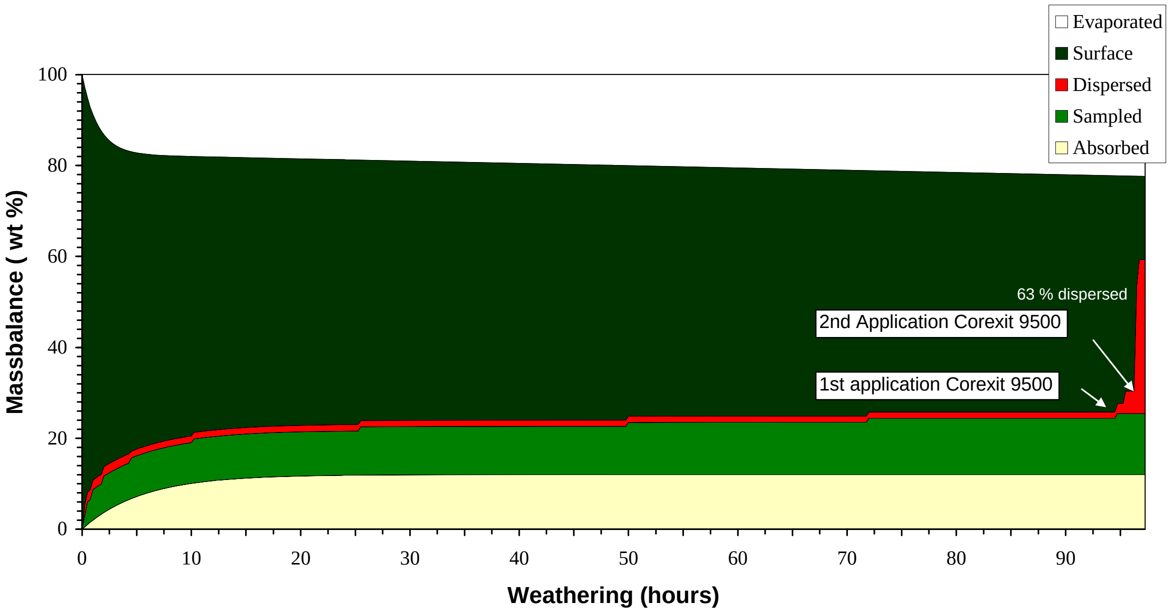

Figure 5.29: Mass balance in a flume experiment performed with Troll B crude oil at -1.8°C, with 30 % ice coverage and application of Corexit 9500 at the end of the experiment.

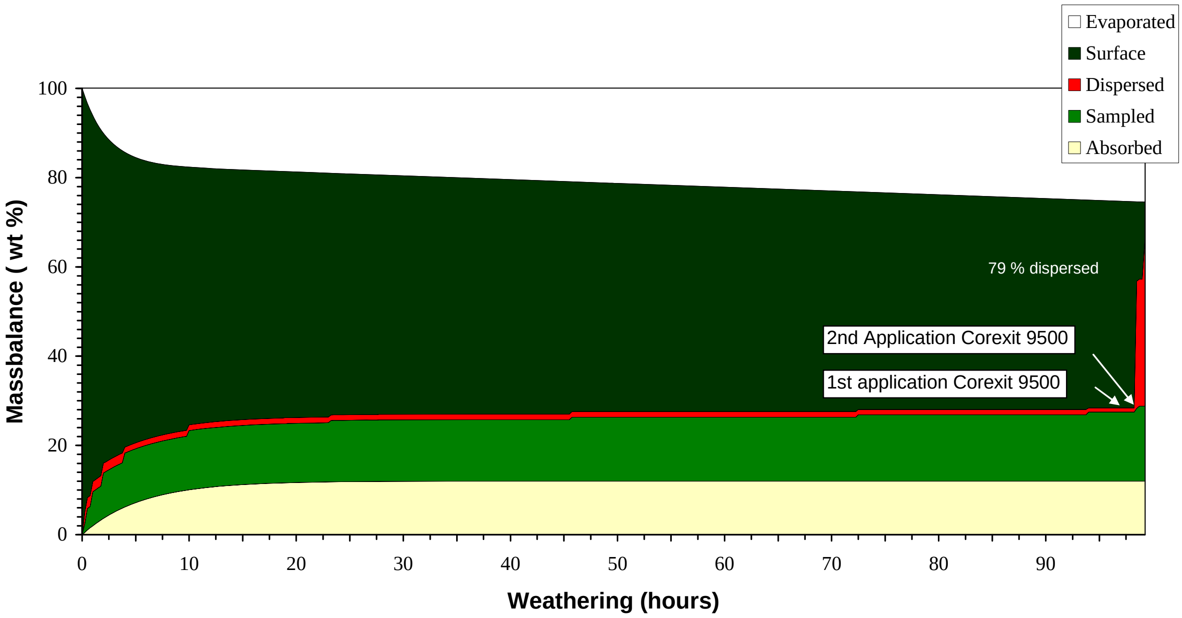

Figure 5.30: Mass balance in flume experiment performed with Troll B crude oil at -1.8°C, with 50 % ice coverage and application of Corexit 9500 at end of experiment.

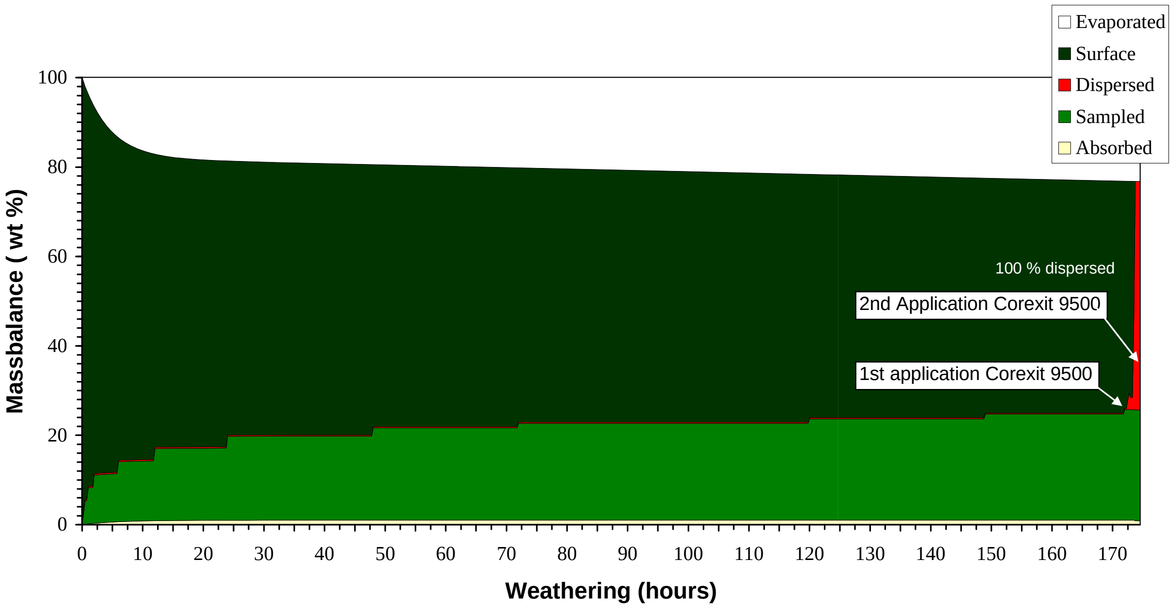

Figure 5.31: Mass balance in flume experiment performed with Troll B crude oil at -1.8°C, with 70 % ice coverage and application of Corexit 9500 at the end of the experiment.

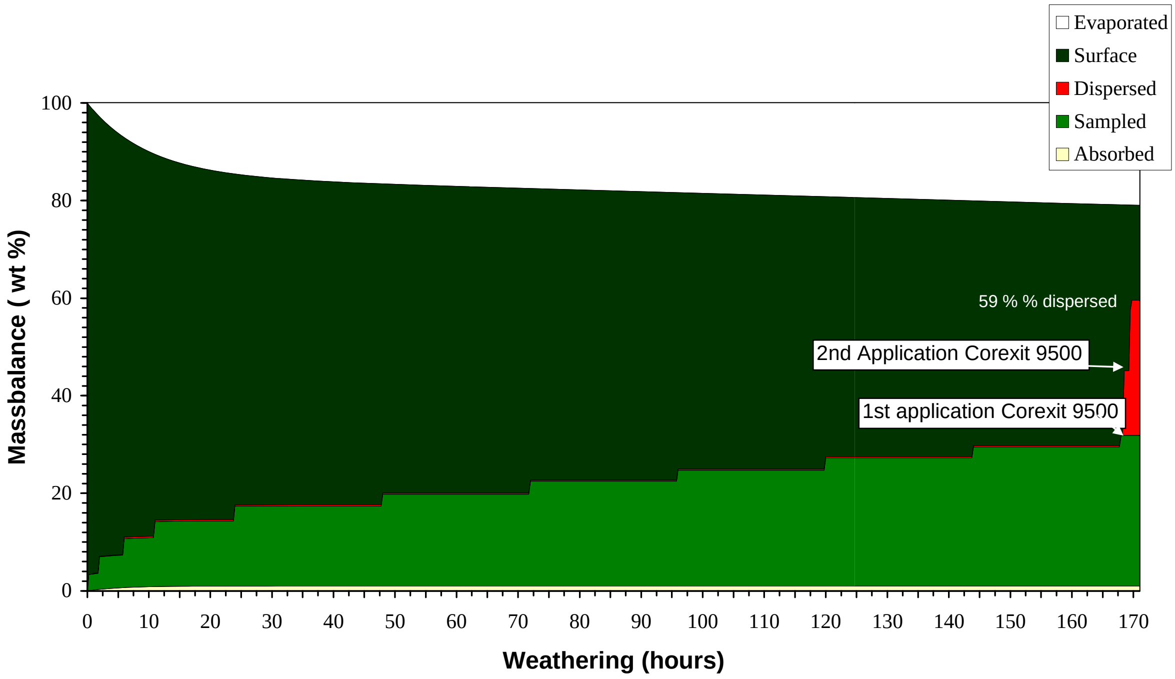

Figure 5.32: Mass balance in flume experiment performed with Troll B crude oil at -1.8°C, with 90 % ice coverage and application of Corexit 9500 at the end of the experiment.

5.2.12 Dispersibility tests on the paraffinic oil, Statfjord

As discussed in section 5.2.1 in regard to the experiments with Statfjord crude, the viscosities after three days of weathering were less than 4000 cP. In previous standard weathering and dispersibility studies with Statfjord crude under simulated North Sea conditions (e.g. Moldestad et al., 2001), the dispersibility borders /limits have been defined as:

- Good dispersibility: < 2000 cP
- Reduced dispersibility: 2000-12000 cP
- Not dispersable: > 12000 cP

As a result, the dispersibilty of the Statfjord emulsions weathered in ice using the MNS test (Figure 5.33. and 5.34) were all in the “good” and “reduced” dispersibility area.

Also for the Statfjord experiments, a good correlation between FET testing and previous studies in defining dispersibility borders was obtained (see Figure 5.35).

Figure 5.36 summarises the *in situ* dispersant treatment at the termination of each experiment, showing the highest dispersibility with the 0% ice experiment (ca. 90% effectiveness), with a slightly reduced effectiveness for the 30-70% ice experiment. In the 90% ice coverage experiment, an effectiveness of only 15% was achieved, likely due to the very low turbulence conditions (only a slight swell). However, the more energetic MNS test show a higher dispersant effectiveness and the FET test show “good” dispersibility at the termination of the 90%-experiment.

Based on the experiences from the FEX 2009 trials (Daling et al., 2010) using artificial turbulence by, e.g. vessel thrusters /water jet systems would likely fulfil the dispersion process of a Statfjord crude weathered for some days in high ice conditions.

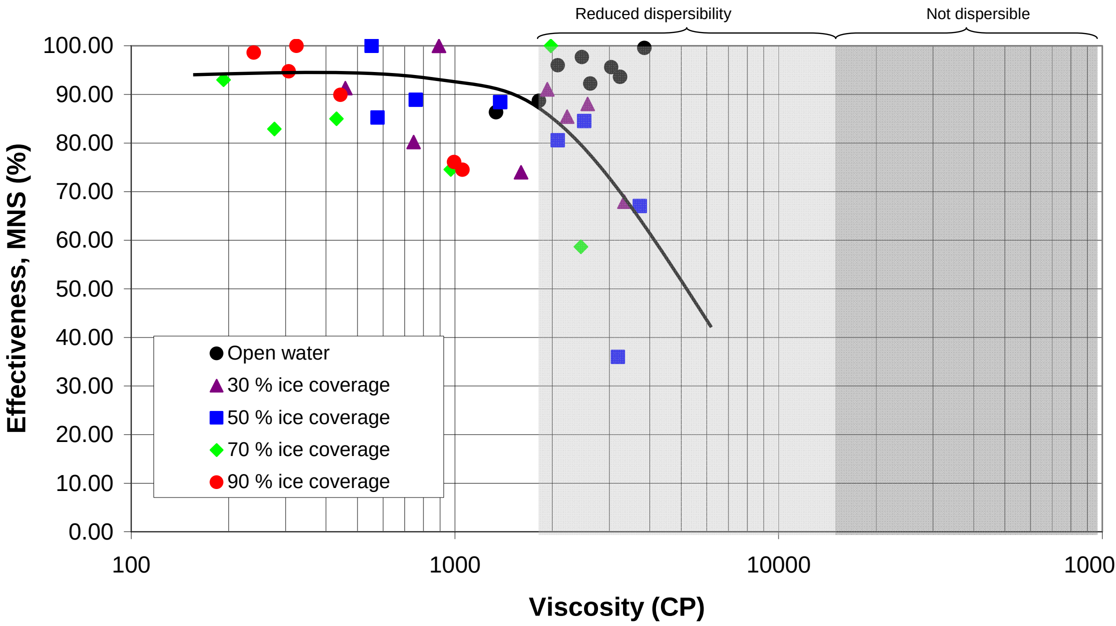

Figure 5.33: Dispersibility in MNS of Statfjord crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion.

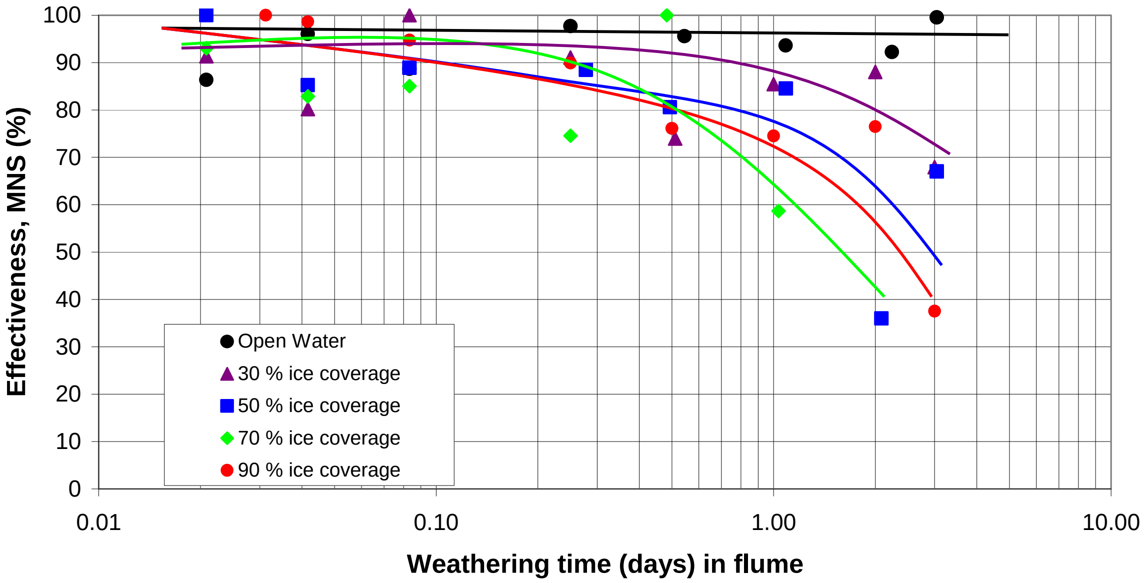

Figure 5.34: Dispersibility in MNS of Statfjord crude oil weathered from 15 minutes to 3 days in flume experiments with varying ice coverage vs. weathering time.

