ARCTIC RESPONSE TECHNOLOGY
OIL SPILL PREPAREDNESS

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EVALUATION OF DISPERSANT EFFICIENCY

ABSTRACT

The overall objective of the project is to build on current knowledge in order to increase understanding of the oil types, oil weathering limits, and environmental conditions where dispersants could be an effective response option.

Boundaries for dispersant effectiveness testing using three commercial dispersants (Corexit 9500, Dasic NS, and OSR-52) and five different oils (Alaska North Slope (paraffinic), Grane (asphalthenic), Troll Blend (mixture of naphthenic and paraffinic), and Oseberg Blend (paraffinic), and a bunker oil (IF80)) were estimated using flume-based experiments varying parameters such as mixing energy, weathering time, and seawater salinity.

The ice cover did not influence the results significantly, but water salinity did with the poorest dispersant effectiveness found for the 5 ppt salinity water. As expected, the dispersant effectiveness varied with both oil type and dispersant type applied, and the effectiveness increased when higher mixing energy conditions were used.

TABLE OF CONTENTS

ABSTRACT ... 2

INTRODUCTION ... 8

MATERIALS AND METHODS ... 9
- Oils and dispersants ... 9
- Test tank preparation ... 10
- In situ weathering of the oil in the flume ... 12
- Dispersant application ... 12
- Test matrix overview ... 12
- Measurements of dispersant effectiveness ... 14

RESULTS AND DISCUSSION ... 16
- Oil types and dispersants ... 16
- Oil weathering time ... 17
- Water salinity ... 18

ADDITIONAL TESTING ... 20
- Tests without ice and without propeller wash ... 21
- Repeatability of the test conditions in the flume ... 21
- Dispersible oil tested at low and high temperature ... 22
- Comparing bench scale testing with mesoscale testing in the flume ... 23
- MNS testing of Troll fresh oil ... 25

FACTORS INFLUENCING THE DISPERSANT EFFECTIVENESS ... 27

REFERENCES ... 29

APPENDIX A SINTEF RESULTS AND DISCUSSION ... 30
- A.1 Test procedure ... 30
- A.2 Background ... 30
- A.3 Tests conducted ... 30
- A.4 Test results and discussion ... 31
- A.5 Summary ... 38

APPENDIX B SL ROSS RESULTS AND DISCUSSION ... 40
- B.1 Test procedure ... 40
- B.2 Background ... 40
- B.3 Tests conducted ... 40
- B.4 Test results and discussion ... 41
- B.5 SL Ross Result Summary Highlights ... 47

APPENDIX C GC CHROMATOGRAMS FROM SINTEF ... 49

APPENDIX D GC CHROMATOGRAMS FROM SL ROSS ... 53

APPENDIX E DATA ON PARTICLE SIZE DISTRIBUTION FROM SINTEF ... 57

APPENDIX F DATA ON PARTICLE SIZE DISTRIBUTION FROM SL ROSS ... 65

LIST OF FIGURES

Figure 2.1 Sketch of the SINTEF and SL Ross flume ... 11

Figure 2.2 SINTEF flume prior to dispersion: LISST positioned horizontally at 50 cm depth (left) and SilCam positioned vertically with monitoring at 50 cm depth (right photo). ... 15

Figure 3.1 Dispersant efficiency vs dispersant type. Oils were weathered for 18 hrs in 80% ice and 35 ppt salinity water. DE measured from water grab samples collected after prop wash. ... 17

Figure 3.2 Dispersant efficiency vs weathering time. Oils were weathered for 6 hrs or 18 hrs in 80% ice and 35 ppt salinity water (Grane Corexit 9500 6hrs not performed). DE measured from water grab samples collected after prop wash..........18

Figure 3.3 Dispersant efficiency vs water salinity. Oils were weathered for 18 hrs in 80% ice. DE measured from water grab samples collected after prop wash. No bars indicate that no testing was performed..........19

Figure A 1 Dispersant efficiency for Troll Blend..........33

Figure A 2 Dispersant efficiency for Oseberg Blend..........34

Figure A 3 Dispersant efficiency for Grane..........35

Figure A 4 Comparing dispersant efficiency in 35 ppt salinity water for the three oil types (HE: High energy, PW: prop wash)..........36

Figure A 5 Comparing dispersant efficiency in 15 ppt salinity water for the three oil types (HE: High energy, PW: prop wash)..........37

Figure A 6 Comparing dispersant efficiency in 5 ppt salinity water for the three oil types (HE: High energy, PW: prop wash)..........37

Figure B 1 Dispersant efficiency for Alaska North Slope crude oil..........44

Figure B 2 Dispersant efficiency for Grane crude oil..........44

Figure B 3 Dispersant efficiency for IFO 80..........45

Figure B 4 Dispersant efficiency in 35 ppt salinity water for ANS and Grane crude oils (HE: High energy, PW: prop wash)..........46

Figure B 5 Dispersant efficiency in 15 ppt salinity water for ANS and Grane crude oils (HE: High energy, PW: prop wash)..........46

Figure C 1 GC chromatograms of Oseberg Blend weathered for 18 hrs in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.5..........49

Figure C 2 GC chromatograms of Troll Blend weathered for 18 hrs in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.5..........50

Figure C 3 GC chromatograms of Grane crude oil weathered for 18 hrs in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.5..........51

Figure C 4 GC chromatograms of the oils prior to dispersant application. Explanation of test identifications is provided in Table 4.1..........52

Figure D 1 GC chromatograms of IFO 80 weathered in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.6..........53

Figure D 2 GC chromatograms of ANS crude oils weathered in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.6..........54

Figure D 3 GC chromatograms of ANS crude oils weathered in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.6..........55

Figure D 4 GC chromatograms of Troll crude oil weathered for 18 hrs in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.6..........55

Figure D 5 GC chromatograms of Grane crude oil weathered in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.6..........56

Figure E 1 TRL-D-80-35..........59

Figure E 2 TRL-D-80-15..........59

Figure E 3 TRL-D-80-05..........59

Figure E 4 TRL-O-80-35..........59

Figure E 5 TRL-O-80-15..........60

Figure E 6 OSB-D-80-35..........60

Figure E 7 OSB-D-80-15..........60

Figure E 8 OSB-D-80-05..........60

Figure E 9 OSB-O-80-35..........61

Figure E 10 OSB-O-80-15..........61

Figure E 11 GRN-D-80-35..........61

Figure E 12 GRN-D-80-15..........61

Figure E 13 GRN-D-80-05..........62

Figure E 14 GRN-C-0-35-L 62
Figure E 15 TRL-C-0-35-L 62
Figure E 16 OSE-C-0-35-L....62
Figure E 17 GRN-C-80-35-A....63
Figure E 18 GRN-C-80-35-B 63
Figure E 19 GRN-C-80-35-C....63
Figure E 20 TRL-C-0-35-F-13....63
Figure E 21 TRL-C-80-35-F-0....64
Figure F1 ANS-D-80-35-6....66
Figure F2 ANS-D-80-15-6....66
Figure F3 ANS-D-80-35-18....67
Figure F4 ANS-D-80-15-18....67
Figure F5 ANS-O-80-35-6 67
Figure F6 ANS-O-80-15-6 68
Figure F7 ANS-O-80-35-18 68
Figure F8 ANS-O-80-15-18 68
Figure F9 ANS-C-80-35-6....69
Figure F10 ANS-C-80-35-18....69
Figure F11 ANS-C-80-15-18....69
Figure F12 GRN-D-50-35-6 70
Figure F13 GRN-D-50-15-6 70
Figure F14 GRN-O-80-35-6....70
Figure F15 GRN-O-80-15-6....71
Figure F16 GRN-C-50-35-18 71
Figure F17 GRN-C-50-15-18 71
Figure F18 IFO-D-80-35-6....72
Figure F19 IFO-D-80-35-18....72
Figure F20 IFO-O-80-35-6....72
Figure F21 IFO-O-80-35-18....73
Figure F22 IFO-C-80-35-6 73
Figure F23 IFO-C-80-35-18 73
Figure F24 TR-C-80-35-18....74
Figure F25 GRN-C-80-35-18 74
Figure F26 ANS-C-0-35-L....74
Figure F27 ANS-C-80-35-A 75
Figure F28 ANS-C-80-35-B 75
Figure F29 ANS-C-80-35-C....75