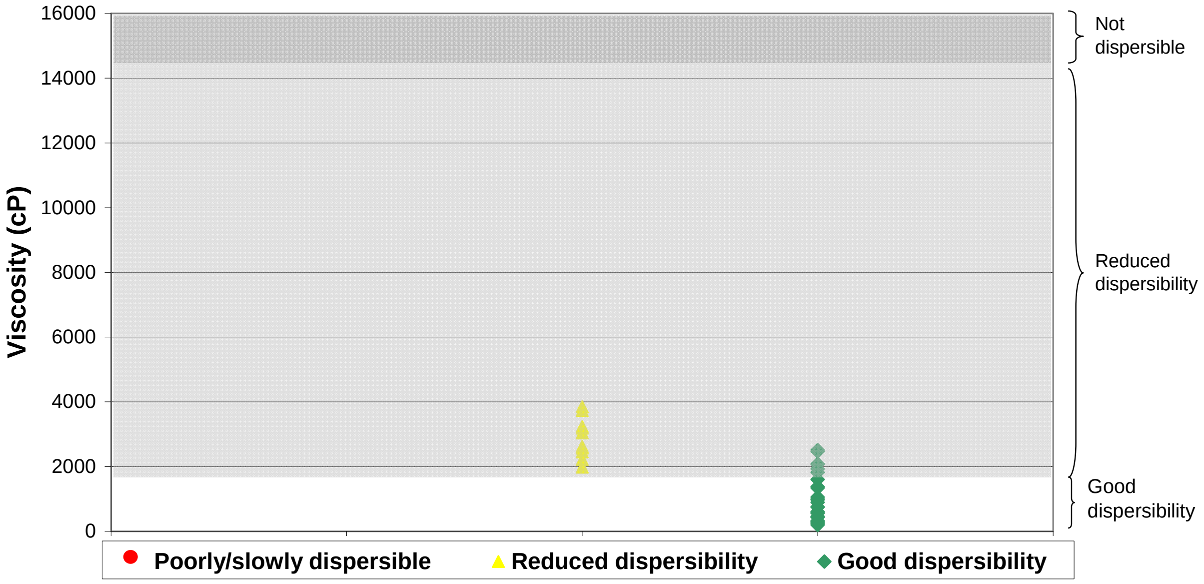

Figure 5.35: Dispersibility in field effectiveness test (FET) of Statfjord crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion and dispersibility limits (good, reduced dispersibility and not dispersible) defined in previous standard dispersibility studies on a different batch of Statfjord crude oil.

Table 5.3 Effectiveness of in situ dispersion of the Statfjord crude in the meso-scale flume at the end of each experiment.

Oil	**Ice coverage**	**Effectiveness of in situ dispersion (%)**	**MNS (%)**	**FET Cate-gory**	**Weathering (days)**	**Viscosity of emulsion at application of dispersant**
Statfjord	Open water	91	100	Red	3	3850
	30%	59	67	Red	3	3340
	50%	70	67	Red	3	3730
	70%	67	-	-	3	4630
	90%	15	38	Good	3	-

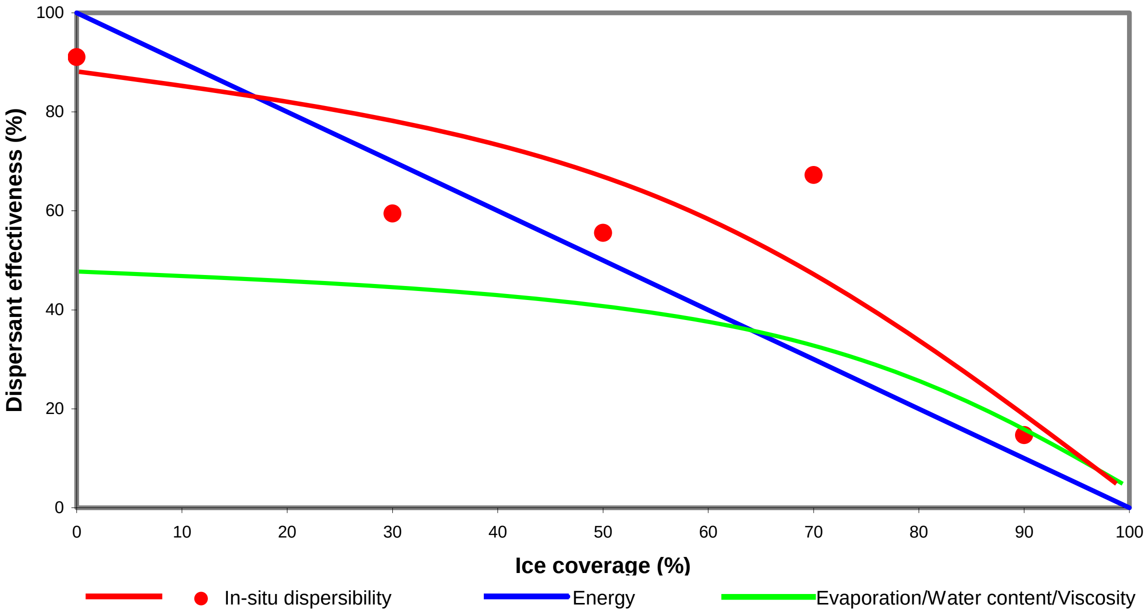

Figure 5.36: In situ dispersibility of Statfjord crude oil in flume experiments with varying ice coverage, energy(waves) and weathering.

5.2.13 Dispersibility tests on the asphaltenic oil, Grane

The dispersibility results of the asphaltenic and relatively viscous Grane crude (Figures 5.37 and 5.38) also fit well into previous standard weathering and dispersibility studies under simulated North Sea conditions (e.g. Støm-Kristiansen et al., 1997) where the dispersibility borders are defined as:

- Good dispersibility: < 12000 cP
- Reduced dispersibility: 12000-30000 cP
- Not dispersable: > 30000 cP

With a few exceptions, a fairly good correlation between FET testing and previous studies in defining dispersibility borders was obtained (see Figure 5.39).

The *in situ* dispersant treatment all showed a low dispersibility. For 0% and 50%, this can be explained by the high viscosity obtained at the termination of the experiment (ca. 30000 cP) which is in accordance to the defined viscosity border for the dispersibility of Grane crude. For the 90% ice coverage experiment, an effectiveness of only 10% was obtained on the emulsion of approximately 14000 cP, which is defined as a “reduced dispersible” emulsion. This is likely due to the very low turbulence conditions (only a slight swell). However, the more energetic MNS test show 100% effectiveness and the FET test show “reduced” dispersibility at the termination of the 90%-experiment.

Based on the experiences from the FEX 2009 trials (Daling et al., 2010) using artificial turbulence by, e.g. vessel thrusters /water jet systems would likely fulfil the dispersion process of a Grane crude weathered for some days in high ice conditions.

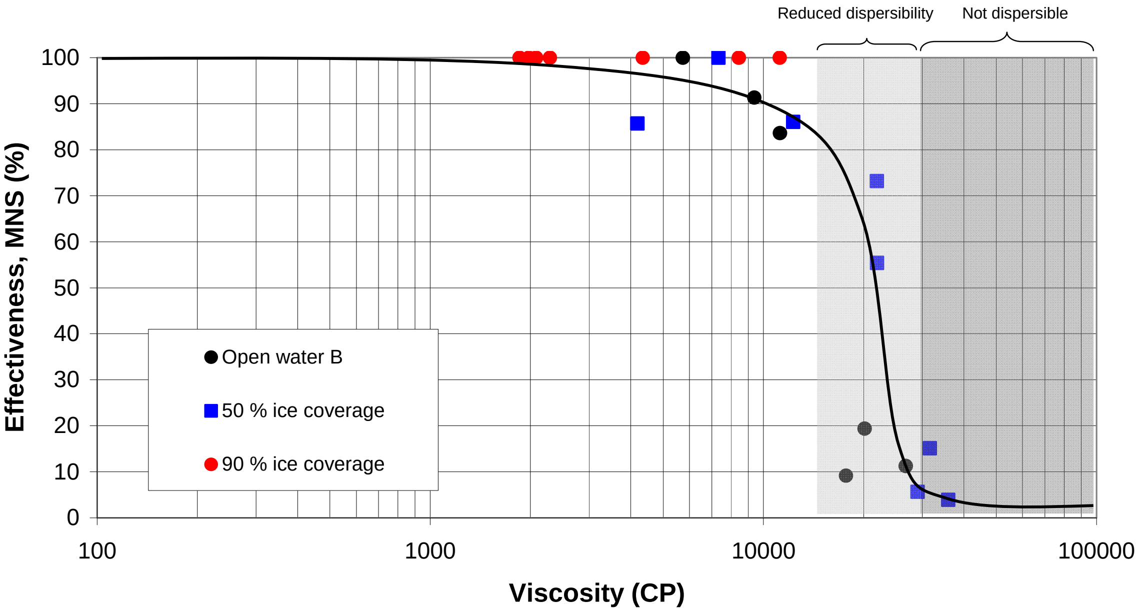

Figure 5.37: Dispersibility in MNS of Grane crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion.

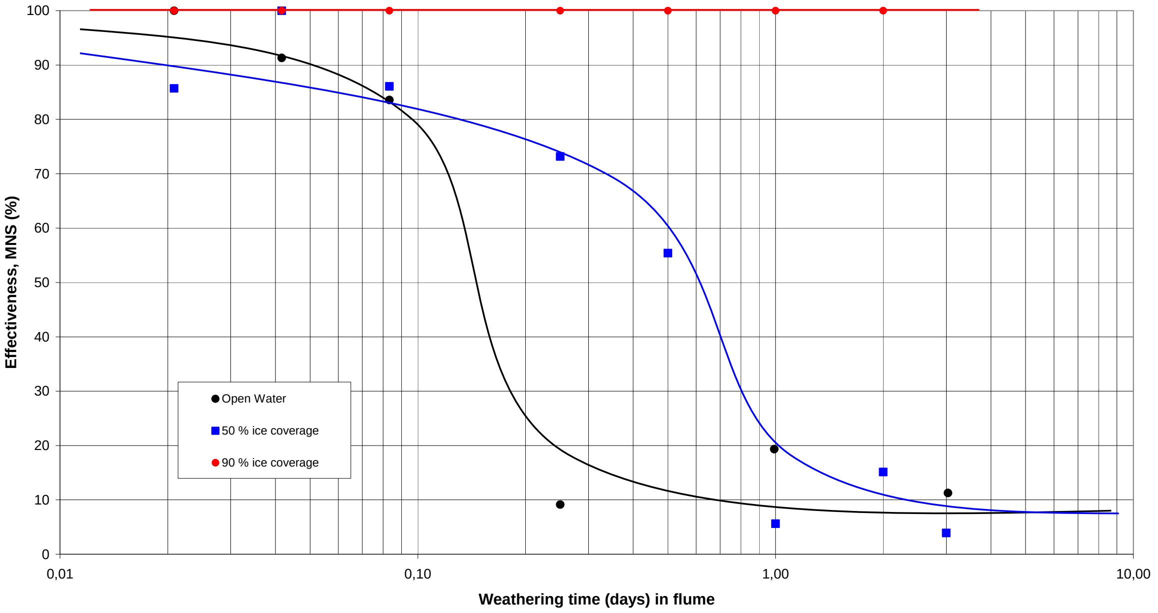

Figure 5.38: Dispersibility in MNS of Grane crude oil weathered from 15 minutes to 3 days in flume experiments with varying ice coverage vs. weathering time.

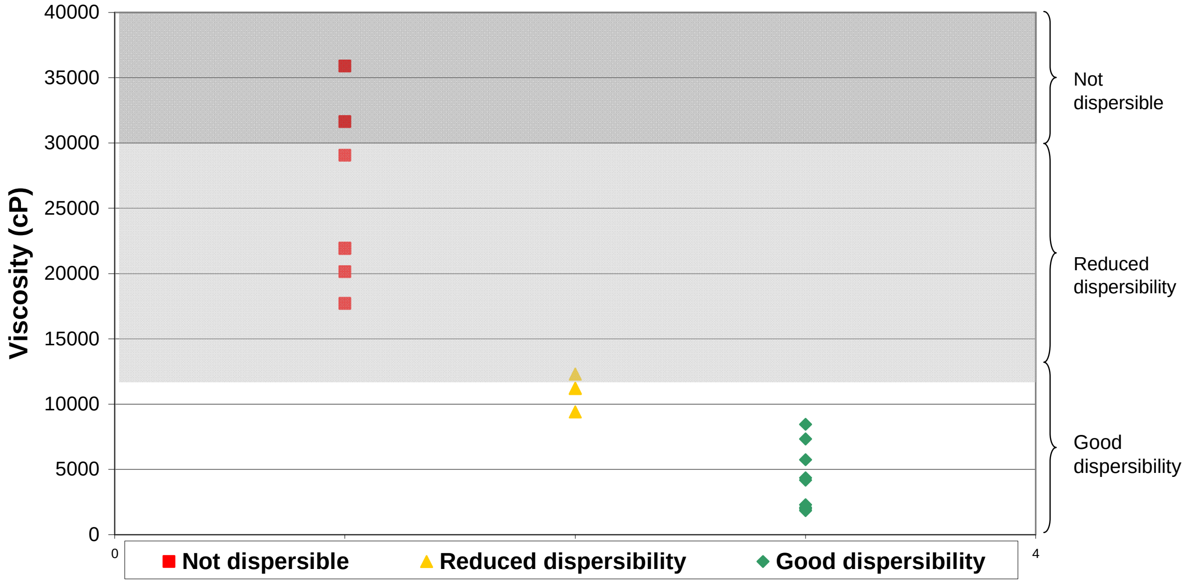

Figure 5.39: Dispersibility in field effectiveness test (FET) of Grane crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion and dispersibility limits (good, reduced dispersibility and not dispersible) defined in previous standard dispersibility studies on a different batch of Grane crude oil.

Table 5.4: Effectiveness of in situ dispersion of the Grane crude in the meso-scale flume at the end of each experiment.

Oil	**Ice coverage**	**Effectiveness of in situ dispersion (%)**	**MNS (%)**	**FET Cate-gory**	**Weathering (days)**	**Viscosity of emulsion at application of dispersant**
Grane	Open water	5	11	Not	3	26753
	50%	3	4	Not	3	35894
	90%	7	100	Red	3	13871

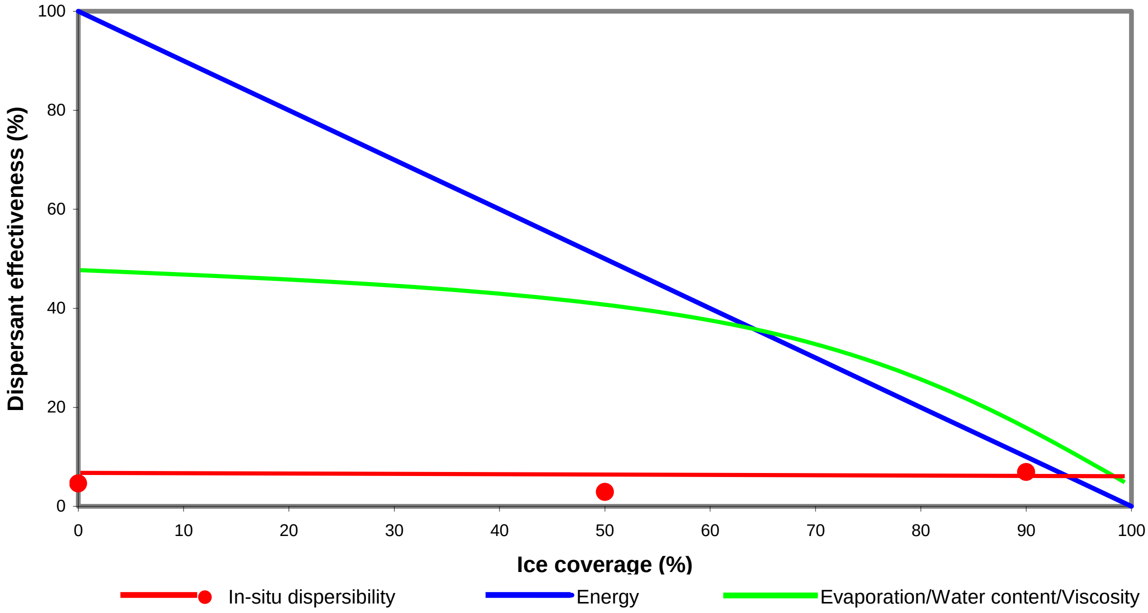

Figure 5.40: In situ dispersibility of Grane crude oil in flume experiments with varying ice coverage, energy(waves) and weathering.

5.2.14 Dispersibility tests on the waxy oil, Norne

The dispersibility tests with Norne crude all gave a “cluster” of relatively low effectiveness with the MNS test (between 2-30% effectiveness, see Figures 5.41 and 5.42). In addition, the in situ treatment at the termination of the experiments gave very low effectiveness, which was not surprising based on previous knowledge of the dispersibility of such waxy crude. At low temperatures, Norne crude becomes partly solidified, meaning that the migration of the dispersant droplets in the solidified oil/emulsion become very low. Also, the more energetic MNS test gave fairly low effectiveness at the termination of the 90%-experiment. The simple FET method seems to give less reliable values for the dispersibility of such waxy crude.

Based on these studies, the potential for using dispersants on such waxy crude in cold/arctic conditions is therefore considered to be generally low. Even by using artificial turbulence after the dispersant treatment would likely given limited effect, because the dispersant droplets simply is not able to penetrate into the partly solidified oil phase.