LIST OF FIGURES

Table 2.1 Density, viscosity and pour point for the crude oils: Troll Blend, Oseberg Blend, and Grane, and density for IFO 80. Viscosity is measured at 2°C at SINTEF and 0°C at SL Ross. 9
Table 2.2 Densities and evaporative loss (in vol %) of fresh oils and residues from artificial weathering in laboratory from previous studies. Density measured at 15.5°C. 10
Table 2.3 Key figures for the flumes 11
Table 2.4 Size distribution of ice in the SINTEF/SL Ross flumes. Note that the number of pieces in the containment area is included in the numbers for the total flume....12
Table 2.5 Tests performed at SINTEF. Weathering time of 18 hrs for all experiments. 12

Table 2.6 Tests performed at SL Ross. DOR of 1 to 20 used in all tests. (L: Low energy; H: High energy; Prop: Prop wash) 13
Table 3.1 Comparison of tests performed at SINTEF and SL Ross in the present phase of the project. 16
Table 4.1 Test matrix overview. Tests with Alaska North Slope were performed at SL Ross, and the remaining tests at SINTEF. One liter of oil, Corexit 9500 and 35 ppt seawater were used in all tests. 20
Table 4.2 Oil properties prior to dispersant application, and oil concentrations in water grab samples (from UV) and estimated dispersant efficiency after low energy exposure for 30 min. Amount dispersed oil is corrected for estimated evaporative loss and sampled oil volume (50 mL). 21
Table 4.3 Replicate tests with average dispersant efficiency (in %) and absolute standard deviation. Oil properties prior to dispersant application, oil concentrations in water grab samples (from UV) and estimated dispersant efficiency after high energy (30 min) and prop wash (10 min). Amount dispersed oil is corrected for estimated evaporative loss and sampled oil volume (50 mL). 21
Table 4.4 Tests comparing dispersant efficiency of fresh Troll oil at low (0 ºC and 80% ice) and high temperature (13 ºC and no ice). Oil properties prior to dispersant application, oil concentrations in water grab samples (from UV) and estimated dispersant efficiency after high energy (30 min) and prop wash (10 min). Amount dispersed oil is corrected for estimated evaporative loss and sampled oil volume (50 mL). 23
Table 4.5 Comparing estimated dispersant efficiency of MNS testing and in situ dispersant testing in the meso scale flume. 25
Table 4.6 Dispersant efficiency for Troll fresh oil dispersed in bench scale (MNS) and in the meso scale flume. 26
Table A 1 Description of the tests performed at SINTEF with Test ID and test parameters. A dispersant to oil ratio of 1 to 20 was used in all tests (Abbreviations used in Test ID are as follows: TRL: Troll, OSB: Oseberg, GRN: Grane; D: Dasic NS, O: OSR-52, E: Experimental dispersant; 80: Ice coverage; 35, 15 or 05: salinity in seawater). 30
Table A 2 Oil properties after in situ weathering and prior to dispersant application. Data for tests with Corexit 9500 are from Faksness et al. (2015). Explanation to Test ID: TRL: Troll, OSB: Oseberg, GRN: Grane; D: Dasic NS, O: OSR-52, 80: Ice coverage; 35, 15 or 05: salinity in seawater, 1 and 2: re-test. 31
Table A 3 Oil concentration in water (from UV measurements) and estimated dispersant efficiency of weathered oil. Estimated evaporative loss is predicted by correlation of density and evaporative loss from artificial weathering performed in previous studies at SINTEF. 32
Table A 4 Overview of the experiments performed in the flume combining the LISST and silhouette camera. 38
Table B 1 Description of the tests performed at SL Ross with Test ID and test parameters. Dispersant to oil ratio of 1 to 20 (by volume) was used in all tests. Test ID codes as follows: ANS: Alaska North Slope, GRN: Grane, IFO 80: IFO; D: Dasic, O: OSR-52; 80 or 50: Ice coverage; 35 or 15: salinity in seawater; 18 or 6: weathering time in hours 40
Table B 2 Oil properties after in situ weathering and prior to dispersant application.). Explanation of Test ID codes is as follows: ANS: Alaska North Slope, GRN: Grane, IFO 80: IFO; D: Dasic, O: OSR-52; 80 or 50: Ice coverage; 35 or 15: salinity in seawater; 18 or 6: weathering time in hours 41
Table B 3 Oil concentration in water (from UV measurements) and estimated dispersant efficiency of weathered oil. Estimated evaporative loss is predicted by correlation of density and evaporative loss from artificial weathering performed in previous studies at SL Ross. 43
Table B 4 Summary of SL Ross Dispersant Effectiveness Results 47
Table E 1 Summary of LISST data and oil concentration in water grab samples from SINTEF. 57
Table E 2 Summary of LISST data and oil concentration in water grab samples from SINTEF. Test parameters for these additional tests are provided in Table 4.1 58
Table F 1 Summary of LISST data and oil concentration in water grab samples from SL Ross. 65

Table F 2 Summary of LISST data and oil concentration in water grab samples for Task 4 tests from SL Ross 66

INTRODUCTION

As a first phase of Task 2 of the Arctic Oil Spill Response Technology – Joint Industry Programme (Arctic JIP) project "Dispersant testing under realistic conditions", CEDRE, SINTEF and SL Ross Environmental Research Ltd. (SL Ross) conducted a calibration between their three flumes. Dispersant effectiveness testing of one oil-dispersant combination was performed using the pre-weathered Norwegian crude oil Grane and Corexit 9500 dispersant at three different energy conditions (low, medium, high). Very similar dispersant efficiencies were achieved in all three flumes, especially at low and high energy levels (Faksness et al., 2014).

In the second phase, natural ice was compared with artificial ice to investigate if polyethylene blocks (PE-blocks) behaved similarly to natural ice, and could replace natural ice in the planned dispersant and mineral fines efficiency testing without sacrificing accuracy. Results demonstrated that natural ice and not PE blocks should be used in the experiments (Faksness and Belore, 2014).

The objective of the third phase established boundaries for dispersant efficiency using Corexit 9500 dispersant applied to the following oils: Alaska North Slope (ANS); the Norwegian crude oils Grane, Troll Blend and Oseberg Blend; and IFO 80. In total 30 tests were performed in the flume basins at SINTEF and SL Ross. The oils were in situ weathered in the flume for 18 hours prior to dispersant application and the test parameters were 50% and 80% ice cover and different salinities (35 ppt, 15 ppt, and 5 ppt). Ice cover did not impact the results, but the median oil droplet size (d50) monitored by the LISST increased with decreasing water salinity, resulting in a lower dispersant efficiency in water with lower salinity. The highest achieved dispersant efficiency was obtained with Troll Blend (a mixture of a naphthenic and paraffinic oil), followed by the asphaltenic crude Grane, the paraffinic Oseberg Blend and the Alaska North Slope crude. More details are provided in Faksness et al. (2016).

In the current phase of the project (Task 4), the five oils noted above were tested with three commercial dispersants (Corexit 9500, Dasic NS, and OSR-52). The same weathering protocol as in Phase 3 was followed. Seawater salinities were varied, and ice coverage of 80% was used in all tests.

Planned testing of an experimental dispersant ("food-grade dispersant") was canceled. Ethanol was used as a solvent in the experimental dispersant, resulting in a flash point of 14 °C, which made the dispersant unsuitable for operational use.

The Arctic JIP commissioned additional meso-scale flume experiments to strengthen the test results.

- Tests at low temperature without ice and prop wash to study if ice movement increases the surface turbulence and thereby the dispersant efficiency.
- Repeatability of test conditions in the flume to determine the bound of uncertainty in the results.
- Dispersible oil tested at low and high temperature to investigate if the test protocol limits the total amount of dispersed oil.
- Compare bench scale dispersant testing with meso-scale testing in the flume.
    - MNS testing of fresh oil at low and high temperature
    - Summarize previous weathering studies of different oil types to look for trends when comparing MNS with meso scale testing.

The results from the additional tests are reported in Chapter 4.

MATERIALS AND METHODS

Oils and dispersants

Five oils were used: Alaska North Slope, a heavy bunker oil (IFO 80) and the three North Sea crudes Troll Blend, Oseberg Blend, and Grane. Properties of the oils are given in Table 2.1. The commercial dispersants Dasic NS and OSR-52 were used in the experiments at a dispersant-to-oil ratio (DOR) of 1:20 by volume. Corexit 9500 has been tested with these oils in a previous phase of the project (Faksness et al., 2016).

The experimental dispersant was delivered for preliminary testing in mid-December, 2015. However, it was decided that the experimental dispersant was unsuited for operational use due to its low flash point (14 °C). Therefore, the planned flume tests using the experimental dispersant were cancelled.

Table 2.1 Density, viscosity and pour point for the crude oils: Troll Blend, Oseberg Blend, and Grane, and density for IFO 80. Viscosity is measured at 2°C at SINTEF and 0°C at SL Ross.

Oil ID	Oil type	Density (g/mL)	Viscosity (cP) 100s^{-1} (10s^{-1})	Pour point (°C)
2014-0335	Troll Blend (SINTEF)	0.855 (15.5 °C)	22 (34)	-30 °C
2015-0060	Oseberg Blend (SINTEF)	0.823 (15.5 °C)	10 (17)	-15 °C
2015-0061	Grane (SINTEF)	0.932 (15.5 °C)	978 (1019)	-15 °C
2015-0061	Grane (SL Ross)	0.926 (20 °C)	1500	-15 °C
2014-BSEE	Alaska North Slope (SL Ross)	0.874 (20 °C)	40	-18 °C
2015-0466	IFO 80* (SL Ross)	0.947 (20 °C)	10160 (10s^{-1})	3 °C
2015-0466	IFO 80 (SINTEF)	0.950 (15.5 °C)	4299 (7718)	3 °C

** IFO 80 is a blend of 17% ADO (automotive diesel oil) and 83% IFO380*

Densities of the fresh oils and the artificially weathered residues of the oils, as reported in previous studies of the crudes, are given in Table 2.2. Troll Blend is a mix of the naphthenic Troll C and the more paraffinic Fram oil, which is transported in the same pipeline to the Mongstad terminal onshore. The mix ratio of the two oils was not known, so the oil was artificially weathered by one-step distillation (Stiver and Mckay, 1984) at SINTEF in August 2015. The evaporative loss was higher than expected, and indicated that in addition to Troll and Fram, the oil could be a blend of the lighter oils Kvitebjørn and Gjøa. Measured density in the oil sampled after the weathering period, combined with the GC chromatograms, were compared with density from the artificial weathering and used to estimate evaporative loss from the test slicks prior to dispersant application.

Table 2.2 Densities and evaporative loss (in vol %) of fresh oils and residues from artificial weathering in laboratory from previous studies. Density measured at 15.5°C.

	Fresh oil	150 °C+		175 °C+		200 °C+		250 °C+	
Oil	Density	Evaporated	Density	Evaporated	Density	Evaporated	Density	Evaporated	Density
Troll Blend[1)]	0.855	18%	0.881	26%	0.890	29%	0.895	41%	0.908
Oseberg Blend[2)]	0.839	22%	0.873	-	-	34%	0.888	45%	0.904
Grane[3)]	0.942	3%	0.948	-	-	5%	0.950	13%	0.960

[1)]Artificially weathered at SINTEF in August 2015. [2)] Leirvik and Resby, 2007. [3)] Singsaas et al., 2005.

Test tank preparation

A sketch of the flume is shown in Figure 2.1. More detailed descriptions of the flumes and their settings are given in detail in the report from the test tank inter-calibration (Faksness et al., 2014). The confinement area for oil weathering was located on the opposite side of the wave maker, as illustrated in Figure 2.1. Key figures and settings for the flumes are provided in Table 2.3.

The LISST was located on the opposite side of the wave generator (position B, outside the confinement area). The water samples were collected using a Siphon system placed next to the LISST at 50 cm depth. The propeller used in the prop wash energy addition was placed in the centre of the flume before position A at 22 cm depth and pointed upwards (second position from vertical on the transom mount).

Approximately 4.8 m^3 of seawater is circulated in the 10 meter long flumes. The SINTEF flume is located in a temperature controlled room (0°C – 20°C). The SL Ross tank sides and cover are insulated to maintain the water and air temperature during the testing. The water in both flumes is cooled by a refrigeration system connected to a cooling coil placed in the tank water. Two fans placed in in a covered wind tunnel allow for control of the wind speed.