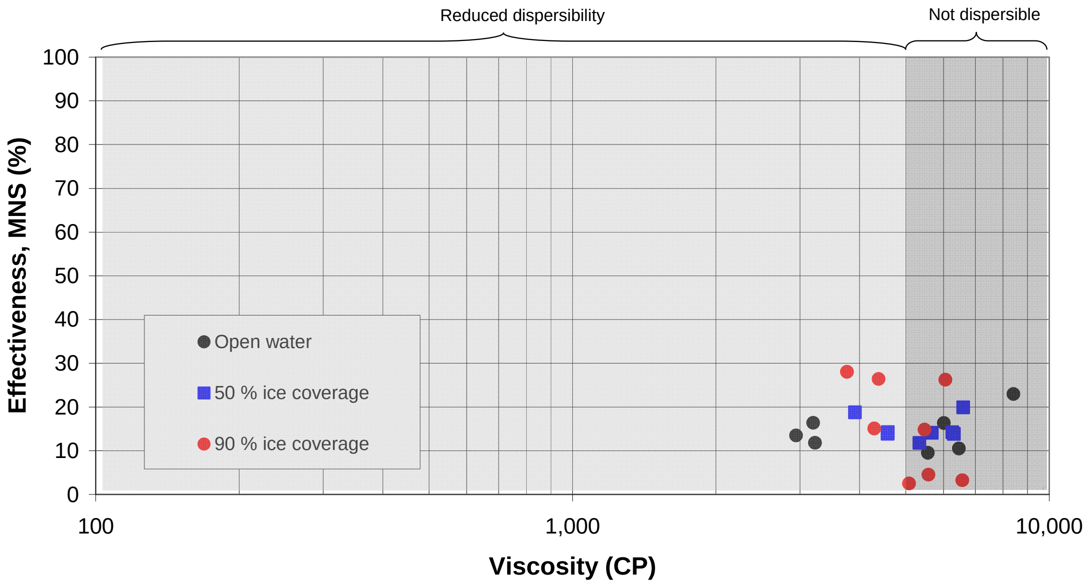

Figure 5.41: Dispersibility in MNS of Norne crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion.

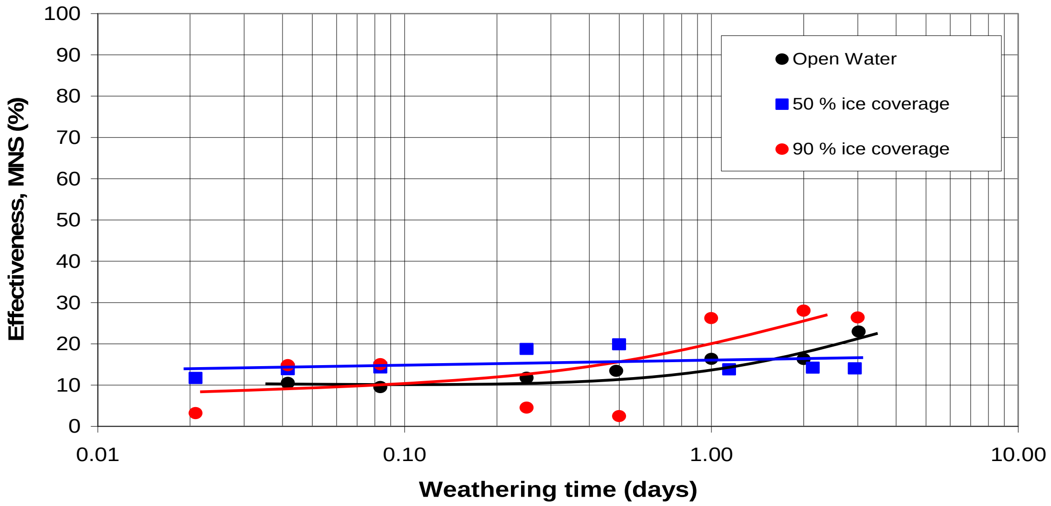

Figure 5.42: Dispersibility in MNS of Norne crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. weathering time.

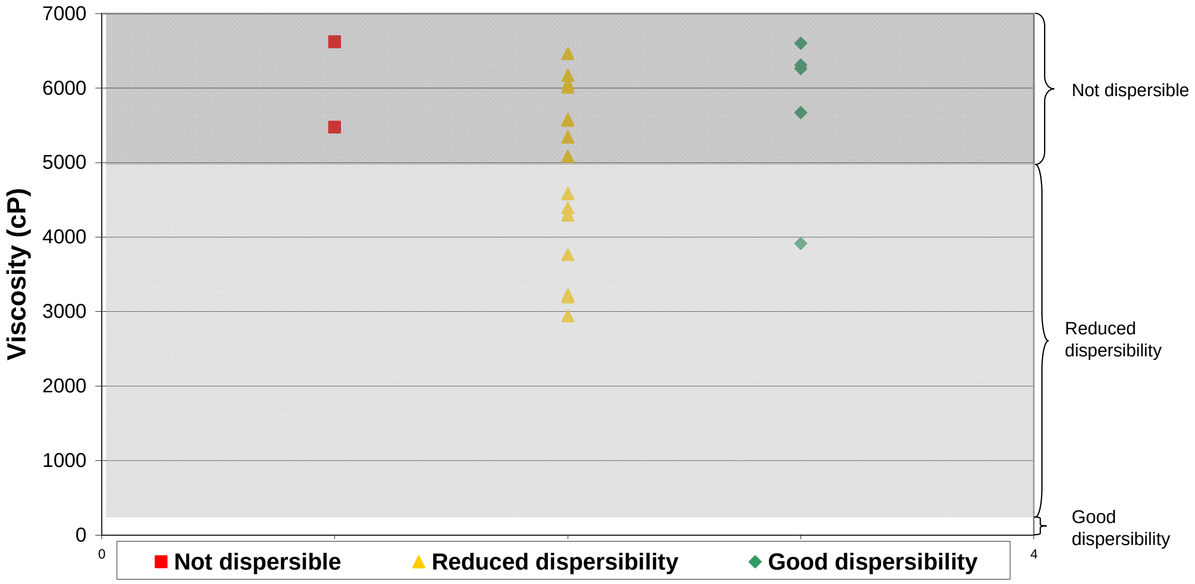

Figure 5.43: Dispersibility in field effectiveness test (FET) of Norne crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion and dispersibility limits (good, reduced dispersibility and not dispersible) defined in previous standard dispersibility studies on a different batch of Norne crude oil.

Table 5.5 : Effectiveness of in situ dispersion of the Norne crude in the meso-scale flume at the end of each experiment.

Oil	**Ice coverage**	**Effectiveness of in situ dispersion (%)**	**MNS (%)**	**FET Cate-gory**	**Weathering (days)**	**Viscosity of emulsion at application of dispersant**
Norne	Open water	0	23	Good	3	8410
	50%	0	14	Good	3	5670
	90%	3	26	Red	2,93	6170

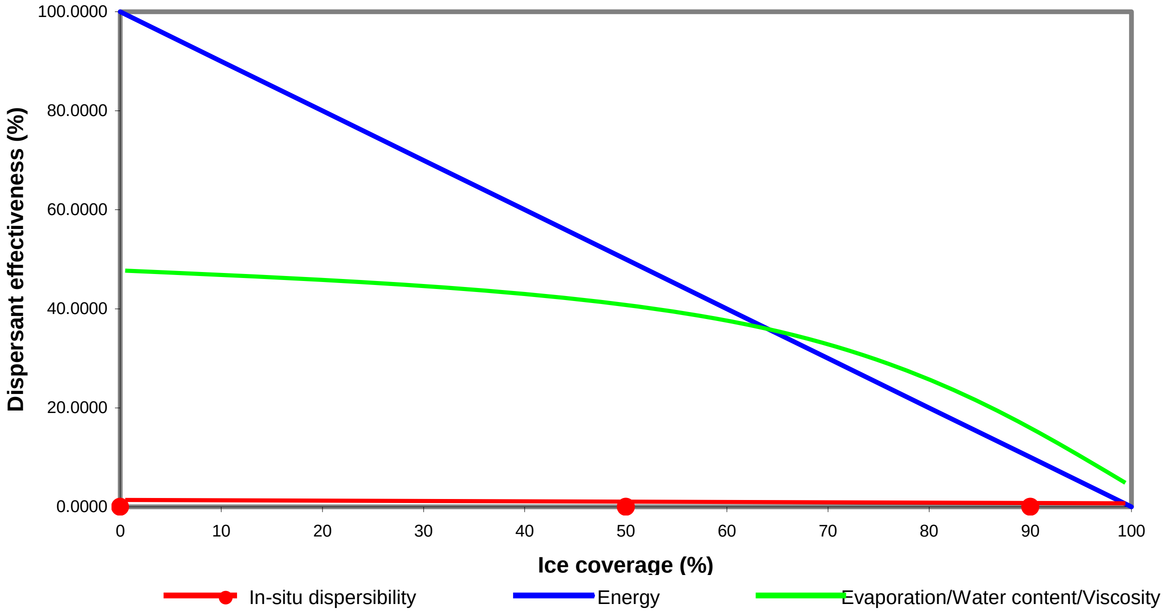

Figure 5.44: In situ dispersibility of Norne crude oil in flume experiments with varying ice coverage, energy (waves) and weathering.

5.2.15 Dispersibility tests on the light oil, Kobbe

Kobbe crude is (as discussed in Chap. 5.2.6) a light, paraffinic crude. When weathering at sea/in ice, a high evaporative loss results in an unstable emulsion with a low viscosity (< 2500 cP). At the same time, this emulsion has an semi-solid character, due to the a high pour point.

The MNS tests gave a relatively wide spreading in the weathering experiments with Kobbe. the 0% ice experiment yielded a significantly lower effectiveness (between 20-40%) compared with the 50 and 90% experiments (see Figures 5.45 and 5.46).

The simple FET method seems to give a limited yet reliable value on the dispersibility for such a light, waxy crude. Due to the relative high energy present in the FET test, all the measurements gave a "good" dispersibility (see Figure 5.47). This is in contrast to the in situ treatment at the end of the experiments which gave very negative results for all three Kobbe experiments (see Figure 5.48). From previous experiences with the dispersibility of such waxy emulsions, we have seen that quite a high energy level is required in order to disperse the emulsion after the dispersant treatment. The energy in the flume is therefore too low to fulfil the dispersion process after the in situ treatment with Kobbe crude.

Based on these laboratory studies and the experiences from the FEX 2009 trials (Daling et al., 2010), the potential for using dispersants on Kobbe emulsion crude in cold/Arctic conditions is present as long as a good dispersant application is followed by artificial turbulence by, e.g. vessel thrusters/water jet systems in order to complete the dispersion process (Daling et al., 2010).

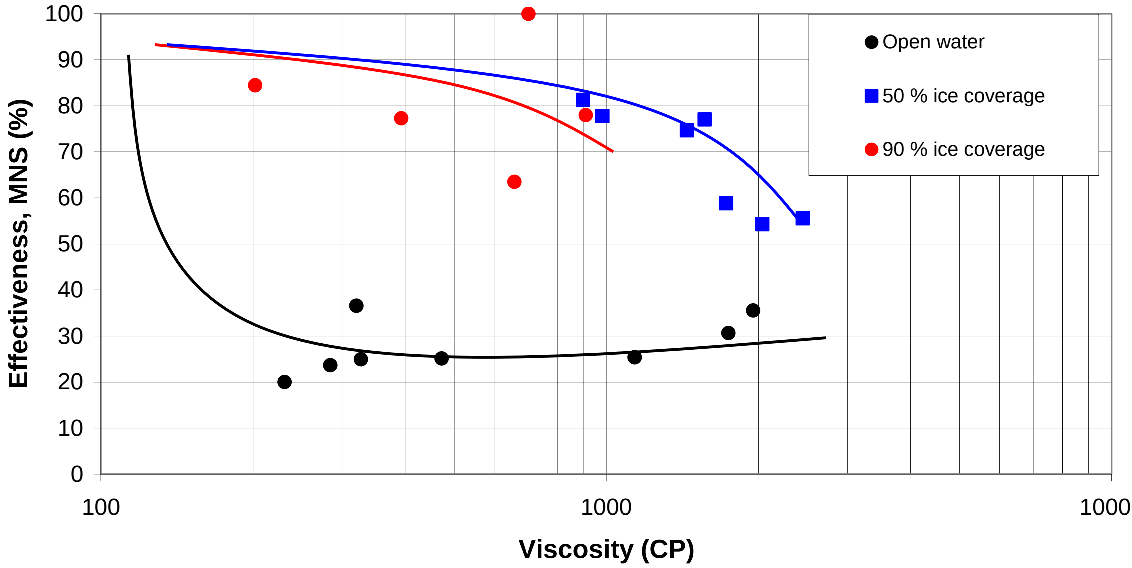

Figure 5.45: Dispersibility in MNS of Kobbe crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion.

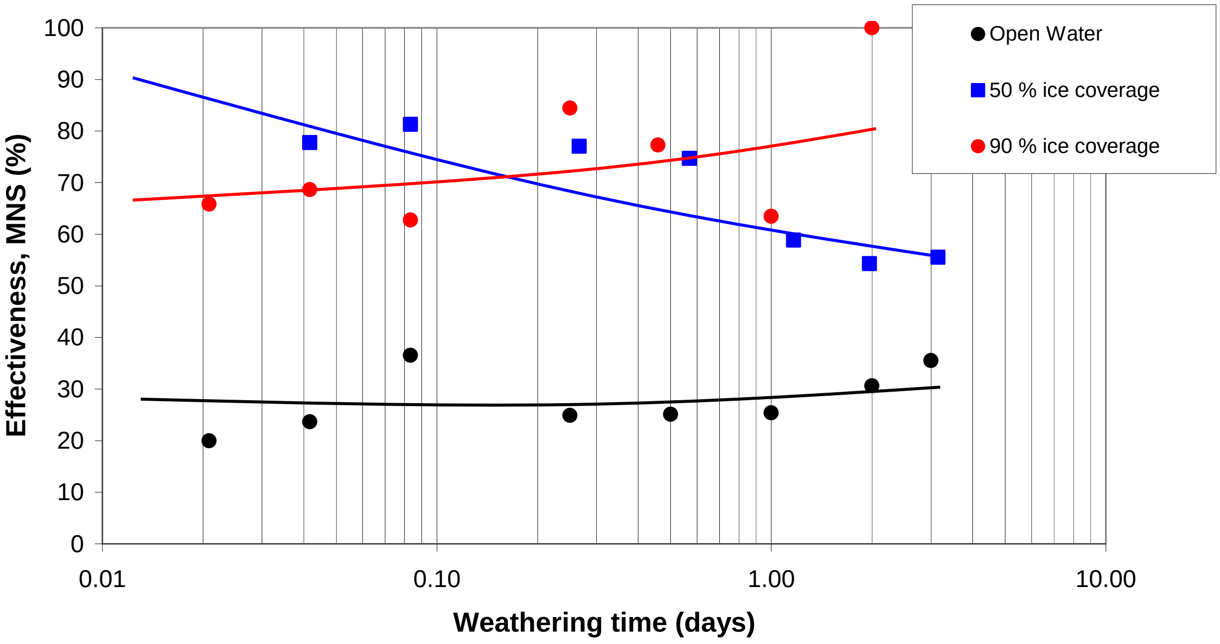

Figure 5.46: Dispersibility in MNS of Kobbe crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. weathering time.

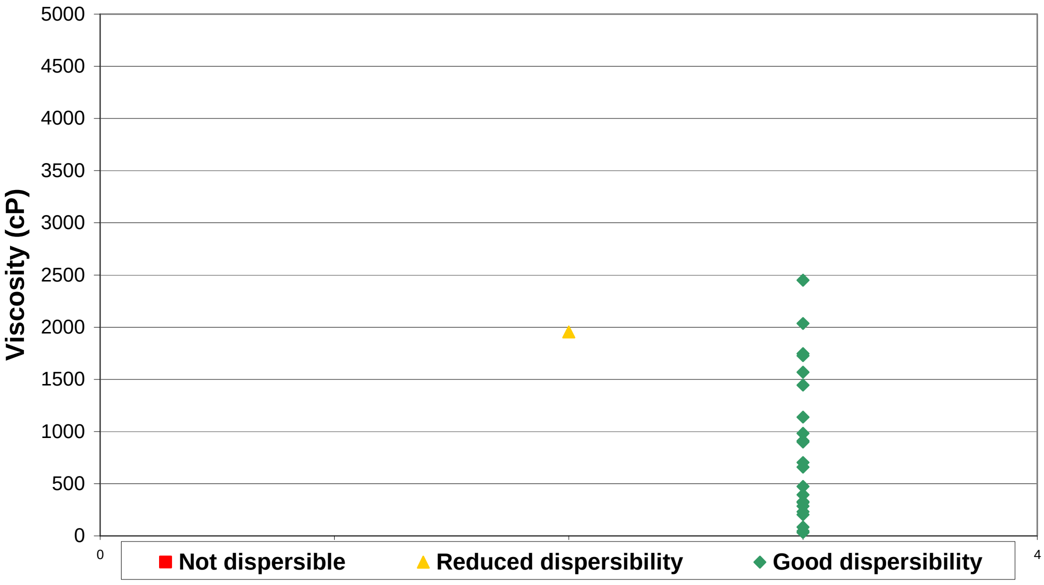

Figure 5.47: Dispersibility in field effectiveness test (FET) of Kobbe crude oil weathered from 15 minutes to 7 days in flume experiments with varying ice coverage vs. viscosity of emulsion and dispersibility limits (good, reduced dispersibility and not dispersible) defined in previous standard dispersibility studies on a different batch of Kobbe crude oil.