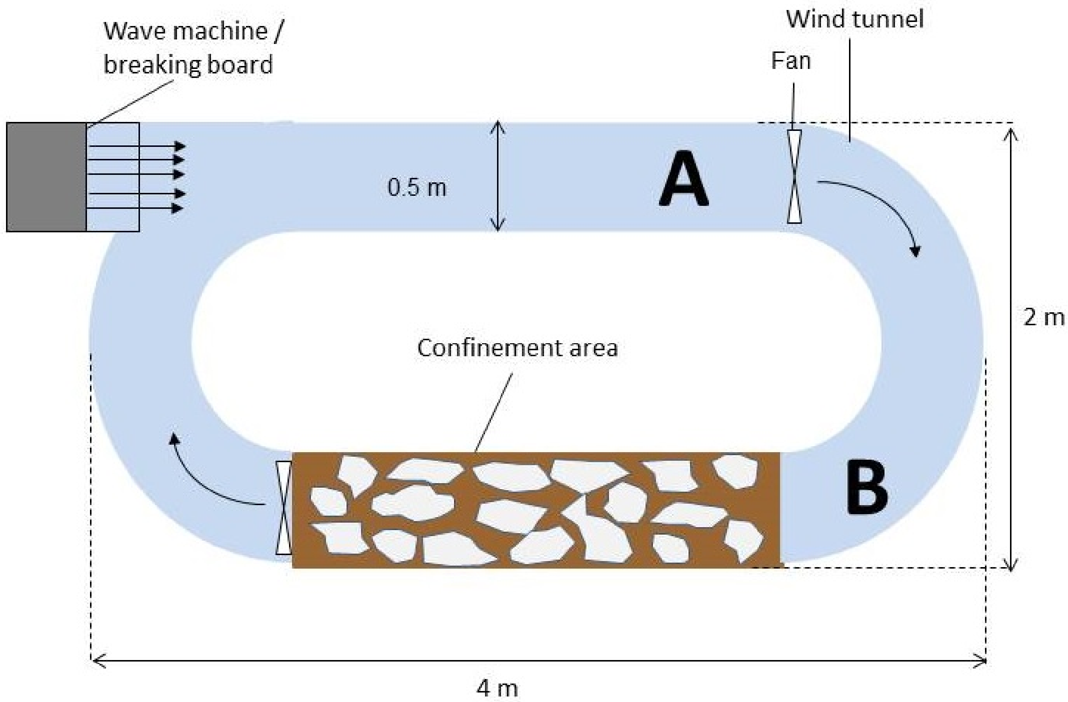

Figure 2.1 Sketch of the SINTEF and SL Ross flume

Table 2.3 Key figures for the flumes

Temperature water	-2 to 0 °C
Flume (circulation) length inner wall	10.2 m
Flume (circulation) length outer wall	16.6 m
Flume height	1.5 m
Flume width	0.5 m
Water depth	1 m
Water volume	4,800 L
Surface area in flume	4.36 m^2
Containment area for oil and dispersant application	1 m^2
Dispersant applicator	Wagner 450
Nozzle size applicator (25% flow capacity)	0.5 mm
Oil volume	1 L
Dispersant to oil ratio (DOR)	1:20
Particle size analyzer	LISST*
Low energy settings	
Frequency wave maker	24 rpm
Amplitude wave maker	12 cm
High energy settings	
Frequency wave maker	30 rpm
Amplitude wave maker	16 cm
Wind speed (reversed wind containment area)	1.2 m/s
Propeller	MinnKota Endura 30

**LISST100x: Laser In-Situ Scattering and Transmissiometry (Sequoia Scientific, Inc.)*

Natural ice blocks of three different sizes were prepared using 0.5% salinity water. The sizes and quantity of the ice blocks used in each test are provided in Table 2.4. The natural ice was replenished in the confinement area during the weathering time as needed to maintain the target ice concentration.

Table 2.4 Size distribution of ice in the SINTEF/SL Ross flumes. Note that the number of pieces in the containment area is included in the numbers for the total flume.

Total flume area (4.36 m^2)		50% ice		80% ice	
	Size (m)	Number	Area (m^2)	Number	Area (m^2)
Squares	0.2 x 0.2	11	0.44	16	0.64
	0.1 x 0.1	84	0.84	141	1.41
	0.05 x 0.05	364	0.91	536	1.34
Containment area (1.0 m^2)					
Squares	0.2 x 0.2	5	0.20	6	0.24
	0.1 x 0.1	20	0.20	31	0.31
	0.05 x 0.05	40	0.10	76	0.19

In situ weathering of the oil in the flume

The protocol and methods described in Faksness et al. (2016) were followed to weather the oil in the flumes, prior to dispersant application.

Dispersant application

There was one deviation from the protocol for dispersant application and efficiency testing compared to Faksness et al. (2016): No low energy input was applied for the dispersant testing, only high energy input (30 min) followed by propeller mixing for 10 minutes. Results to date indicated that low wave energy was producing limited dispersant effectiveness and may have reduced the dispersant effectiveness in subsequent high energy periods, probably due to loss of dispersant from the oil during the low energy mixing.

Test matrix overview

The experiments performed at SINTEF are described in Table 2.5. SINTEF has followed the protocol described above for in situ weathering, dispersant application, and energy regime. Exceptions are commented in Table 2.5 (no test with the experimental dispersant were performed). More details are provided in Appendix A.

Table 2.5 Tests performed at SINTEF. Weathering time of 18 hrs for all experiments.

Test ID	Oil	Dispersant	Ice conc	Weathering time	Energy	Salinity	Comments
TRL-D-80-35	Troll Blend	Dasic	80%	18 hrs	H+P	35 ppt	
TRL-D-80-15	Troll Blend	Dasic	80%	18 hrs	H+P	15 ppt	
TRL-D-80-05	Troll Blend	Dasic	80%	18 hrs	H+P	5 ppt	
OSB-D-80-35	Oseberg Blend	Dasic	80%	18 hrs	H+P	35 ppt	
OSB-D-80-15	Oseberg Blend	Dasic	80%	18 hrs	H+P	15 ppt	
OSB-D-80-05	Oseberg	Dasic	80%	18 hrs	H+P	5 ppt	

Test ID	Oil	Dispersant	Ice conc	Weathering time	Energy	Salinity	Comments
GRN-D-80-35	Grane	Dasic	80%	18 hrs	H+P	35 ppt	
GRN-D-80-15	Grane	Dasic	80%	18 hrs	H+P	15 ppt	
GRN-D-80-05	Grane	Dasic	80%	18 hrs	H+P	5 ppt	
TRL-O-80-35	Troll Blend	OSR-52	80%	18 hrs	H+P	35 ppt	
TRL-O-80-15	Troll Blend	OSR-52	80%	18 hrs	H+P	15 ppt	
OSB-O-80-35	Oseberg Blend	OSR-52	80%	18 hrs	H+P	35 ppt	
OSB-O-80-15	Oseberg Blend	OSR-52	80%	18 hrs	H+P	15 ppt	
GRN-O-80-35	Grane	OSR-52	80%	18 hrs	H+P	35 ppt	
GRN-O-80-15	Grane	OSR-52	80%	18 hrs	H+P	15 ppt	
TRL-E-80-35	Troll Blend	Exp disp	80%	18 hrs	H+P	35 ppt	Cancelled
TRL-E-80-15	Troll Blend	Exp disp	80%	18 hrs	H+P	15 ppt	Cancelled
OSB-E-80-35	Oseberg Blend	Exp disp	80%	18 hrs	H+P	35 ppt	Cancelled
OSB-E-80-15	Oseberg Blend	Exp disp	80%	18 hrs	H+P	15 ppt	Cancelled
GRN-E-80-35	Grane	Exp disp	80%	18 hrs	H+P	35 ppt	Cancelled
GRN-E-80-15	Grane	Exp disp	80%	18 hrs	H+P	15 ppt	Cancelled

Table 2.6 gives the tests performed at SL Ross. SL Ross has followed the protocol for in situ weathering and dispersant application, but has varied the weathering time in some of the tests. Tests with the bunker oil are reported here, as no bunker oil was available in the previous phase of the project. More details are provided in Appendix B.