Table 5.6 : Effectiveness of in situ dispersion of the Kobbe crude in the meso-scale flume at the end of each experiment.

Oil	**Ice coverage**	**Effectiveness of in situ dispersion (%)**	**MNS (%)**	**FET Cate-gory**	**Weathering (days)**	**Viscosity of emulsion at application of dispersant**
Norne	Open water	0	35	Good	3	1950
	50%	0	55	Good	3	2450
	90%	0	100	Good	3	911

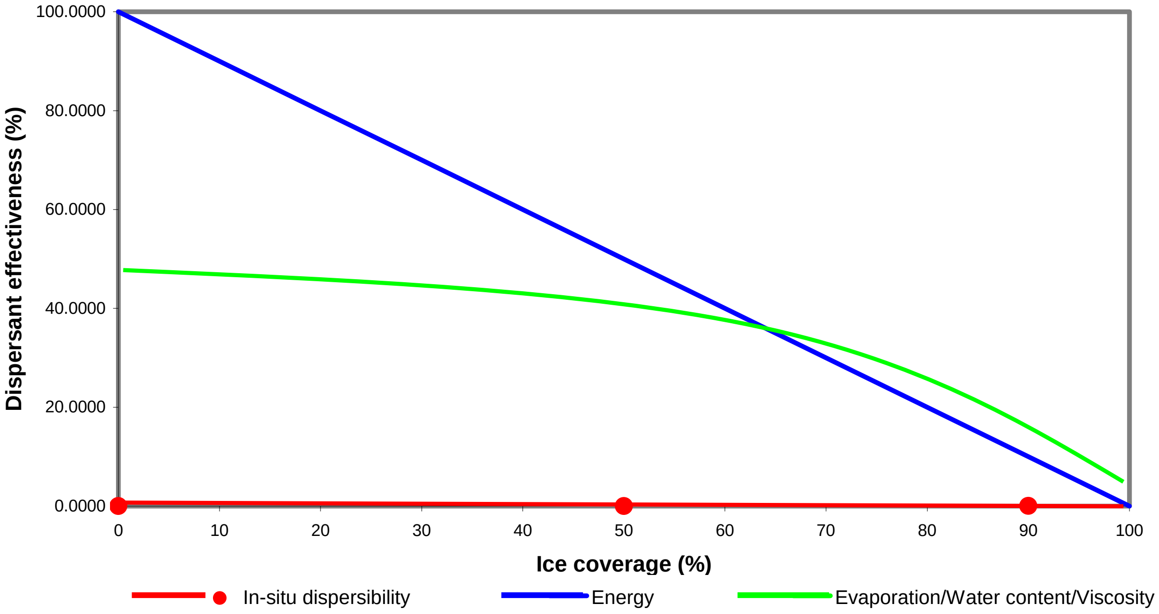

Figure 5.48: In situ dispersibility of Kobbe crude oil in flume experiments with varying ice coverage, energy (waves) and weathering.

5.2.16 All oils - dispersibility versus viscosity and weathering time

Figures 5.49 and 5.50 below compare dispersibility (MNS test) as a function of viscosity and weathering time for all five oil types at 0, 50 and 90% ice coverage.

In Figure 5.49, we have attempted to put the “span” of dispersibility data for the various oils into “clusters” as a function of viscosity. We see that these “clusters” are very different for the different crude oils, and also that for some of the crude oils there is some significant “drifting” in the dispersibility clusters. One general trend is the reduced viscosity when weathering in high ice coverage that may lead to a significant change (increase) in dispersibility (dispersant effectiveness), particularly for crude oils such as Grane, Troll and Kobbe in high ice coverage. Statfjord and Troll crude both generally show a fairly high performance with the MNS test, while the Norne crude demonstrates its low potential for dispersibility in cold areas both with and without the presence of ice.

In Figure 5.50, we have summarised the dispersibility trends as a function of weathering time for the various ice conditions in the flume basin. For some of the crude oils like Grane and Troll, there is a significant increase in both dispersant effectiveness and the dispersibility “time window” with increasing ice coverage. This is probably due to a slower increase in viscosity at high ice coverage for these two oils. Also for Kobbe, the dispersant effectiveness in the MNS test seems to increase with increasing ice coverage, and there is no limit in the “time window” within the experimental weathering time of three days. For Statfjord, there seems to be a slight decrease in effectiveness after 2-3 days of weathering with increasing ice coverage, likely because of its paraffinic character with a relatively high wax content that may precipitate with high ice and calm turbulence-like conditions. Again, the Norne crude shows a low dispersibility at any weathering stage both with and without ice present due to its high properties of elasticity in cold weather conditions.

The dispersibility results from the meso-scale weathering studiesm show that:

- The viscosity boarders for dispersibility established for the specific oils based on previous weathering and dispersibility studies in open water conditions, can be used also for ice-covered conditions
- Of the five crudes tested in this study, all except the waxy Norne crude will have a potential to be effectively dispersed when treated with dispersant when spilled in ice-covered water
- Due to reduced weathering, the “time window” for use of dispersant will be larger for these oils in ice-coverage water compared to open water
- In high ice coverage (above 50 -70 % ice) additional mixing energy is required in order to fulfil the dispersion process after the dispersant treatment

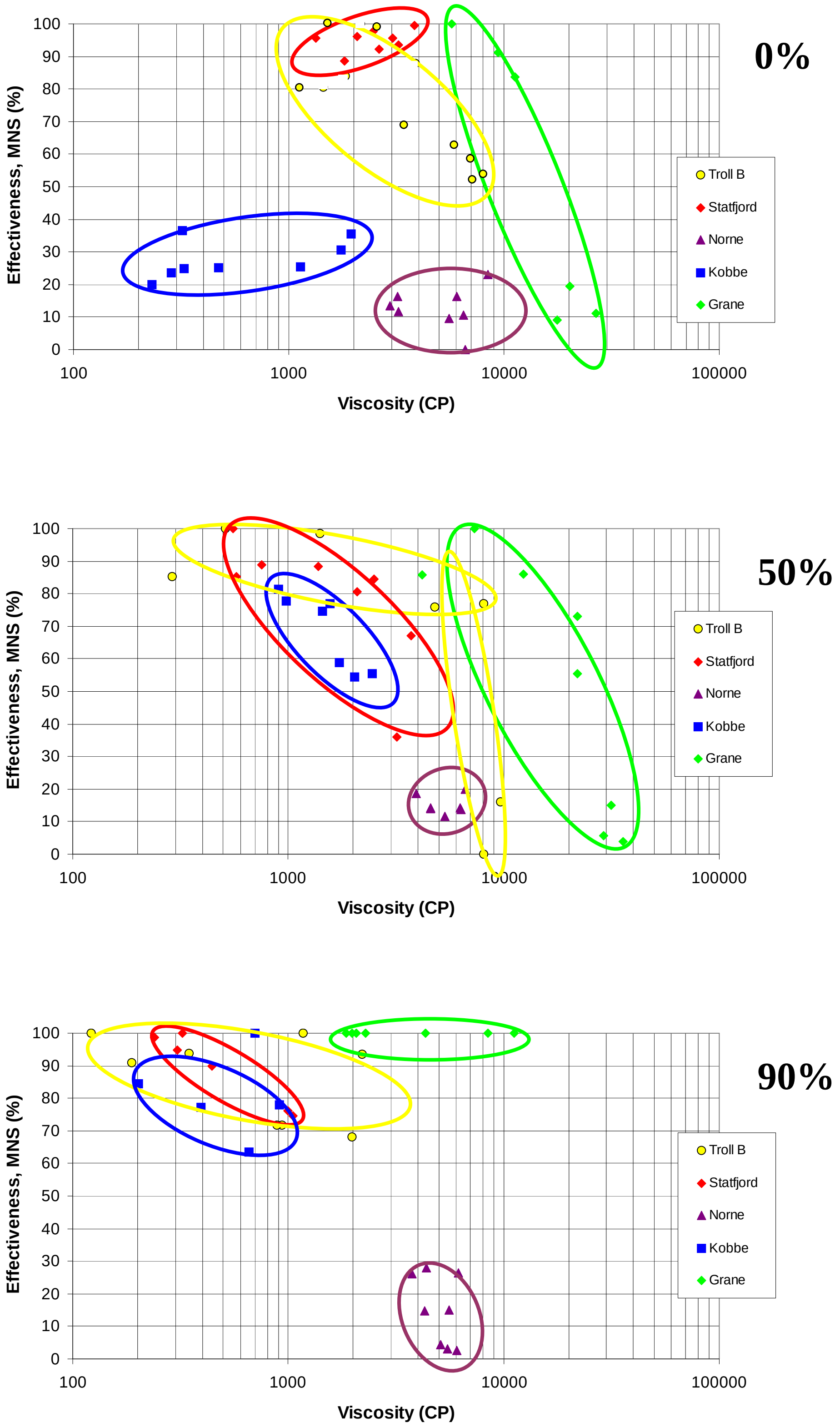

Figure 5.49: Dispersibility for all oil types at 0%, 50% and 90% ice coverage, as measured on weathered samples from flume experiments versus emulsion viscosity.

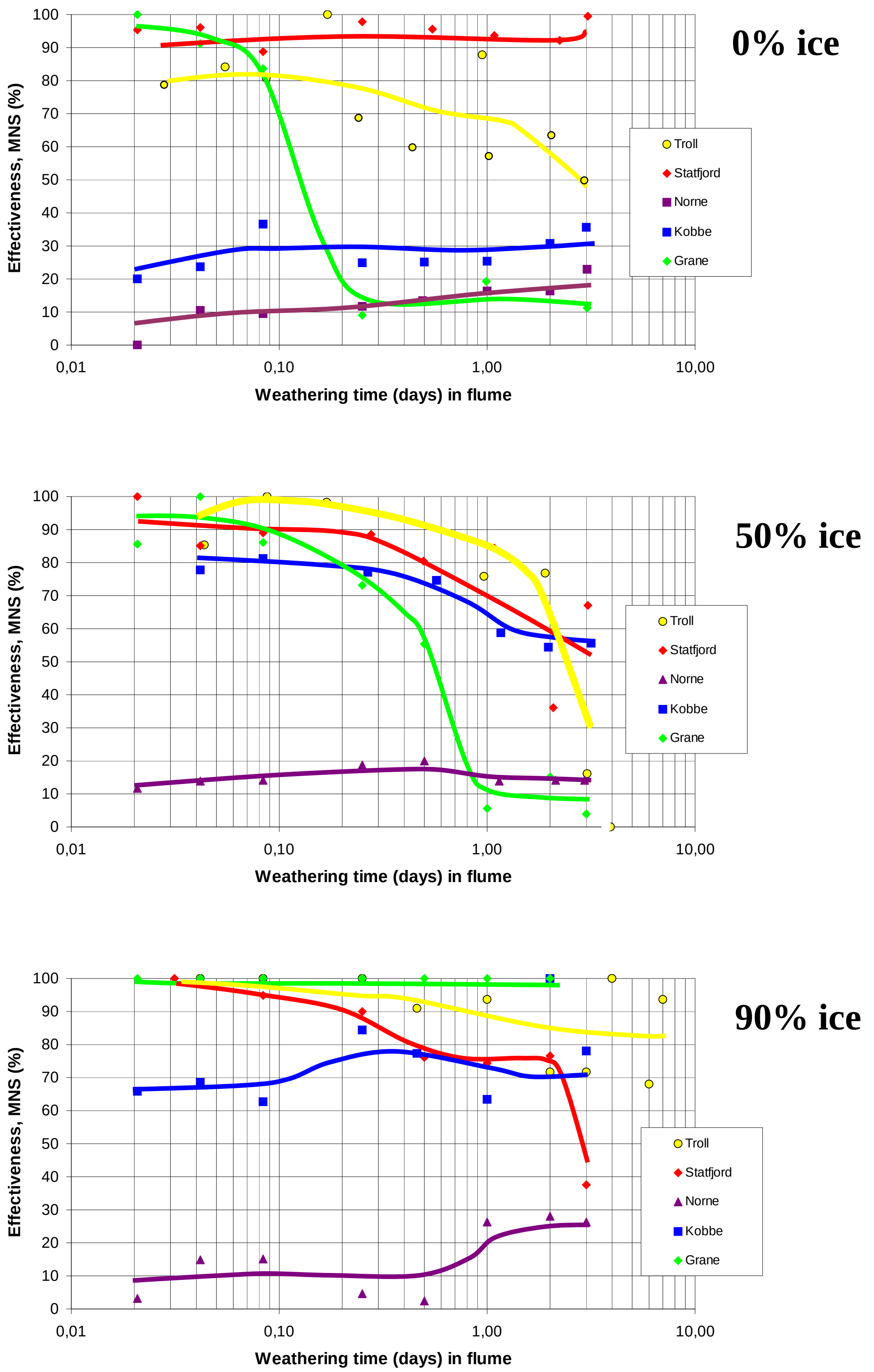

Figure 5.50: Dispersibility for all oil types at 0%, 50% and 90% ice coverage, as measured on weathered samples from flume experiments versus weathering time.

5.3 In situ burning

Burning experiments were performed using the experimental burning cell (see Chapter 4.5) with weathered oil samples from the meso-scale weathering plume. Testing of the ignitability and burning effectiveness were tested with all oils used in this study, but mainly on the open water (0% ice), 50% ice and 90% ice experiments. Oil samples were taken from the meso-scale flume and the physical-chemical properties and burning properties were measured from the same samples. The weathering properties are presented in an earlier chapter (see Chapter 5.2), while the burning properties are presented in this chapter.

The burning effectiveness is presented as BE%-Corrected to adjust for the different degree of weathering (water content) as defined in Equation 3.2.

The upper limit of the "window for ignitability" is estimated as the midpoint between the first experiment giving "no ignitability" (or zero BE%) and the last experiment where the oil was "ignitable". In the figure below, this 50% ice scenario gives an upper limit of seven hours (4.4 + (9.9-4.4)/2 = 7). These upper limits are also given on the figures in this chapter.

5.3.1 Meso-scale SeaLab: Napthenic oil, Troll B

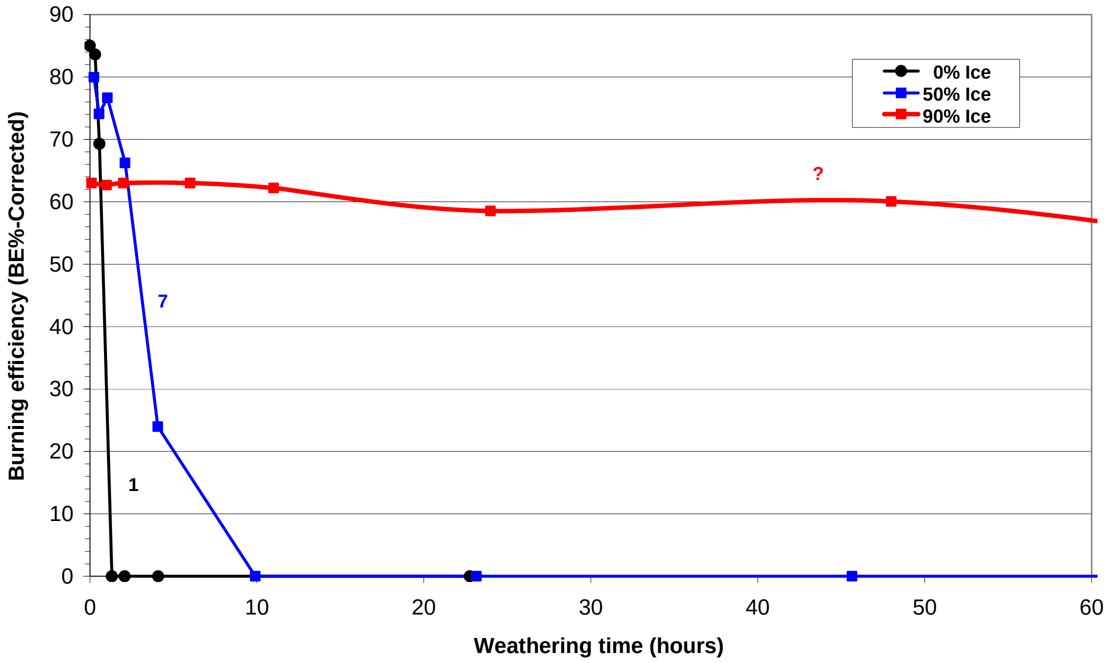

Figure 5.51: Troll B crude – Burning effectiveness as a function of weathering time in the meso-scale flume. Numbers on the graphs are calculated as the upper limits for "ignitability".