Table 2.6 Tests performed at SL Ross. DOR of 1 to 20 used in all tests. (L: Low energy; H: High energy; Prop: Prop wash)

Test ID	Oil	Dispersant	Ice conc.	Weathering time	Energy	Salinity	Comment
ANS-D-80-35-6	ANS	Dasic	80%	6 hrs	H+P	35 ppt	
ANS-D-80-15-6	ANS	Dasic	80%	6 hrs	H+P	15 ppt	
ANS-D-80-35-18	ANS	Dasic	80%	18 hrs	H+P	35 ppt	
ANS-D-80-15-18	ANS	Dasic	80%	18 hrs	H+P	15 ppt	
GRN-D-50-35-6	Grane	Dasic	50%	6 hrs	H+P	35 ppt	
GRN-D-50-15-6	Grane	Dasic	50%	6 hrs	H+P	15 ppt	
IFO-D-80-35-18	IFO 80	Dasic	80%	18 hrs	H+P	35 ppt	
IFO-D-80-35-6	IFO 80	Dasic	80%	18 hrs	H+P	35 ppt	
ANS-O-80-35-6	ANS	OSR-52	80%	6 hrs	H+P	35 ppt	
ANS-O-80-15-6	ANS	OSR-52	80%	6 hrs	H+P	15 ppt	
ANS-O-80-35-18	ANS	OSR-52	80%	18 hrs	H+P	35 ppt	
ANS-O-80-15-18	ANS	OSR-52	80%	18 hrs	H+P	15 ppt	
GRN-O-80-35-6	Grane	OSR-52	80%	6 hrs	H+P	35 ppt	
GRN-O-80-15-6	Grane	OSR-52	80%	6 hrs	H+P	15 ppt	
IFO-O-80-35-18	IFO 80	OSR-52	80%	18 hrs	H+P	35 ppt	
IFO-O-80-35-6	IFO 80	OSR-52	80%	6 hrs	H+P	35 ppt	
	ANS	Exp disp	80%	18 hrs	H+P	35 ppt	Cancelled
	ANS	Exp disp	80%	18 hrs	H+P	15 ppt	Cancelled

Test ID	Oil	Dispersant	Ice conc.	Weathering time	Energy	Salinity	Comment
	IFO 80	Exp disp	80%	18 hrs	H+P	35 ppt	Cancelled
	IFO 80	Exp disp	80%	18 hrs	H+P	15 ppt	Cancelled
ANS-C-80-35-18	ANS	Corexit 9500	80%	18 hrs	H+P	35 ppt	Repeat of Task 2 test
ANS-C-80-15-18	ANS	Corexit 9500	80%	18 hrs	H+P	35 ppt	Task 2 test
GRN-C-50-35-18	Grane	Corexit 9500	80%	18hrs	L+H+P	35 ppt	Interlab comparison
IFO-C-80-35-18	IFO 80	Corexit 9500	80%	18 hrs	H+P	35 ppt	
IFO-C-80-35-6	IFO 80	Corexit 9500	80%	6 hrs	H+P	35 ppt	
TR-C-80-35-18	Troll	Corexit 9500	80%	18 hrs	L+H+P	35 ppt	Interlab comparison

Measurements of dispersant effectiveness

To quantify the dispersant effectiveness, both SINTEF and SL Ross have extensive experience with the use of the combination of LISST and water sampling to measure oil droplet size and oil concentration in the water column. The oil concentration in water samples was determined by liquid-liquid extraction with dichloromethane followed by colorimetric analysis of concentration using a response curve for a weathered oil samples (methods described in Faksness and Belore (2014)).

In addition, SINTEF tested a silhouette camera (SilCam) in combination with the LISST in three of the tests in order to measure the particle size distribution. The silhouette camera was placed in such a way that the observation path, through which the water flows, was approximately 50 cm above the floor of the flume, at a similar height as the LISST observation path. The silhouette camera and LISST instruments were placed after each other in one of the bends of the flume. This positioning was done in order to have the measurements of the silhouette camera and the LISST as close to each other as possible (Figure 2.2).

The LISST is a system based on laser diffraction. The LISST used in the experiments was a LISST-100x type C, which can detect droplets in the range of 5-500 µm. A silhouette camera was added to the study to measure droplets outside the range of the LISST.

Figure 2.2 SINTEF flume prior to dispersion: LISST positioned horizontally at 50 cm depth (left) and SilCam positioned vertically with monitoring at 50 cm depth (right photo).

RESULTS AND DISCUSSION

Detailed results and discussion from SINTEF are provided in Appendix A and from SL Ross in Appendix B. A summary of the results is provided below, with a focus on conditions and parameters that could possibly influence boundaries for dispersant effectiveness.

SINTEF and SL Ross have performed two similar tests in this phase of the project to confirm that the results obtained by each laboratory are comparable. The results are presented in Table 3.1. SINTEF and SL Ross have previously performed two inter-calibration studies to compare methodology and tank settings (Faksness et al. (2014) and Faksness and Belore (2014)). These studies indicated that there was a very good correlation between the two tanks.

Grane crude was tested in both tanks in the recent testing (Table 3.1), and the results confirmed that the dispersant efficiency correlated well. Different ice concentrations were used, but this parameter appears to have a small impact on the results based on other test outcomes (Faksness et al., 2016).

Table 3.1 Comparison of tests performed at SINTEF and SL Ross in the present phase of the project.

		Oil in water from UV (ppm)		Dispersant efficiency (%)	
Test ID	Estimated evap loss (wt%)	High energy	Prop wash	High energy	Prop wash
GRN-C-80-35 SINTEF	5	129	121	73	68
GRN-C-50-35 SL Ross	6	101	104	61	63

Oil types and dispersants

The relative dispersant effectiveness (DE) of four crude oils and one bunker oil has been tested in this phase of the project: Alaska North Slope, IFO 80 and Norwegian crudes Troll Blend, Oseberg Blend, and Grane. Dasic NS and Finasol OSR-52 dispersants were used in the experiments, while Corexit 9500 dispersant has been tested in a previous phase of the project (Faksness et al., 2016). The results are included for comparison.

The IFO80 used in this study was blended from IFO380 and diesel fuel to meet the specifications of IFO80 (i.e., a kinematic viscosity of 80 cSt at 50 ºC). Other properties (e.g. pour point, density, flash point) are not specified by the IFO classification, and may vary depending on the characteristics of the parent oils. Therefore, the IFO80 tested here may behave differently from other blends that meet that classification. The pour point of this IFO80 was higher than the crudes tested (i.e., +3 ºC, Table 2.1), and higher than the water temperature in the flumes. Previous studies have shown that under simulated breaking wave conditions (e.g. using the MNS dispersant effectiveness test), oils can be chemically dispersible even at sea temperatures 10 to 15 ºC below their pour point, because the movements on open water retard the lattice formation of wax crystals in the oil (Daling and Strøm, 1999). However, when the oil is weathered for 6 to 18 hours under very low energy conditions as in the containment area, a reduced dispersant effectiveness may appear for oils with pour point closer to the sea temperature. This is because the precipitation of waxes in combination with the relative high viscosity of the oil may retard the migration of the dispersants into the oil.

DE for all oils is compared in Figure 3.1. The oils were weathered for 18 hrs in 80% ice and 35 ppt salinity water, and DE was measured from water grab samples collected after propeller wash. As expected, the DE varied with both oil type and dispersant type applied.

Troll Blend (a mixture of naphthenic and paraffinic oil) was overall the most dispersible of the tested oils, independent of the dispersant applied. The highest DE was obtained with Corexit 9500 and OSR-52 (> 80%), while Dasic NS was less efficient (64 %). Low DE was calculated for IFO80, Dasic being more efficient (28%) than OSR-52 and Corexit 9500 (12%).

Under the conditions discussed here, Corexit 9500 seems to be the most efficient dispersant for the North Sea crudes tested. As concluded in Faksness et al. (2016), highest estimated DE using Corexit 9500 was obtained for Troll Blend followed by the asphaltenic crude Grane and the paraffinic Oseberg Blend. Corexit 9500 was the least effective dispersant for ANS (<50%), and OSR-52 the most effective dispersant (70%). The results from these tests indicate that OSR-52 works best for Troll, good for the paraffinic oils ANS and Oseberg, and was less effective for Grane. Dasic NS seems to be a slightly better dispersant for Troll, than for ANS and Oseberg. Lowest dispersant efficiency for Dasic NS was observed when testing Grane, but not as low as OSR-52.

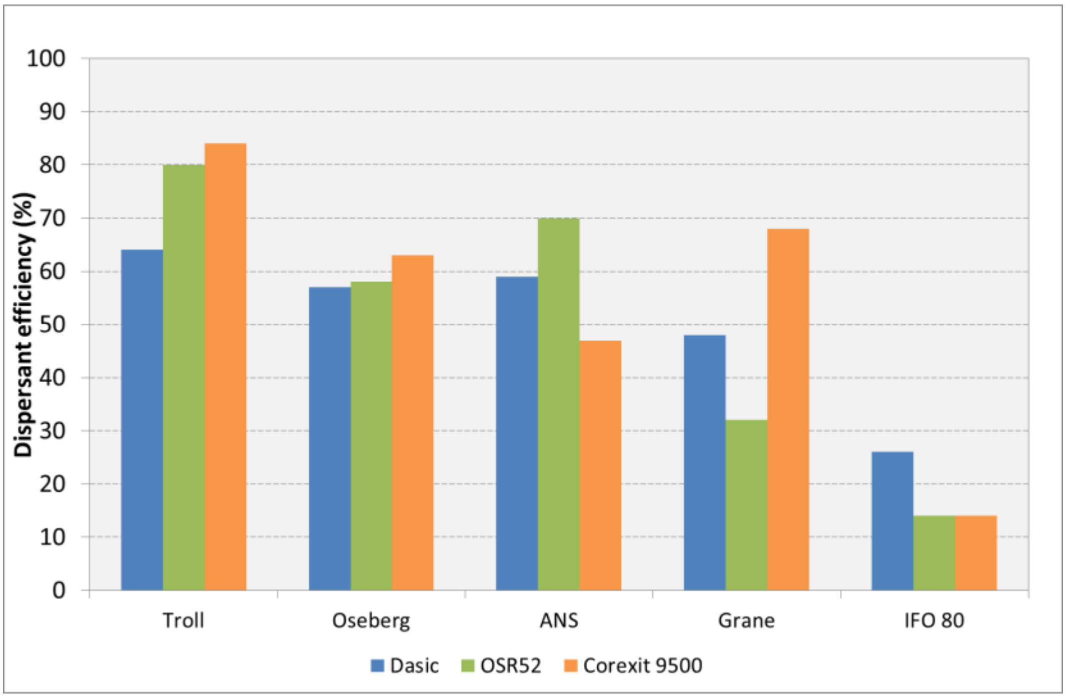

Figure 3.1 Dispersant efficiency vs dispersant type. Oils were weathered for 18 hrs in 80% ice and 35 ppt salinity water. DE measured from water grab samples collected after prop wash.

Oil weathering time

Tests with shorter weathering time (6 hrs vs 18 hrs) were performed for ANS, Grane, and IFO 80. DE after prop wash in 35 ppt water is given in Figure 3.2. The results show that shorter weathering time matters especially for the bunker oil, where the DE is reduced to approximately half when the weathering time is increased from 6 hours to 18 hours. Also Grane is less dispersible after the longer weathering time. The results for ANS indicate that the weathering time does not influence the final dispersibility as much as the other oils. Tests with Grane dispersed with Corexit 9500 after 6 hrs weathering were not performed.

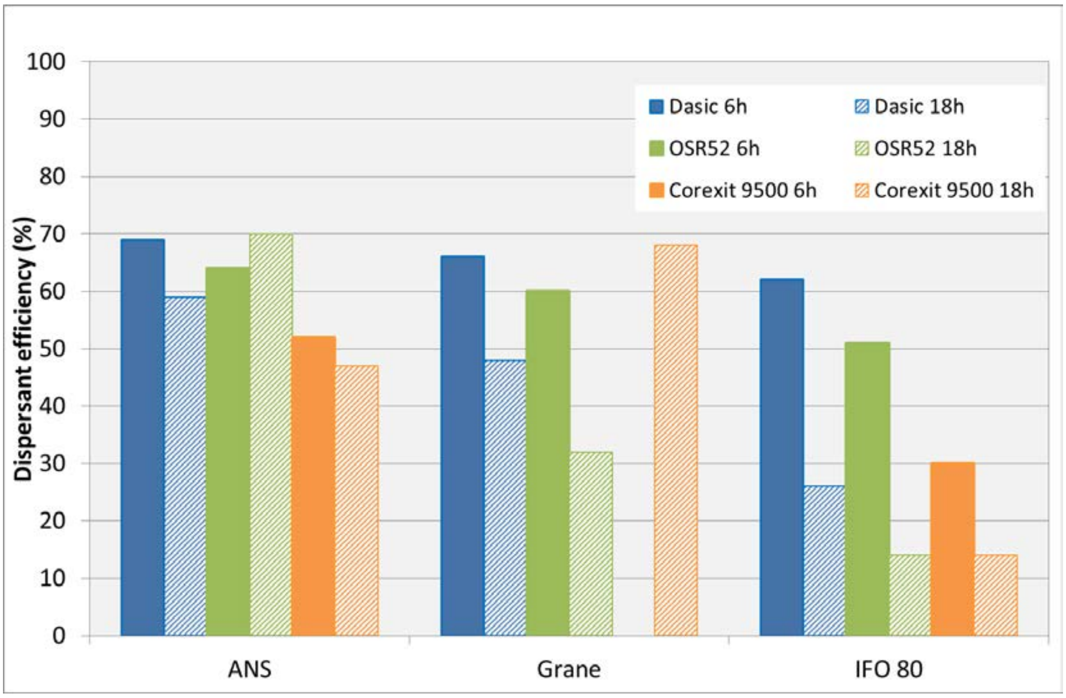

Figure 3.2 Dispersant efficiency vs weathering time. Oils were weathered for 6 hrs or 18 hrs in 80% ice and 35 ppt salinity water (Grane Corexit 9500 6hrs not performed). DE measured from water grab samples collected after prop wash

Water salinity

Previous results have shown that the salinity of the water is an important factor regarding dispersant effectiveness of Corexit 9500, and that Corexit 9500 is more suited in natural seawater with 35 ppt than in more brackish water (Faksness et al., 2016). As it can be seen in Figure 3.3, the testing performed in the present phase of the project has shown that water salinity affects the performance of the dispersants depending on the oil type.

For Troll Blend, Dasic's performance was not reduced over the range of salinities tested whereas Corexit 9500 and OSR52 had similar reductions in DE with reduced water salinity.

With the Oseberg Blend and Grane oils, both Dasic NS and OSR52 performed well at both 35 and 15 ppt water salinities whereas the Corexit 9500 had a drop in DE when the salinity dropped to 15 ppt.

For ANS crude oil, both Dasic and Corexit 9500 showed similar reduction in DE when the salinity dropped to 15 ppt but OSR52 performed similarly at the two salinities.