The Troll B crude was the first oil tested in the meso-scale flume as a part of this programme (Oil-in-Ice JIP). At that point, the laboratory burning cell was still under construction and testing (the first quarter of 2007). For this reason, only a minor part of the meso-scale experiments with this oil was used for the burning experiments. However, later in 2008 the Troll crude was tested at Svalbard with both meso-scale experiments and the laboratory burning cell (see **Figure 5.52**).

5.3.2 Meso-scale Svalbard: Napthenic oil, Troll B

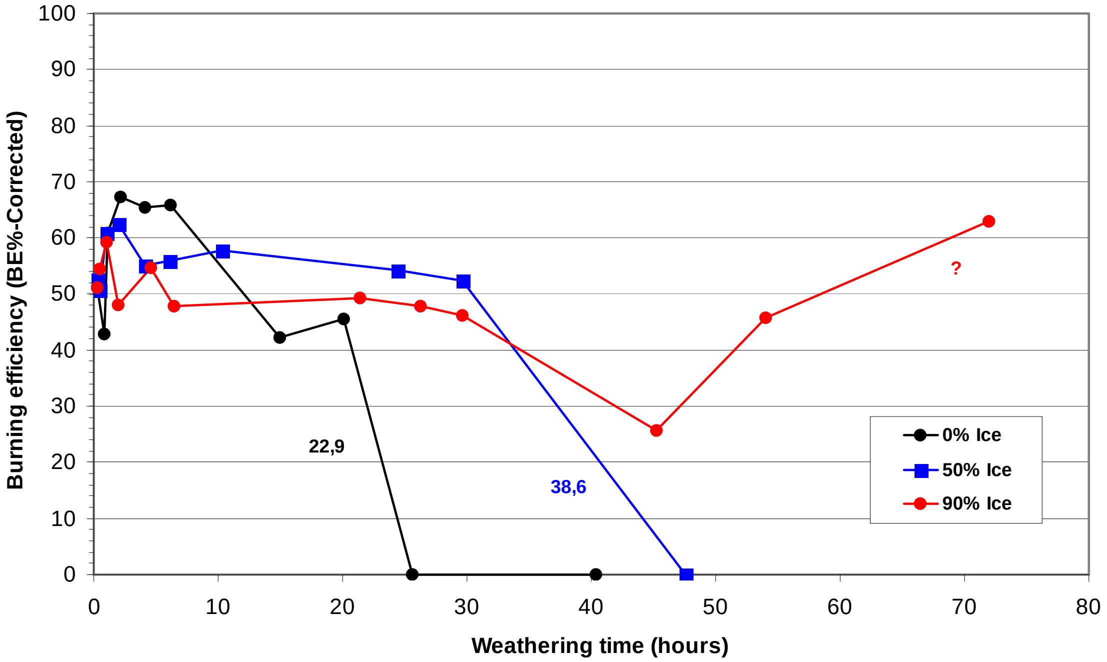

Figure 5.52: Troll B crude – Burning effectiveness as a function of weathering time in the meso-scale flume during the field work performed in April 2008 on Svalbard. The numbers on the graphs are calculated as the upper limit for “ignitability” (hours).

The burning effectiveness for Troll crude as a function of weathering time is shown in the figure above. The samples are taken from the meso-scale experiment performed on a larger scale (200 L) in a basin made from of first-year sea ice at the SINTEF field research station in Svea on Svalbard.

Figure 5.52 shows the burning effectiveness as a function of weathering time for the three types of ice coverage/energy levels tested at Svalbard (open water (0% ice), 50% and 90% ice). For the open water experiment, the oil is “ignitable” (high burning effectiveness) for up to 20 hours and then drops to zero at 26 hours. The samples taken after 40 hours also show a zero burning effectiveness. The interpretation of this is that the oil is ignitable for up to 23 hours (the midpoint between 20 and 26 hours), and then becomes too emulsified/evaporated to be ignited.

The meso-scale experiment performed at 50% ice shows the same drastic drop in burning effectiveness between 30 and 48 hours. The interpretation of this is that for this ice/energy scenario, the oil is ignitable for up to 39 hours (30 + (48-30/2)).

The meso-scale experiments performed at the low energy scenario 90% ice show no such sudden drop in burning effectiveness, most likely because of the low emulsification and evaporative loss of this experiment. Even after 72 hours, the weathered oils are still “ignitable”.

The absolute values of the measured parameter “burning effectiveness” or BE%-Corrected are not important. It is the drastic drop in BE%, indicating the upper limit for in situ burning, which is important.

5.3.3 Meso-scale SeaLab: Paraffinic oil, Statfjord

Meso-scale weathering experiments were performed with the paraffinic crude Statfjord at all ice conditions and energy levels from open water (0% ice) to 90% ice. During this period, the laboratory burning cell was still under construction and the testing of ignitability was not performed for the 30% ice experiment.

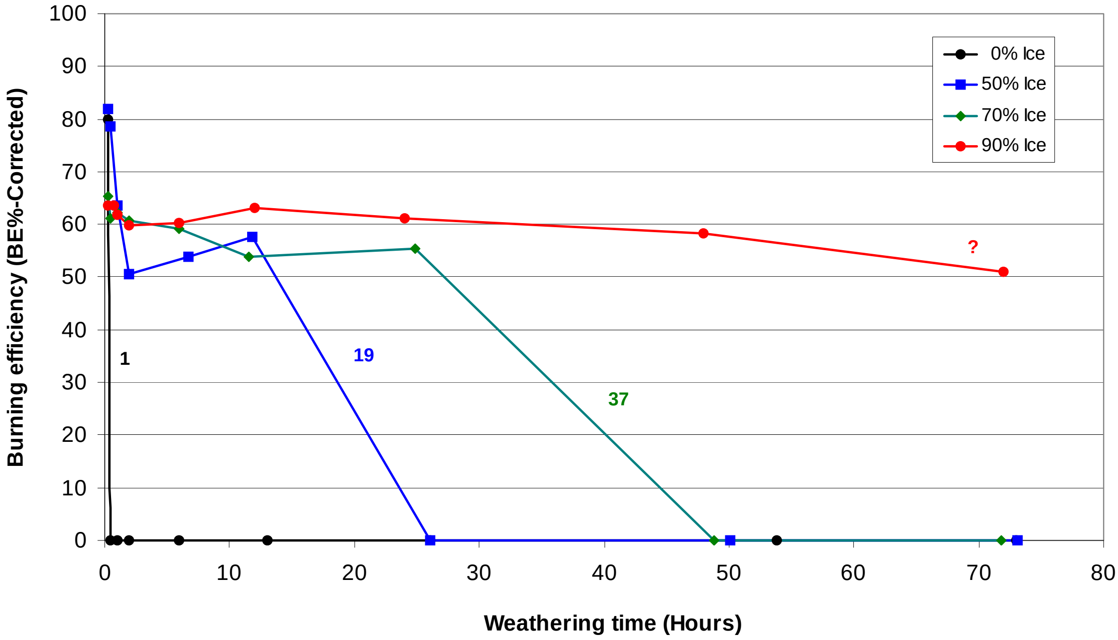

Figure 5.53: Statfjord crude – Burning effectiveness as a function of weathering time in the meso-scale flume. The numbers on the graphs are calculated as the upper limit for “ignitability” (hours).

Figure 5.53 shows the burning effectiveness as a function of weathering time for the three types of ice coverage/energy levels tested at the SINTEF SeaLab (50, 70 and 90% ice). For the 50% ice experiment, the oil is “ignitable” (high burning effectiveness) for up to 12 hours and then drops to zero at 26 hours. The samples taken later also show a zero burning effectiveness (not ignitable). The interpretation of this is that for this ice/energy scenario, the oil is ignitable up until 19 hours (12 + (26-12/2)).

The meso-scale experiment performed at 70% ice shows the same drastic drop in burning effectiveness between 24 and 31 hours. The interpretation of this is that for this ice/energy scenario, the oil is ignitable up until 37 hours (31 + (31-24/2)).

The 90% ice experiments show no such sudden drop in burning effectiveness. This is due to the low emulsification and evaporative loss of this experiment. Even after 72 hours, the oil is still “ignitable”.

5.3.4 Meso-scale SeaLab: Asphaltenic oil, Grane

The burning effectiveness (BE%-Corrected) measured with the laboratory burning cell is presented in the figure below. Samples with different weathering degrees from open water (0% ice), 50% ice and 90% ice meso-scale experiments were tested in the laboratory burning cell.

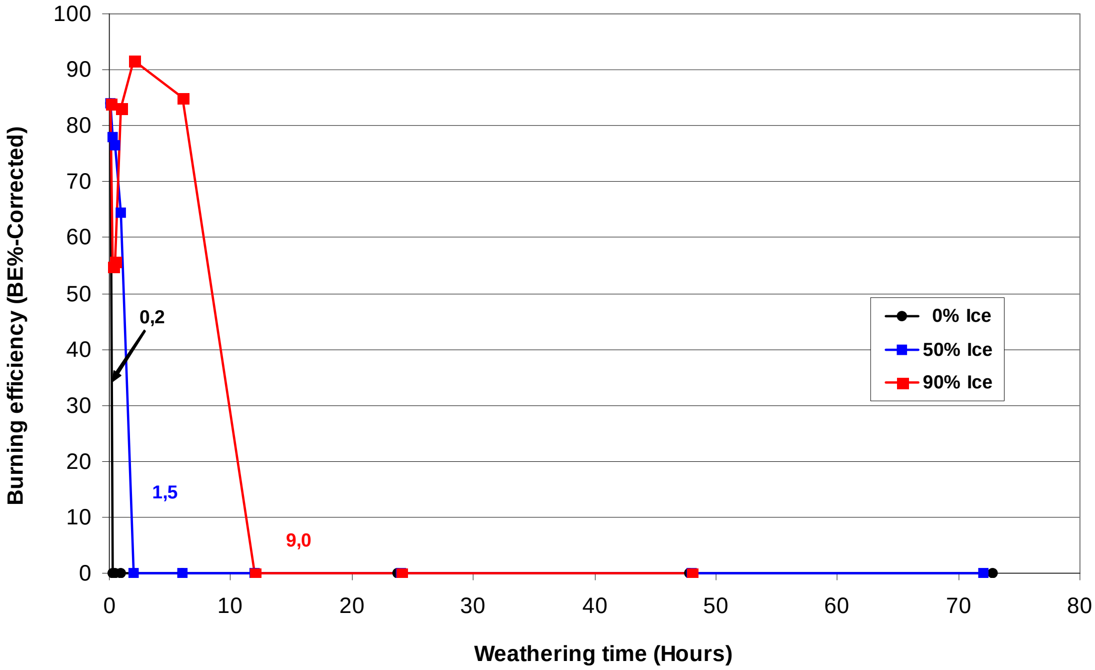

Figure 5.54: Grane crude – Burning effectiveness as a function of weathering time in the meso-scale flume. Numbers on the graphs are calculated as the upper limit for “ignitability”.

Grane crude has a very rapid water uptake and forms stable w/o emulsions (see **Figure 5.10** and **Figure 5.11**), and also has a very low content of volatile components (**Figure 5.12**). These stable emulsions with a high water content and a low content of volatile components become “ignitable” after a very short weathering time (0.2-9 hours), which indicates a very short operational window for the in situ burning of such oil types.

5.3.5 Meso-scale SeaLab: Waxy oil, Norne

The burning effectiveness (BE%) measured with the laboratory burning cell is presented in the figure below. Samples with different weathering degrees from the open water (0% ice), 50% ice and 90% ice meso-scale experiments were used in the laboratory burning cell.

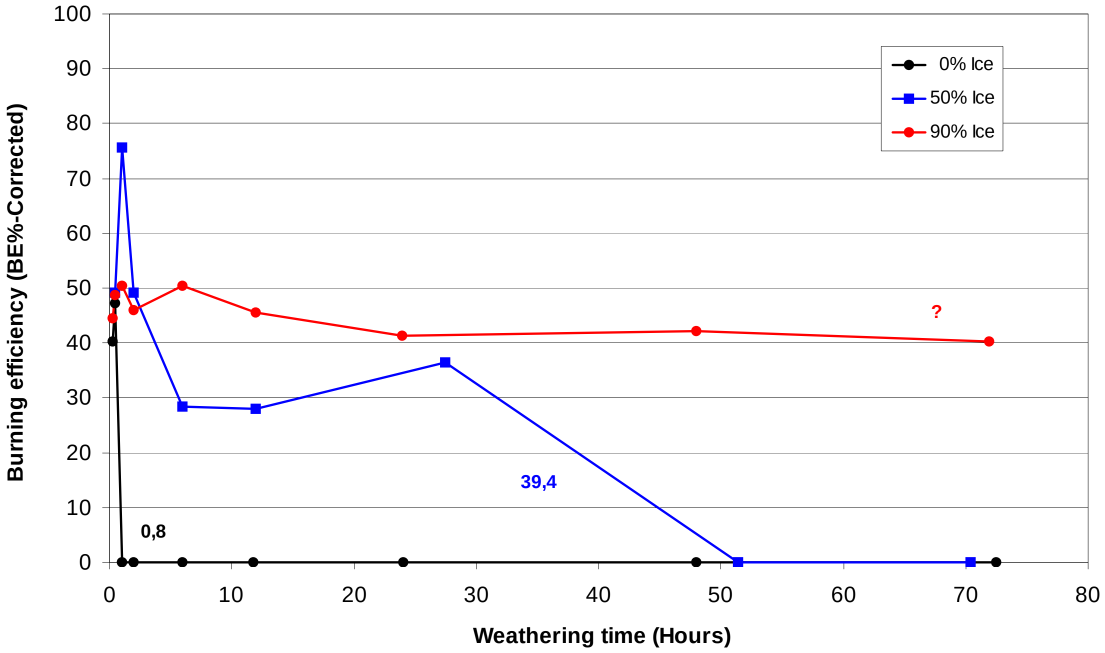

Figure 5.55: Norne crude – Burning effectiveness as a function of weathering time in the meso-scale flume. The numbers on the graphs are calculated as the upper limit for "ignitability" (hours).

In one of the previous chapters (Chapter 5.2.5), we experienced the fact that the difference in water uptake among the three different meso-scale experiments with Norne crude: open water (0% ice), 50% and 90% ice is very significant (see **Figure 5.13**), which is reflected in the measured burning efficiencies in the figure above (**Figure 5.55**).

The rapid water uptake for the open water experiment shows emulsions with a high water content and a very low BE%. The consequence of this is that the oil very rapidly becomes "not ignitable", thus the time window for in situ burning also becomes very short (0.8 hours).

The meso-scale experiment performed at 50% ice also shows a drastic drop in burning effectiveness between 28 and 52 hours. The interpretation of this is that for this ice/energy scenario, the oil is ignitable up until 39 hours (28 + (52-28/2)).

The meso-scale experiments performed at the low energy scenario 90% ice show no such drop in burning effectiveness due to the low emulsification and evaporative loss of this experiment. Even after 72 hours, the oil is still "ignitable".

5.3.6 Meso-scale SeaLab: Light oil, Kobbe

The burning effectiveness (BE%) measured with the laboratory burning cell light oil Kobbe is presented in the figure below. Samples with different weathering degrees from the open water (0% ice), 50% ice and 90% ice meso-scale experiments were ignited and burned in the laboratory burning cell.

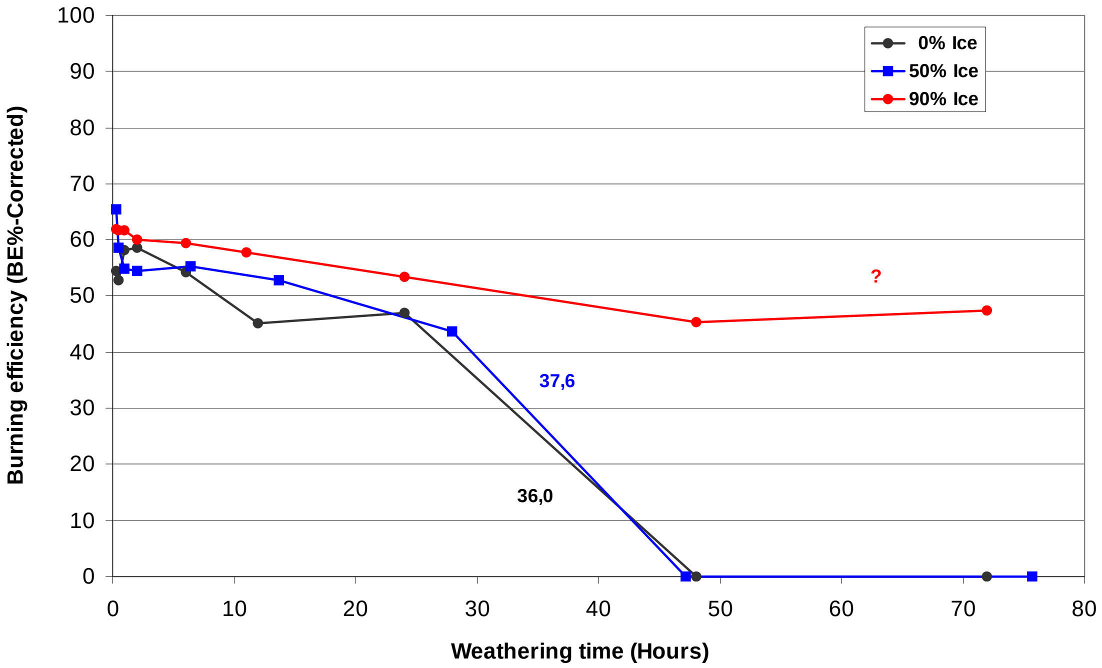

Figure 5.56: Kobbe – Burning effectiveness as a function of weathering time in the meso-scale flume. The numbers on the graphs are calculated the upper limit for "ignitability" (hours).