Overall, Dasic NS and OSR-52 were less affected by changing salinity than Corexit 9500, and the results indicate that they work as good or better in 15 ppt versus 35 ppt water on some but not all oils. The asphalthenic oil Grane was poorly dispersible in low salinity water (5 ppt). The bunker oil was only tested in seawater (35 ppt) as the DE was less than 30 % for all dispersants. It was also observed that the median oil droplet size increased when the salinity decreased.

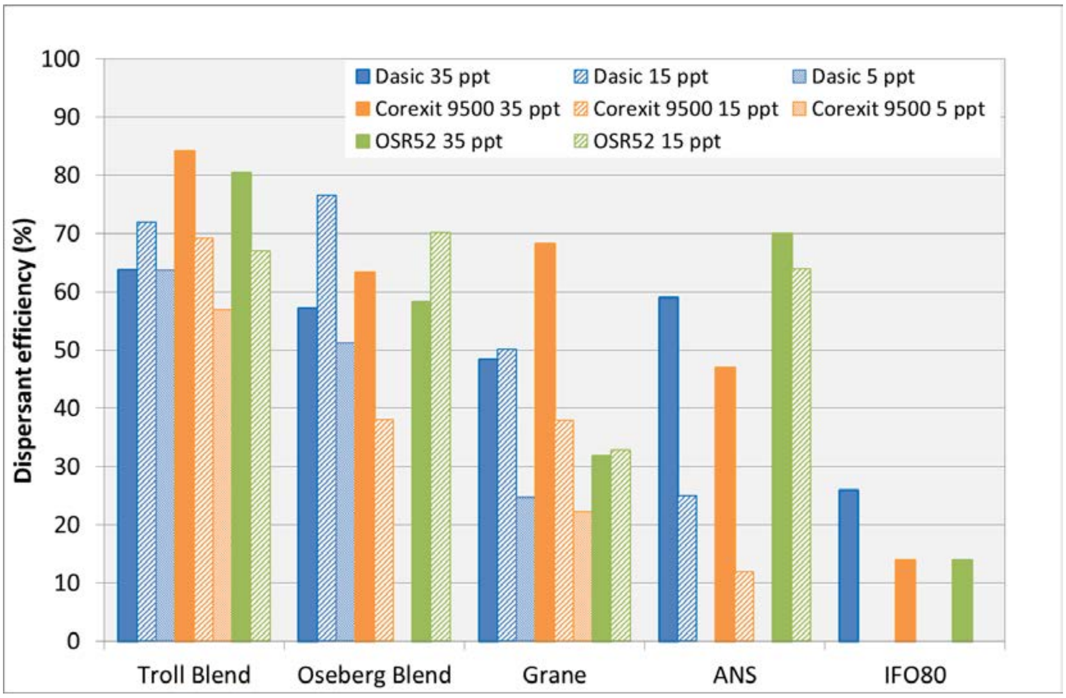

Figure 3.3 Dispersant efficiency vs water salinity. Oils were weathered for 18 hrs in 80% ice. DE measured from water grab samples collected after prop wash. No bars indicate that no testing was performed.

ADDITIONAL TESTING

To get more information about behaviour and effectiveness of dispersant testing in the meso-scale flumes, additional testing was performed:

- Tests at low temperature without ice and prop wash to study if ice movement increases the surface turbulence and thereby the DE.
- Repeatability of test conditions in the flume to determine the bound of uncertainty in the results.
- Dispersible oil tested at low and high temperature to investigate if the test protocol limits the total amount of dispersed oil.
- Compare bench scale dispersant testing with meso scale testing in the flume.
    - MNS testing of fresh oil at low and high temperature
    - Summarize previous weathering studies of different oil types to look for trends when comparing MNS with meso scale testing.

The test matrix for the additional tests were based on discussions between TWG and SINTEF and is described in Table 4.1. The test protocol described in Faksness et al. (2016) was followed to weather the oil. In tests without ice, the confinement area was reduced to maintain the same oil thickness as used in tests with ice (i.e. 5 mm average thickness). One liter of oil, seawater with 35 ppt salinity, and Corexit 9500 dispersant were used in all tests.

Table 4.1 Test matrix overview. Tests with Alaska North Slope were performed at SL Ross, and the remaining tests at SINTEF. One liter of oil, Corexit 9500 and 35 ppt seawater were used in all tests.

Test ID	Oil	Dispersant	Ice conc	Weathering time	Energy	Salinity	Comments
GRN-C-0-35-L	Grane	Corexit 9500	No ice	18 hrs	Low	35 ppt	Section 4.1
TRL-C-0-35-L	Troll Blend	Corexit 9500	No ice	18 hrs	Low	35 ppt	Section 4.1
OSB-C-0-35-L	Oseberg Blend	Corexit 9500	No ice	18 hrs	Low	35 ppt	Section 4.1
ANS-C-0-35-L	Alaska North Slope	Corexit 9500	No ice	18 hrs	Low	35 ppt	Section 4.1
GRN-C-80-35-A	Oseberg Blend	Corexit 9500	80%	18 hrs	H+P	35 ppt	Section 4.2
GRN-C-80-35-B	Oseberg Blend	Corexit 9500	80%	18 hrs	H+P	35 ppt	Section 4.2
GRN-C-80-35-C	Oseberg Blend	Corexit 9500	80%	18 hrs	H+P	35 ppt	Section 4.2
ANS-C-80-35-A	Alaska North Slope	Corexit 9500	80%	18 hrs	H+P	35 ppt	Section 4.2
ANS-C-80-35-B	Alaska North Slope	Corexit 9500	80%	18 hrs	H+P	35 ppt	Section 4.2
ANS-C-80-35-C	Alaska North Slope	Corexit 9500	80%	18 hrs	H+P	35 ppt	Section 4.2
TRL-C-80-35-F-0	Troll Blend	Corexit 9500	80%	10 min	H+P	35 ppt	Sect 4.3 (Temp 0 ºC)
TRL-C-0-35-F-13	Troll Blend	Corexit 9500	No ice	10 min	H+P	35 ppt	Sect 4.3 (Temp 13 ºC)

The GC chromatograms from all tests are given in Figure C 4 in Attachment C, and the results from the droplet size monitoring (LISST) in Attachment E (Table E 2 and Figure E 14 to Figure E 21) and Attachment F (Table F 2 and Figure F 25 to Figure F 29).

Tests without ice and without propeller wash

In order to show if ice movement increases the surface turbulence and thereby increases dispersion, tests comparing non-breaking waves in open water with non-breaking waves in ice were done.

Four tests without ice present and low energy conditions were performed using the test parameters described in Table 4.1. The results were compare to results from Task 2 (reported in Faksness et al., 2016) with ice (Table 4.2).

The results gave no clear indications of the influence of ice movement on the DE. The DE was higher in the tests without ice for Grane, Troll, and ANS, but was lower for Oseberg. The difference in efficiency between ice and ice-free tests was small for the ANS and Oseberg crudes (< 8%), but was higher for the tests with Grane and Troll crudes (13 and 25% respectively). Further testing is needed before definitive conclusions can be drawn.

Table 4.2 Oil properties prior to dispersant application, and oil concentrations in water grab samples (from UV) and estimated dispersant efficiency after low energy exposure for 30 min. Amount dispersed oil is corrected for estimated evaporative loss and sampled oil volume (50 mL).