In Chapter 5.2.6, we experienced the fact that the water uptake among the three different meso-scale experiments with Kobbe show large differences. The difference in water uptake for Kobbe open water (0% ice), 50% and 90% ice is large (65, 41 and 8%, see **Figure 5.16**), but not so clearly reflected in the measured burning efficiencies in the figure above (**Figure 5.56**).

Despite the relatively quick water uptake for the open water and 50% ice, the emulsions that are formed are relatively unstable and can be easily broken by the heat from the igniter. This is due to the low content of natural emulsion stabilising components (wax, asphaltenes and resins) in this light oil. The emulsified oil is ignitable for up until one and a half days after these two experiments (open water and 50% ice, see **Figure 5.56**). Neither experiment shows a drastic drop in burning effectiveness for the samples taken until 48 hours. The interpretation of this is that for these ice/energy scenarios, the oil is ignitable for the 0% ice scenario up until 36 hours and the same for the 50% scenario up until 38 hours.

The meso-scale experiments performed at the low energy scenario 90% ice show no such sudden drop in burning effectiveness. This is due to the low emulsification and evaporative loss of this experiment, and even after 72 hours, the oils is still "ignitable".

5.3.7 All oils – burning effectiveness (BE%-Corrected) versus ice coverage

The burning effectiveness for all the oils as a function of ice coverage is given in the figures below:

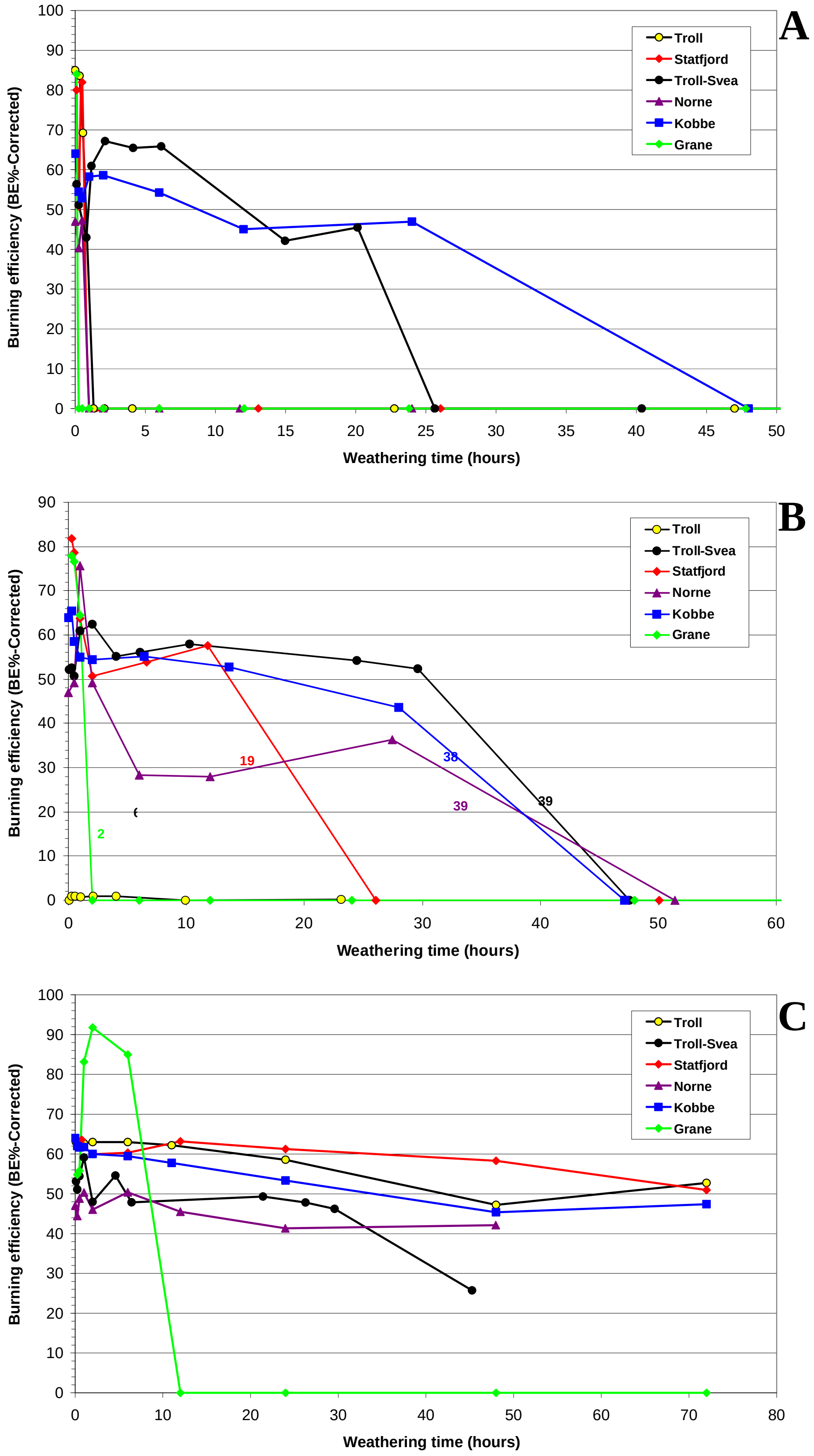

Figure 5.57: Burning effectiveness for all oil types at 0% (**A**), 50% (**B**) and 90% ice coverage (**C**). BE%-Corrected as a function of weathering time in the meso-scale flume.

The burning effectiveness (BE%-Corrected) and ignitability are strongly dependent on the water content, emulsion stability and residual content of volatile components in the oil. **Figure 5.57** shows that the drop in BE% is highly dependent on the rate of the weathering processes.

The difference is very clear between the 50 and 90% ice experiments. The slow water uptake and evaporation due to the low energy present, together with the high ice coverage (90% ice), make the oils burnable with a high effectiveness for an extended period of time. Only Grane, which forms very stable emulsions at a low energy, shows a drop in BE% and becomes “not ignitable” during the experiment. The other oils are ignitable and burn with a high BE% at the end of the experiments.

In the 50% ice experiments, we can observe a broader variation in burning effectiveness dependent on the properties of the emulsions that are formed. The emulsions which are mainly stabilised by waxes (Norne, Kobbe and Statfjord) have an extended time window for burning due to the tendency to break when heated by the igniter. Grane, with a higher asphaltene content, forms more stable emulsions which are not so easily broken by heat and has a shorter time window for in situ burning.

In the open water experiments, the high and rapid water uptakes should make the oil become “not ignitable” within a shorter time than at 50 and 90% ice, although this trend is not so clear due to the low number of burning cell experiments performed with the open water experiments.

Since this data is going to be used to implement algorithms for predicting “Ignitability” in the SINTEF oil weathering model (OWM) the absolute value of BE% is not so significant, the main issue is if the weathered oil is ignitable or not. The data could be presented in a more binary form after the following criterias; BE% > 30 the oil is “Ignitable” and BE%<30 the oil is “Not Ignitable”. A presentation of the ISB data in this form is given below (same data as presented in **Figure 5.57**b).

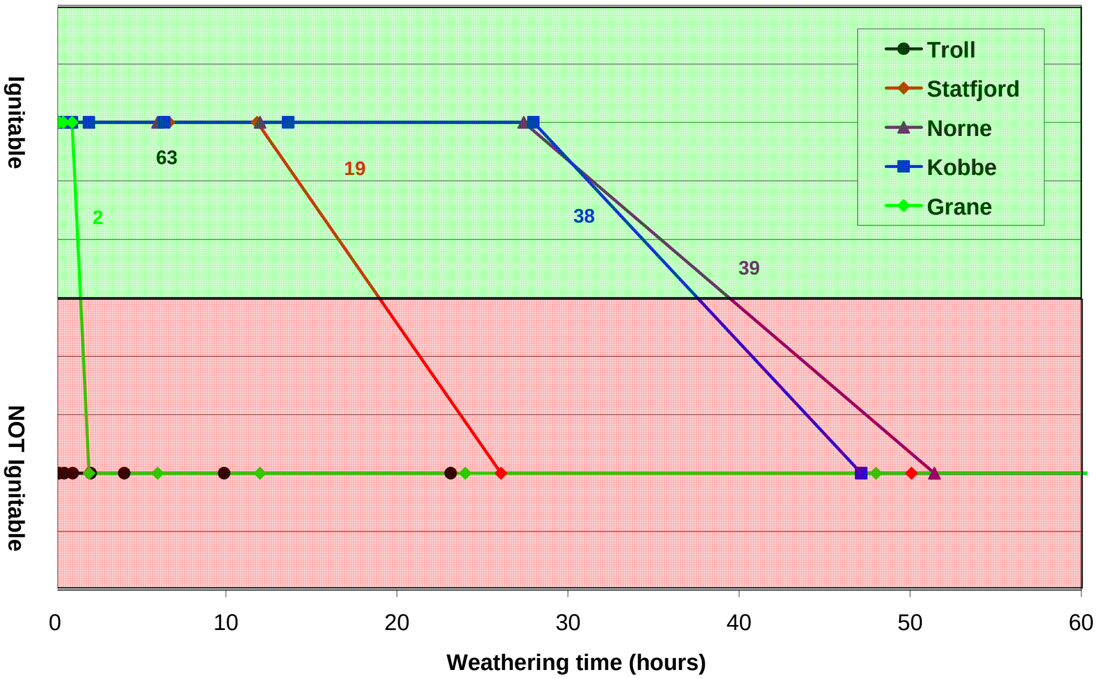

Figure 5.58: Ignitability for all oil types at 50% ice coverage. Ignitability is as a function of weathering time in the meso-scale flume.

6 Conclusions

This chapter summarises the conclusions from the previous chapters with regard to weathering, dispersibility testing and in situ burning.

6.1 Meso-scale weathering

The general conclusion from this study of five very different oil types is that the rate of weathering processes (water uptake, viscosity of w/o emulsion and evaporative loss) is very dependent on oil composition and the energy and ice conditions present. In the open water experiments (0% ice), the processes are generally rapid and high compared to the experiments performed at 50 and 90% ice. With high ice coverage and low energy (90% ice), the oils generally have a slow and low water uptake, as well as a lower viscosity and evaporative loss due to the high ice coverage and low energy content.

However, the naphtenic/asphaltenic crudes (Troll and Grane) also form stable emulsions at medium and high ice coverage. These oil types demand less energy to form stable emulsions due to their broad content of emulsion stabilising components and mobility at low temperature (low pour point). In particular, the asphaltenic Grane is able to form stable emulsions with a high water content and viscosity even in experiments with a high ice coverage and low energy.

Ideally, since evaporation is a surface phenomenon it should be a direct function of ice coverage. This is complicated by the emulsification that creates thicker layers of oil (80% water increases oil film thickness by a factor of five), showing the opposite trend with respect to ice coverage. This is also dependent on the oil’s behaviour at low temperatures, in addition to whether the oil spreads out evenly like naphtenic Troll (low pour point), or if it forms “lumps” during emulsification like the waxy Norne (very high pour point).

The difference in evaporative loss between the five different oils used in this study usually reflects their varying content of light components and ice conditions. The only exception from this general dependency on the content of light components is the waxy Norne. A reduced evaporative loss of approximately 10% for the waxy Norne is probably caused by the oil solidifying in lumps due to its high pour point.

The general trend in the properties used to describe the main weathering processes:

1. Water uptake, uptake rate (T½) and maximum water content (vol. %)
2. Emulsion stability (viscosity at a shear rate of 10 s^{-1})
3. Evaporative loss and content of remaining volatile components

is that the increasing presence of ice and the dampening of waves reduces the rate of these processes in the oil slick. This reduction in weathering has consequences for contingency strategies for oil spills in ice. The operational influence on the use of dispersants and in situ burning is discussed in the next two chapters.

This data regarding weathering of oil in ice is used to update the algorithms in the SINTEF Oil Weathering Model (Brandvik et al., 2010c) and improve its ability to describe oil weathering in ice.

6.2 Dispersibility testing

Dispersant effectiveness is dependent on the physical properties of the weathered oil on which it is applied. If the oil is too viscous (e.g. due to emulsification) or has become semi-solid (due to wax precipitation), the dispersant cannot penetrate into the weathered oil and can be washed off into the sea.

Primarily due to this dependency of oil properties, some clear trends regarding dispersant effectiveness can be observed in this combined weathering and dispersibility study.

The reduced viscosity caused by slower weathering gives a significant increase in dispersibility, particularly for crude oils such as Grane, Troll and Kobbe in high ice coverage. Statfjord and Troll crude generally show a fairly high performance, while the Norne crude demonstrates its low potential for dispersibility in cold areas both with and without the presence of ice.

For some of the crude oils such as Grane and Troll, there is a significant increase in both dispersant effectiveness and the “time window” for dispersant use with increasing ice coverage that is most probably due to a reduced increase in viscosity at high ice coverage for both these oils. Also for Kobbe, the dispersant effectiveness in the MNS test seems to increase with increasing ice coverage, and there is no limit in the “time window” within the experimental weathering time of three days. For Statfjord, there seems to be a slight decrease in effectiveness after 2-3 days of weathering with increasing ice coverage, likely because of its paraffinic character with a relatively high wax content that may precipitate in high ice and calm turbulence conditions. Again, the Norne crude shows a low dispersibility at any weathering stage both with and without ice present due to its high elastic property in cold conditions, which inhibits the dispersant droplets from being effectively blended into the oil/emulsion during application.

Based on the findings from:

1. This combined weathering/dispersibility study
2. The FEX 2009 trials which introduced artificial turbulence by vessel thrusters/water jet systems to fulfil the dispersion process (Daling et al., 2010),

this opens the “window-of-opportunity” for the effective use of dispersants in Arctic and ice-covered areas for certain types of crude oils to a larger extent than previously anticipated.

The time window for using dispersants can be predicted using the updated version of the SINTEF OWM with a better description of weathering of oil in ice.

6.3 In situ burning

The ignitability of an oil spill is very dependent on the weathering state of the oil. If the water content is too high and the amount of volatile components in the weathered oil is too low, the heat from the igniter will not be sufficient to ignite the oil. The presence of small water droplets in the emulsion makes it difficult to heat the emulsion above 100°C. For this reason, the emulsion must be broken, the water expelled and the residual water free oil heated to create the necessary concentration of hydrocarbons above the oil to make it burn (1.5-8%).

The general trend in this study is that the oil in the beginning of the meso-scale weathering experiments is ignitable and burns with a high effectiveness (BE%). At a certain time in the weathering, the combination of water content, emulsion stability and the lack of volatile components make it difficult to ignite the weathered oil. At this stage, the oil is close to being not ignitable.

In practice, this weathering time is defined as the midpoint between the last measurement with the burning laboratory cell giving a high burning effectiveness and the first experiment showing a very low effectiveness. At this weathering time, the oil is characterised as “not ignitable”.

For most of the experiments, this trend follows the different weathering for the various oil types, which implies that the reduced weathering observed by a higher ice coverage and lower wave energy offer an extended window of opportunity for in situ burning.

This can clearly be observed by comparing the 50 and 90% ice experiments. The slow water uptake and reduced evaporation due to the low energy present together with the high ice coverage (90% ice) make the oils burnable with a high effectiveness for an extended period of time. Only Grane, which forms very stable emulsions at a low energy, shows a drop in BE% and becomes “not ignitable” during the experiment. The other oils are ignitable and burned with a high BE% at the end of the experiments.

We can observe a broader variation in the burning effectiveness among the 50% ice experiments that are dependent on the properties of the emulsions which are formed. The emulsions which are mainly stabilised by waxes (Norne, Kobbe and Statfjord) have an extended time window for burning due to their tendency to break when heated by the igniter. Grane, with higher asphaltene content, forms more stable emulsions which are not so easily broken by heat and has a shorter time window for in situ burning.

This data is analysed and used to establish algorithms in the SINTEF Oil Weathering Model (Brandvik et al., 2010c) to predict the window of opportunity for in situ burning based on the findings described above.

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Appendix A: Tables – Weathering properties

Troll

0% Ice A

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	2007-02-28	0,0	0	0	0,0	0	0
1	2007-02-28	0,3	27	289	7,0	0,8964	0,40
2	2007-02-28	0,6	61	1110	8,0	0,9000	0,20
3	2007-02-28	1,3	69	1830	11,0	0,9013	0,20
4	2007-02-28	2,1	72	1450	12,0	0,9046	0,88
5	2007-02-28	4,1	73	2160	14,0	0,9064	0,68
7	2007-03-01	22,8	81	3890	19,0	0,9139	0,57
8	2007-03-02	47,0	84	6100	21,0	0,9166	0,12
9	2007-03-03	70,8	81	9070	22,0	0,9177	0,23
10	2007-03-04	95,3	80	8250	22,4	0,9198	0,03
11	2007-03-06	120,3	77	9420	23,1	0,9206	0,03
		t0.5	0,36				

0% Ice B

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	2007-12-03	0,1	0	0	0,0	0,8920	0
1	2007-12-03	0,3	36	363	8,1	0,9029	0
2	2007-12-03	0,6	54	1100	10,4	0,9057	0
3	2007-12-03	1,0	61	1520	12,3	0,9079	0
4	2007-12-03	2,0	71	2440	13,9	0,9097	0
5	2007-12-03	6,0	82	3630	17,0	0,9135	0
6	2007-12-03	11,2	84	6230	18,0	0,9146	0
7	2007-12-04	24,1	79	6790	20,5	0,9176	0,25
8	2007-12-05	47,7	71	5850	22,0	0,9194	0,20
9	2007-12-06	71,0	73	6130	23,1	0,9206	0
		t0.5	0,35				

30% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
1	2007-03-12	0,3	24	230	5,2	0,8996	0,11
2	2007-03-12	0,6	30	286	8,0	0,9028	0,06
3	2007-03-12	1,1	48	821	10,1	0,9053	0,04
4	2007-03-12	2,2	61	2080	12,1	0,9077	0,04
5	2007-03-12	4,5	72	3040	14,6	0,9106	0,25
6	2007-03-12	10,3	78	3430	17,0	0,9134	0,29
7	2007-03-13	25,6	74	5440	19,4	0,9163	0,35
8	2007-03-14	50,0	74	3280	21,1	0,9183	0,34
9	2007-03-15	72,1	72	3910	21,9	0,9192	0,24
10	2007-03-16	94,8	72	4730	21,6	0,9189	0,71
		t0.5	0,68				

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	2007-03-26	0,1	0	0	0.0	0,8920	0
1	2007-03-26	0,3	20	71,1	1.8	0,8955	0,86
2	2007-03-26	0,6	27	173	4.8	0,8990	0,88
3	2007-03-26	1,1	27	289	8.5	0,9034	0,69
4	2007-03-26	2,1	35	510	11.3	0,9067	0,85
5	2007-03-26	4,1	51	1410	14.3	0,9102	0,90
6	2007-03-26	9,9	69	4000	17.1	0,9135	0,07
7	2007-03-27	23,2	80	4800	20.4	0,9174	0,22
8	2007-03-28	45,7	75	8110	19.8	0,9167	0,15
9	2007-03-29	72,4	78	9680	23.0	0,9205	0,03
10	2007-03-30	93,9	77	8050	24.5	0,9222	0,05
		t0.5	2,1				

70% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	2007-11-06	0,1	0	0	0,0	0,8920	0,00
1	2007-11-06	0,3	0	128	2,8	0,8967	0,00
2	2007-11-06	0,5	13	193	6,2	0,9007	0,58
3	2007-11-06	1,0	0	277	4,6	0,8988	0,00
4	2007-11-06	2,1	3	431	7,1	0,9018	0,00
5	2007-11-06	6,1	7	972	11,1	0,9065	0,89
6	2007-11-06	12,1	4	1983	13,5	0,9093	0,00
7	2007-11-07	24,1	7	2452	15,9	0,9121	0,00
8	2007-11-08	48,1	34	2826	18,7	0,9154	0,29
9	2007-11-09	72,1	65	4634	20,4	0,9175	0,00
10	2007-11-11	120,1	64	4143	21,7	0,9190	0,00
11	2007-11-12	149,2	64	8830	23,0	0,9205	0,00
12	2007-11-14	169,8	65	4686	23,0	0,9204	0,00
		t0.5	45				

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	2007-11-19	0,1	0	0	0,0	0,8920	0!
1	2007-11-19	1,0	1	85,8	2,4	0,8963	0
2	2007-11-19	2,0	0	87,8	2,6	0,8965	0
3	2007-11-19	6,0	0	122	6,5	0,9011	0
4	2007-11-19	11,0	2	188	10,1	0,9053	0
5	2007-11-20	24,0	11	346	14,6	0,9106	0,30
6	2007-11-21	48,0	30	939	15,9	0,9121	0,09
7	2007-11-22	72,0	22	885	17,4	0,9139	0,24
8	2007-11-23	96,0	34	1170	18,2	0,9148	0,22
9	2007-11-24	120,0	26	1180	19,5	0,9164	0,22
10	2007-11-26	144,0	35	1970	20,1	0,9171	0
11	2007-11-27	168,0	31	2210	20,7	0,9177	0

Statfjord

0% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	07-01-08	0.1	0	0	0.0	0.892	0.0
1	07-01-08	0.25	59	605	17.8	0.857	0.0
2	07-01-08	0.5	64	1340	20.3	0.861	0.0
3	07-01-08	1	69	2080	22.9	0.865	0.0
4	07-01-08	2	72	1820	25.5	0.869	0.0
5	07-01-08	6	74	2470	29.8	0.875	0.0
6	07-01-08	13	71	3040	32.7	0.879	0.0
7	08-01-08	26	70	3240	36.1	0.884	0.0
8	09-01-08	54	65	2620	37.2	0.886	0.0
9	10-01-08	73	63	3850	38.8	0.888	0.0
		t0.5	0.14				

30% Ice

Ice slush formation (temp regulation problems) during experiment caused wave damping and low energy input

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	14-01-08	0.1	0	0	0.0	0.892	0.0
1	14-01-08	0.25	5	440	19.3	0.860	0.0
2	14-01-08	0.5	10	459	20.9	0.862	0.0
3	14-01-08	1	15	746	24.7	0.868	0.0
4	14-01-08	2	18	893	27.4	0.871	0.0
5	14-01-08	6	29	1930	32.4	0.879	0.0
6	14-01-08	12	44	1600	34.4	0.882	0.0
7	15-01-08	24	33	2220	33.3	0.880	0.0
8	16-01-08	48	29	2570	38.8	0.888	0.0
9	17-01-08	72	27	3340	40.8	0.891	0.0
		t0.5	2.2				

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	21-01-08	0.1	0	0	0.0	0.892	0.0
1	21-01-08	0.25	1	687	16.1	0.855	0.0
2	21-01-08	0.5	2	553	19.4	0.860	0.0
3	21-01-08	1	4	577	23.9	0.866	0.0
4	21-01-08	2	9	757	26.9	0.871	0.0
5	21-01-08	7	13	1380	31.0	0.877	0.0
6	21-01-08	12	29	2080	34.2	0.881	0.0
7	22-01-08	26	29	2510	36.7	0.885	0.0
8	23-01-08	50	58	3190	39.1	0.888	0.0
9	24-01-08	73	57	3730	40.4	0.890	0.0
		t0.5	12				

70% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	28-01-08	0.1	0	0	0.0	0.892	0.0
1	28-01-08	0.25	5	128	7.5	0.842	0.0
2	28-01-08	0.5	2	193	11.4	0.848	0.0
3	28-01-08	1	5	277	14.5	0.853	0.0
4	28-01-08	2	8	431	19.0	0.859	0.0
5	28-01-08	6	14	972	27.1	0.871	0.0
6	28-01-08	12	26	1980	33.7	0.881	0.0
7	29-01-08	25	24	2450	36.3	0.884	0.0
8	30-01-08	49	31	2830	38.6	0.888	0.0
9	31-01-08	72	42	4630	40.0	0.890	0.0
		t0.5	10				

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	04-02-08	0.1	0	0	0.0	0.892	0.0
1	04-02-08	0.25	1	251	3.9	0.837	0.0
2	04-02-08	0.75	4	324	3.8	0.837	0.0
3	04-02-08	1	6	239	4.6	0.838	0.0
4	04-02-08	2	3	307	7.4	0.842	0.0
5	04-02-08	6	2	443	12.6	0.850	0.0
6	04-02-08	12	8	995	24.0	0.866	0.0
7	05-02-08	24	5	1056	27.7	0.872	0.0
8	06-02-08	48	4		31.8	0.878	0.0
9	07-02-08	72	6		33.6	0.880	0.0
		t0.5	0.70				

Grane

0% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	2008-02-11	0.1	0	0	0.0	0.8920	0.00
1	2008-02-11	0.25	34	4170	1.9	0.9415	0.34
2	2008-02-11	0.5	53	5737	3.3	0.9427	0.23
3	2008-02-11	1	59	9401	4.7	0.9440	0.25
4	2008-02-11	2	67	11228	5.8	0.9450	0.27
5	2008-02-11	6	74	17710	7.6	0.9467	0.40
6	2008-02-11	12.05	74	20130	8.6	0.9475	0.12
7	2008-02-12	23.8	74	20147	11.1	0.9499	0.22
8	2008-02-13	47.8	69	28141	10.3	0.9491	0.11
9	2008-02-14	72.8	67	26753	13.5	0.9521	0.00
		t0.5	0.28				

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	18.02.08	0.1	0	0	0.0	0.8920	0.00
1	18.02.08	0.25	28	3460	2.5	0.9420	0.52
2	18.02.08	0.5	36	4186	3.3	0.9427	0.67
3	18.02.08	1	52	7332	5.1	0.9444	0.48
4	18.02.08	2	62	12295	6.8	0.9459	0.32
5	18.02.08	6	70	21915	7.8	0.9468	0.23
6	18.02.08	12	72	21943	9.3	0.9482	0.23
7	19.02.08	24	67	29064	12.5	0.9511	-
8	20.02.08	48	68	31647	12.8	0.9514	-
9	21.02.08	72	68	35894	12.1	0.9508	0.18
		t0.5	0.47				

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	25.02.08	0.1	0	0	0.9	0.8920	0.00
1	25.02.08	0.25	0	1777.7	0.1	0.9396	0.00
2	25.02.08	0.5	3	1854.2	0.2	0.9398	0.00
3	25.02.08	1	17	2078.7	0.3	0.9373	0.63
4	25.02.08	2	3	1978.6	0.4	0.9398	0.00
5	25.02.08	6	7	2290.1	1.6	0.9412	0.72
6	25.02.08	12	20	4343.2	4.6	0.9439	0.26
7	26.02.08	24	47	8448.8	7.3	0.9464	0.00
8	27.02.08	48	53	11200	9.6	0.9485	0.00
9	28.02.08	72	72	13871	10.6	0.9494	0.00
		t0.5	21				

Kobbe

0% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	2008-09-15	0	0	5	0	0.7970	0.00
1	2008-09-15	0.25	49	193	18	0.8361	0.13
2	2008-09-15	0.5	60	231	22	0.8402	0.83
3	2008-09-15	1	59	284	26	0.8453	0.10
4	2008-09-15	2	54	320	28	0.8480	0.00
5	2008-09-15	6	61	327	34	0.8560	0.14
6	2008-09-15	12	62	472	36	0.8581	0.13
7	2008-09-16	24	64	1139	39	0.8629	0.74
8	2008-09-17	48	65	1746	42	0.8667	0.77
9	2008-09-18	72	61	1954	44	0.8682	0.00
		t0,5	0.2				

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	2008-09-22	0.0	0	5	0	0.7970	0.00
1	2008-09-22	0.25	13	613	12	0.8284	0.00
2	2008-09-22	0.5	16	776	18	0.8355	0.00
3	2008-09-22	1	20	983	24	0.8433	0.00
4	2008-09-22	2	14	900	27	0.8475	0.00
5	2008-09-22	6	15	1567	33	0.8546	0.00
6	2008-09-22	14	20	1445	37	0.8594	0.00
7	2008-09-23	28	36	1726	41	0.8648	0.00
8	2008-09-24	47	43	2036	42	0.8661	0.00
9	2008-09-25	76	42	2450	47	0.8724	0.17
		t0,5	1.1				

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
start	2008-09-29	0	0	5	0	0.7970	0.00
Pr. 1	2008-09-29	0.25	0	19	8	0.8221	0.00
Pr. 2	2008-09-29	0.5	1	33	8	0.8224	0.00
Pr. 3	2008-09-29	1	3	46	15	0.8319	0.00
Pr. 4	2008-09-29	2	10	84	19	0.8373	0.00
Pr. 5	2008-09-29	6	1	202	26	0.8451	0.00
Pr. 6	2008-09-29	11	1	393	29	0.8495	0.00
Pr. 7	2008-09-30	24	1	658	34	0.8562	0.00
Pr. 8	2008-10-01	48	5	702	39	0.8622	0.00
Pr. 9	2008-10-02	72	7	911	37	0.8600	0.00
		t0,5	2.0				

Norne

0% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	2008-06-16	0	0.0	7283	0.0	0.0000	0.00
1	2008-06-16	0.25	7.8	7283	7.2	0.8582	0.00
2	2008-06-16	0.5	7.0	6621	7.8	0.8603	0.00
3	2008-06-16	1	11.3	6463	8.2	0.8617	0.00
4	2008-06-16	2	21.5	5567	9.4	0.8660	0.00
5	2008-06-16	6	39.5	3228	11.0	0.8721	0.00
6	2008-06-16	12	40.1	2944	11.8	0.8748	0.27
7	2008-06-17	24	49.7	3198	12.8	0.8784	0.00
8	2008-06-18	48	26.6	6012	13.7	0.8818	0.00
9	2008-06-19	73	21.0	8414	13.4	0.8809	0.00
		to,5	0.640				

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	2008-06-23	0	0	0	0.0	0.0000	0.00
1	2008-06-23	0.5	9	5342	7.6	0.8597	0.00
2	2008-06-23	1	14	4581	8.5	0.8628	0.00
3	2008-06-23	2	10	4585	8.7	0.8637	0.00
4	2008-06-23	6	23	3914	9.9	0.8679	0.00
5	2008-06-23	12	19	6602	11.3	0.8730	0.00
6	2008-06-24	27	20	6310	11.5	0.8739	0.00
7	2008-06-25	51	27	6261	12.2	0.8765	0.00
8	2008-06-26	70	20	5671	13.2	0.8801	0.00
		to,5	0.920				

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	Water uptake (%)	Viscosity(cP)	Evaporation (vol%)	Density (g/mL)	Stability D
0	2008-06-30	0.0	0	0	0.0	0.0000	0.00
1	2008-06-30	0.3	10	6570	5.8	0.8530	0.00
2	2008-06-30	0.5	10	5474	7.7	0.8598	0.00
3	2008-06-30	1	7	4295	7.9	0.8608	0.00
4	2008-06-30	2	9	5582	8.0	0.8611	0.00
5	2008-06-30	6	9	5084	7.9	0.8607	0.00
6	2008-06-30	12	10	6056	7.8	0.8603	0.00
7	2008-07-01	24	3	3766	9.5	0.8666	0.00
8	2008-07-02	48	5	4388	10.5	0.8703	0.00
9	2008-07-03	72	8	6173	12.4	0.8770	0.00
		to,5	0.010				

Appendix B: Tables - Dispersibility testing

Statfjord

0% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS%	
0	07-01-08	0.1	NA		
1	07-01-08	0.25	NA		Good dispersibility
2	07-01-08	0.5	95	95	Good dispersibility
3	07-01-08	1	96	96	Good dispersibility
4	07-01-08	2	89	89	Good dispersibility
5	07-01-08	6	98	98	Good dispersibility
6	07-01-08	13	96	96	Reduced dispersibility
7	08-01-08	26	94	94	Reduced dispersibility
8	09-01-08	54	92	92	Reduced dispersibility
9	10-01-08	73	100	100	Reduced dispersibility

30% Ice

Ice slush formation (temp regulation problems) during experiment caused wave damping and low energy input

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS%	
0	14-01-08	0.1	NA		
1	14-01-08	0.25	NA		
2	14-01-08	0.5	101	91	Good dispersibility
3	14-01-08	1	89	80	Good dispersibility
4	14-01-08	2	111	100	Good dispersibility
5	14-01-08	6	101	91	Good dispersibility
6	14-01-08	12	82	74	Good dispersibility
7	15-01-08	24	94	85	Reduced dispersibility
8	16-01-08	48	97	88	Reduced dispersibility
9	17-01-08	72	75	68	

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS%	
0	21-01-08	0.1	NA		
1	21-01-08	0.25	NA		
2	21-01-08	0.5	114	100	Good dispersibility
3	21-01-08	1	97	85	Good dispersibility
4	21-01-08	2	102	89	Good dispersibility
5	21-01-08	7	101	88	Good dispersibility
6	21-01-08	12	92	81	Good dispersibility
7	22-01-08	26	96	85	Good dispersibility
8	23-01-08	50	41	36	Reduced dispersibility
9	24-01-08	73	77	67	Reduced dispersibility

70% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS%	
0	28-01-08	0.1	NA		
1	28-01-08	0.25	NA		
2	28-01-08	0.5	106	93	Good dispersibility
3	28-01-08	1	95	83	Good dispersibility
4	28-01-08	2	97	85	Good dispersibility
5	28-01-08	6	85	75	Good dispersibility
6	28-01-08	12	114	100	Reduced dispersibility
7	29-01-08	25	67	59	Reduced dispersibility
8	30-01-08	49	NA		
9	31-01-08	72	NA		

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS%	
0	04-02-08	0.1	NA		
1	04-02-08	0.25	NA		
2	04-02-08	0.75	129	100	Good dispersibility
3	04-02-08	1	127	99	Good dispersibility
4	04-02-08	2	123	95	Good dispersibility
5	04-02-08	6	116	90	Good dispersibility
6	04-02-08	12	98	76	Good dispersibility
7	05-02-08	24	96	75	Good dispersibility
8	06-02-08	48	99	76	Good dispersibility
9	07-02-08	72	49	38	Good dispersibility

Troll

0% Ice A

Sample nr:	Date:	Cum. Time (hurs)	Adj MNS	FET
0	2007-02-28	0,0		
1	2007-02-28	0,3	NA	
2	2007-02-28	0,6	NA	Good dispersibility
3	2007-02-28	1,3	84	Reduced dispersibility
4	2007-02-28	2,1	81	Reduced dispersibility
5	2007-02-28	4,1	100	Reduced dispersibility
7	2007-03-01	22,8	88	Not dispersible
8	2007-03-02	47,0	NA	Not dispersible
9	2007-03-03	70,8	NA	Not dispersible
10	2007-03-04	95,3	NA	Not dispersible
11	2007-03-06	120,3	NA	Not dispersible

0% Ice B

Sample nr:	Date:	Cum. Time (hurs)	Adjusted MNS	
0	2007-12-03	0,1		
1	2007-12-03	0,3	NA	Good dispersibility
2	2007-12-03	0,6	81	Good dispersibility
3	2007-12-03	1,0	100	Good dispersibility
4	2007-12-03	2,0	98	Good dispersibility
5	2007-12-03	6,0	69	Reduced dispersibility
6	2007-12-03	11,2	59	Reduced dispersibility
7	2007-12-04	24,1	54	Reduced dispersibility
8	2007-12-05	47,7	64	Reduced dispersibility
9	2007-12-06	71,0	52	Reduced dispersibility

30% Ice

Sample nr:	Date:	Cum. Time (hurs)	Adjusted MNS	
1	2007-03-12	0,3	NA	Good dispersibility
2	2007-03-12	0,6	NA	Good to reduced dispersibility
3	2007-03-12	1,1	100	Good to reduced dispersibility
4	2007-03-12	2,2	94	Good to reduced dispersibility
5	2007-03-12	4,5	90	Good to reduced dispersibility
6	2007-03-12	10,3	NA	Reduced dispersibility
7	2007-03-13	25,6	56	Reduced dispersibility
8	2007-03-14	50,0	79	Reduced dispersibility
9	2007-03-15	72,1	82	Reduced dispersibility
10	2007-03-16	94,8	82	Reduced dispersibility

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	Adjusted MNS	
0	2007-03-26	0,1		
1	2007-03-26	0,3	NA	Good dispersibility
2	2007-03-26	0,6	NA	Good dispersibility
3	2007-03-26	1,1	85	Good dispersibility
4	2007-03-26	2,1	100	Good dispersibility
5	2007-03-26	4,1	98	Good dispersibility
6	2007-03-26	9,9	NA	Good dispersibility
7	2007-03-27	23,2	76	Good to reduced dispersibility
8	2007-03-28	45,7	77	Reduced dispersibility
9	2007-03-29	72,4	16	
10	2007-03-30	93,9		

70% Ice

Sample nr:	Date:	Cum. Time (hurs)	Adj MNS	
0	2007-11-06	0,1		
1	2007-11-06	0,3	91	Good dispersibility
2	2007-11-06	0,5	51	Good dispersibility
3	2007-11-06	1,0	100	Good dispersibility
4	2007-11-06	2,1	94	Good dispersibility
5	2007-11-06	6,1	71	Good dispersibility
6	2007-11-06	12,1	80	Good dispersibility
7	2007-11-07	24,1	87	Good dispersibility
8	2007-11-08	48,1	72	Good dispersibility
9	2007-11-09	72,1	77	Good dispersibility
10	2007-11-11	120,1	NA	Good dispersibility
11	2007-11-12	149,2	74	Good dispersibility
12	2007-11-14	169,8	90	Good dispersibility

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	Adj MNS	
0	2007-11-19	0,1		
1	2007-11-19	1,0	100	Good dispersibility
2	2007-11-19	2,0	100	Good dispersibility
3	2007-11-19	6,0	100	Good dispersibility
4	2007-11-19	11,0	91	Good dispersibility
5	2007-11-20	24,0	94	Good dispersibility
6	2007-11-21	48,0	72	Good dispersibility
7	2007-11-22	72,0	72	Good dispersibility
8	2007-11-23	96,0	100	Good dispersibility
9	2007-11-24	120,0	NA	Good dispersibility
10	2007-11-26	144,0	68	Good dispersibility
11	2007-11-27	168,0	94	Good dispersibility

Grane

0% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS	FET adjust
0	2008-02-11	0.1	NA		
1	2008-02-11	0.25	NA		
2	2008-02-11	0.5	100	100	Good dispersibility
3	2008-02-11	1	91	91	Redused dispersibility
4	2008-02-11	2	84	84	Redused dispersibility
5	2008-02-11	6	9	9	Not Dispersible
6	2008-02-11	12.05	NA	NA	Not Dispersible
7	2008-02-12	23.8	19	19	Not Dispersible
8	2008-02-13	47.8	NA	NA	Not Dispersible
9	2008-02-14	72.8	11	11	

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS	
0	18.02.08	0.1	NA		
1	18.02.08	0.25	NA		
2	18.02.08	0.5	86	86	Good dispersibility
3	18.02.08	1	100	100	Good dispersibility
4	18.02.08	2	86	86	Redused dispersibility
5	18.02.08	6	73	73	Not Dispersible
6	18.02.08	12	55	55	Not Dispersible
7	19.02.08	24	6	6	Not Dispersible
8	20.02.08	48	15	15	Not Dispersible
9	21.02.08	72	4	4	Not Dispersible

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS	
0	25.02.08	0.1	NA		
1	25.02.08	0.25	NA		
2	25.02.08	0.5	100	100	Good dispersibility
3	25.02.08	1	100	100	Good dispersibility
4	25.02.08	2	100	100	Good dispersibility
5	25.02.08	6	100	100	Good dispersibility
6	25.02.08	12	100	100	Good dispersibility
7	26.02.08	24	100	100	Good dispersibility
8	27.02.08	48	100	100	Redused dispersibility
9	28.02.08	72	NA		

Kobbe

0% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS%	FET
0	2008-09-15	0	0	na	NA
1	2008-09-15	0.25	na	na	Godt dispergerbar
2	2008-09-15	0.5	20	20	Godt dispergerbar
3	2008-09-15	1	24	24	Godt dispergerbar
4	2008-09-15	2	37	37	Godt dispergerbar
5	2008-09-15	6	25	25	Godt dispergerbar
6	2008-09-15	12	25	25	Godt dispergerbar
7	2008-09-16	24	25	25	Godt dispergerbar
8	2008-09-17	48	31	31	Godt dispergerbar
9	2008-09-18	72	36	36	redusert dispergerbarhet

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS%	FET
0	2008-09-22	0.0	0	na	
1	2008-09-22	0.25	NA	na	ikke målt
2	2008-09-22	0.5	NA	na	Godt dispergerbar
3	2008-09-22	1	78	78	Godt dispergerbar
4	2008-09-22	2	81	81	Godt dispergerbar
5	2008-09-22	6	77	77	Godt dispergerbar
6	2008-09-22	14	75	75	Godt dispergerbar, med noe større dråper enn foregående prøver
7	2008-09-23	28	59	59	Godt dispergerbar, med noe større dråper
8	2008-09-24	47	54	54	Godt dispergerbar, med noe større dråper
9	2008-09-25	76	56	56	Godt dispergerbar, med noe større dråper

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS%	FET
0	2008-09-29	0	0	na	
1	2008-09-29	0.25	NA	na	
2	2008-09-29	0.5	73	66	godt dispergerbar
3	2008-09-29	1	76	69	godt dispergerbar
4	2008-09-29	2	69	63	godt dispergerbar
5	2008-09-29	6	93	84	godt dispergerbar
6	2008-09-29	11	85	77	godt dispergerbar
7	2008-09-30	24	70	63	godt dispergerbar (noen større dråper)
8	2008-10-01	48	110	100	godt dispergerbar (noen større dråper)
9	2008-10-02	72	86	78	godt dispergerbar (noen større dråper)

Norne

0% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS%	FET
0	2008-06-16	0	NA		
1	2008-06-16	0.25	NA		Not dispersible
2	2008-06-16	0.5	0	0	Not dispersible
3	2008-06-16	1	11	11	Redused dispersibility
4	2008-06-16	2	10	10	Redused dispersibility
5	2008-06-16	6	12	12	Redused dispersibility
6	2008-06-16	12	13	13	Good dispersibility
7	2008-06-17	24	16	16	Good dispersibility
8	2008-06-18	48	16	16	Good dispersibility
9	2008-06-19	73	23	23	Good dispersibility

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS%	FET
0	2008-06-23	0	0	0	
1	2008-06-23	0.5	12	12	Redused dispersibility
2	2008-06-23	1	14	14	Redused dispersibility
3	2008-06-23	2	14	14	Redused dispersibility
4	2008-06-23	6	19	19	Good dispersibility
5	2008-06-23	12	20	20	Good dispersibility
6	2008-06-24	27	14	14	Good dispersibility
7	2008-06-25	51	14	14	Good dispersibility
8	2008-06-26	70	14	14	Good dispersibility

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	MNS%	Adjusted MNS%	FET
0	2008-06-30	0.0	0	0	
1	2008-06-30	0.3	NA		
2	2008-06-30	0.5	3	3	Not dispersible
3	2008-06-30	1	15	15	Redused dispersibility
4	2008-06-30	2	15	15	Redused dispersibility
5	2008-06-30	6	5	5	Redused dispersibility
6	2008-06-30	12	2	2	Redused dispersibility
7	2008-07-01	24	26	26	Redused dispersibility
8	2008-07-02	48	28	28	Redused dispersibility
9	2008-07-03	72	26	26	Redused dispersibility

Appendix C: Tables – In situ burning

Statfjord

0% Ice

Sample nr:	Date:	days	Cum. Time (hurs)	BE%	BE%-Corr
0	07-01-08	0.00	0.1	80	80
1	07-01-08	0.01	0.25	80	51
2	07-01-08	0.02	0.5	82	50
3	07-01-08	0.04	1	0	0
4	07-01-08	0.08	2	0	0
5	07-01-08	0.25	6	0	0
6	07-01-08	0.54	13	0	0
7	08-01-08	1.09	26	0	0
8	09-01-08	2.24	54	0	0
9	10-01-08	3.04	73	0	0

50% Ice

Sample nr:	Date:	days	Cum. Time (hurs)	BE%	BE%-Corr
0	21-01-08	0.00	0.1	82	82
1	21-01-08	0.01	0.25	82	82
2	21-01-08	0.02	0.5	79	79
3	21-01-08	0.04	1	65	64
4	21-01-08	0.08	2	55	51
5	21-01-08	0.28	7	60	54
6	21-01-08	0.49	12	70	58
7	22-01-08	1.09	26	0	0
8	23-01-08	2.09	50	0	0
9	24-01-08	3.05	73	0	0

90% Ice

Sample nr:	Date:	days	Cum. Time (hurs)	BE%	BE%-Corr
0	04-02-08	0.00	0.1	82	82
1	04-02-08	0.01	0.25	64	64
2	04-02-08	0.03	0.75	65	64
3	04-02-08	0.04	1	64	62
4	04-02-08	0.08	2	61	60
5	04-02-08	0.25	6	61	60
6	04-02-08	0.50	12	66	63
7	05-02-08	1.00	24	63	61
8	06-02-08	2.00	48	60	58
9	07-02-08	3.00	72	54	51

Troll

0% Ice A

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	2007-02-28	0,0	85	85
1	2007-02-28	0,3	88	84
2	2007-02-28	0,6	88	69
3	2007-02-28	1,3	0	0
4	2007-02-28	2,1	0	0
5	2007-02-28	4,1	0	0
7	2007-03-01	22,8		0
8	2007-03-02	47,0		
9	2007-03-03	70,8		
10	2007-03-04	95,3		
11	2007-03-06	120,3		

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	2007-03-26	0,1	88	88
1	2007-03-26	0,3	84	80
2	2007-03-26	0,6	81	74
3	2007-03-26	1,1	83	77
4	2007-03-26	2,1	78	66
5	2007-03-26	4,1	63	24
6	2007-03-26	9,9	0	0
7	2007-03-27	23,2	0	0
8	2007-03-28	45,7	0	0
9	2007-03-29	72,4	0	0
10	2007-03-30	93,9	0	0

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	2007-11-19	0,1	63	63
1	2007-11-19	1,0	63	63
2	2007-11-19	2,0	63	63
3	2007-11-19	6,0	63	63
4	2007-11-19	11,0	63	62
5	2007-11-20	24,0	63	59
6	2007-11-21	48,0	72	60
7	2007-11-22	72,0	63	53
8	2007-11-23	96,0	63	44
9	2007-11-24	120,0	63	50
10	2007-11-26	144,0	82	72
11	2007-11-27	168,0	0	0

Grane

0% Ice

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	2008-02-11	0.1	84	84
1	2008-02-11	0.25	0	0
2	2008-02-11	0.5	0	0
3	2008-02-11	1	0	0
4	2008-02-11	2	0	0
5	2008-02-11	6	0	0
6	2008-02-11	12.05	0	0
7	2008-02-12	23.8	0	0
8	2008-02-13	47.8	0	0
9	2008-02-14	72.8	0	0

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	18.02.08	0.1	84	84
1	18.02.08	0.25	84	78
2	18.02.08	0.5	85	77
3	18.02.08	1	83	64
4	18.02.08	2	0	0
5	18.02.08	6	0	0
6	18.02.08	12	0	0
7	19.02.08	24	0	0
8	20.02.08	48	0	0
9	21.02.08	72	0	0

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	25.02.08	0.1	84	84
1	25.02.08	0.25	55	55
2	25.02.08	0.5	57	56
3	25.02.08	1	86	83
4	25.02.08	2	92	92
5	25.02.08	6	86	85
6	25.02.08	12	0	0
7	26.02.08	24	0	0
8	27.02.08	48	0	0
9	28.02.08	72		0

Kobbe

0% Ice

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	2008-09-15	0	64	64
1	2008-09-15	0.25	77	54
2	2008-09-15	0.5	81	53
3	2008-09-15	1	83	58
4	2008-09-15	2	81	59
5	2008-09-15	6	82	54
6	2008-09-15	12	79	45
7	2008-09-16	24	81	47
8	2008-09-17	48	0	0
9	2008-09-18	72	0	0

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	2008-09-22	0.0	64	64
1	2008-09-22	0.25	70	65
2	2008-09-22	0.5	65	59
3	2008-09-22	1	64	55
4	2008-09-22	2	61	54
5	2008-09-22	6	62	55
6	2008-09-22	14	62	53
7	2008-09-23	28	64	44
8	2008-09-24	47	0	0
9	2008-09-25	76	0	0

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	2008-09-29	0	64	64
1	2008-09-29	0.25	62	62
2	2008-09-29	0.5	62	62
3	2008-09-29	1	63	62
4	2008-09-29	2	64	60
5	2008-09-29	6	60	59
6	2008-09-29	11	58	58
7	2008-09-30	24	54	53
8	2008-10-01	48	48	45
9	2008-10-02	72	51	47

Norne

0% Ice

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	2008-06-16	0	47	47
1	2008-06-16	0.25	45	40
2	2008-06-16	0.5	51	47
3	2008-06-16	1	0	0
4	2008-06-16	2	0	0
5	2008-06-16	6	0	0
6	2008-06-16	12	0	0
7	2008-06-17	24	0	0
8	2008-06-18	48	0	0
9	2008-06-19	73	0	0

50% Ice

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	2008-06-23	0	47	47
1	2008-06-23	0.5	54	49
2	2008-06-23	1	79	76
3	2008-06-23	2	54	49
4	2008-06-23	6	45	28
5	2008-06-23	12	42	28
6	2008-06-24	27	49	36
7	2008-06-25	51	0	0
8	2008-06-26	70	0	0

90% Ice

Sample nr:	Date:	Cum. Time (hurs)	BE%	BE%-Corr
0	2008-06-30	0.0	47	47
1	2008-06-30	0.3	50	44
2	2008-06-30	0.5	54	49
3	2008-06-30	1	54	50
4	2008-06-30	2	51	46
5	2008-06-30	6	55	50
6	2008-06-30	12	51	46
7	2008-07-01	24	43	41
8	2008-07-02	48	45	42
9	2008-07-03	72	45	40