		Oil properties prior to dispersant application				Low energy		
Test ID	Dispersed oil (g)	Density (g/mL)	Viscosity (cP @ 100s-1)	Water content (%)	Estimated evap loss (wt%)	Oil in water (ppm)	Dispersant efficiency (%)	Comments
GRN-C-0-35-L	869	0.944	2344	7	5	74	43	Without ice
GRN-C-80-35	851	0.941	2747	6.1	5	53	30	Task 2, with ice
TRL-C-0-35-L	768	0.888	151	18	25	31	26	Without ice
TRL-C-80-35	763	0.891	187	4.9	27	0.5	0.4	Task 2, with ice
OSB-C-0-35-L	783	0.874	328	18	33	6.1	5.6	Without ice
OSB-C-80-35	761	0.868	175	10	32	16	14	Task 2, with ice
ANS-C-0-35-L	866	0.911	484	0	19	16	12	Without ice
ANS-C-80-35 (ANS1)	863	0.916	667	0	21	6.6	5	Task 2, with ice

Repeatability of the test conditions in the flume

The bound of uncertainty in the results have been discussed several times. Parallel tests have earlier been done using the Troll oil (Faksness et al. 2014). Knowing that oils with different properties could behave differently, three parallel tests with two additional oils (Grane and ANS) were performed in order to estimate the uncertainty in the results. The tests parameters are provided in Table 4.1.

The results from the tests are provided in Table 4.3 and include triplicate tests with Troll Blend completed earlier (Faksness et al., 2014). Average DE and absolute standard deviation were calculated.

Table 4.3 Replicate tests with average dispersant efficiency (in %) and absolute standard deviation. Oil properties prior to dispersant application, oil concentrations in water grab samples (from UV) and estimated dispersant efficiency after high energy (30 min) and prop wash (10 min). Amount dispersed oil is corrected for estimated evaporative loss and sampled oil volume (50 mL).

		Oil properties prior to dispersant appl				High energy		Prop wash	
Test ID	Applied oil (g)	Density (g/mL)	Viscosity cP ($100s^{-1}$)	Water content (%)	Estimated evap loss (wt%)	Oil in water (ppm)	Dispersant efficiency (%)	Oil in water (ppm)	Dispersant efficiency (%)
GRN-C-80-35-A	853	0.940	2461	11	5	127	75	109	64
GRN-C-80-35-B	861	0.941	4035	22	6	111	66	124	74
GRN-C-80-35-C	852	0.941	3161	27	5	85	50	92	55
Average							*64*		*64*
Abs std deviation							*10*		*8*
TRL-C-80-35-A*	772	0.895	NM	21	30	63	76	56	68
TRL-C-80-35-B*	808	0.893	200	NM	28	77	86	64	71
TRL-C-80-35-C*	765	NM	289	NM	28	90	90	78	78
Average							*84*		*72*
Abs std deviation							*6*		*5*
ANS-C-80-35-A	851	0.908	331	0	17	35	26	42	31
ANS-C-80-35-B	864	0.917	695	0	22	37	28	39	30
ANS-C-80-35-C	877	0.917	695	0	22	14	11	58	44
Average							*22*		*35*
Abs std deviation							*8*		*6*

*NM: Not measured; *) Initial tests from Faksness et al. (2014).*

DE for Grane, replicate C, is lower than A and B, and this results in a higher absolute standard deviation. Grane was tested under the same conditions earlier (Table A3), and DE was in the same range as A and B (73 %). If test C is considered an outlier and the previous test is included, the average DE will be 71 and 69 % for high energy and prop wash, respectively, with an absolute standard deviation of 5% DE.

Results from the triplicate tests with Troll Blend are from the initial testing comparing natural ice with polyethylene blocks. Here, DE from testing of natural ice is provided. Troll Blend was also tested under the same conditions later (Table A3), and the DE was in the same range as the average DE from the triplicate tests (90 %). Average DE was 84 % and 72% for high energy and propeller wash, respectively, with an absolute standard deviation of 7 and 6 %.

Replicate results for ANS were similar to those obtained for Troll Blend and Oseberg Blend crude oils. The average DE was 22% after the high energy wave period, and 35% after the propeller wash period. The absolute standard deviations for the same periods were 8% and 6%, respectively.

The triplicate tests indicate that some outliers may occur, but that the absolute standard deviation in the dispersant efficiency results for tests, independent of oil type, seems to be 10% or lower.

Dispersible oil tested at low and high temperature

To determine if the test protocol limits the total amount of dispersion, a fresh Troll oil was tested under more favorable conditions for dispersant use, at higher temperature (13 °C) without ice, and then under less favorable conditions at low temperature (0 °C) with ice (80 %). Dispersant was applied on the oil after 10 min in the containment area. The amount of oil available for dispersion was adjusted for evaporative loss and amount of oil sampled.

The results are given in Table 4.4 and the calculated DE for Troll Blend is approximately 80% and 90%, respectively at 0 ºC and 13 ºC. No oil was observed on the surface, but there were small amounts of oil on the flume walls and on the ice blocks that was not collected or estimated. It is assumed that this oil possibly account for less than 5 % of the total amount of the Troll oil applied, but could be higher at 0 ºC than 13 ºC. This indicate the total amount of dispersed oil is not limited by the test protocol followed.

Table 4.4 Tests comparing dispersant efficiency of fresh Troll oil at low (0 ºC and 80% ice) and high temperature (13 ºC and no ice). Oil properties prior to dispersant application, oil concentrations in water grab samples (from UV) and estimated dispersant efficiency after high energy (30 min) and prop wash (10 min). Amount dispersed oil is corrected for estimated evaporative loss and sampled oil volume (50 mL).

		Oil properties prior to dispersant appl				High energy		Prop wash		
Test ID	Applied oil (g)	Density (g/mL)	Viscosity cP ($100s^{-1}$)	Water content (%)	Estimated evap loss (wt%)	Oil in water (ppm)	Dispersant efficiency (%)	Oil in water (ppm)	Dispersant efficiency (%)	Comments
TRL-C-80-35-F-0	786	0.859	23	4	3	128	81	115	72	Temp 0 ºC
TRL-C-0-35-F-13	800	0.867	40	5	9	134	88	139	91	Temp 13 ºC

Comparing bench scale testing with mesoscale testing in the flume

Both SINTEF and SL Ross have previously correlated dispersant efficiency obtained in their flume tanks with at-sea trials on open water (e.g. Daling and Strøm, 1999; Belore et al., 2005; Lewis et al, 1995). The flumes provide a useful middle ground between the laboratory-scale studies and full-scale sea trials. Experience from field trials with application of dispersants on a weathered/emulsified crude oil indicated that the laboratory-derived dispersibility viscosity boundaries were in good agreement with the field observations.

SINTEF has performed more than 200 weathering studies with different oils. A large number of these studies included weathering of fresh oil (9 L) in the flume for 3-4 days followed by application of chemical dispersant. In some of these tests, no oil was observed on the surface after dispersion, but the water grab samples indicated that not 100% of the oil was dispersed. However, these observations have not been systematically summarized earlier, only been commented in the individual weathering reports. The weathering studies also included dispersant effectiveness testing of the oils using the Mackay-Nadeau-Steelman (MNS) test (Mackay and Szeto, 1980). The MNS system consists of a circular vessel containing 6 L of seawater, and 10 mL of oil is placed in a containment ring. The dispersant is added homogenously to the oil. After a soaking time of 1.5 min, the energy is supplied to the system by a horizontal, tangential air stream, producing a circular wave motion of the surface water. After a mixing period of 5 min, a sample of the oily water is taken under dynamic conditions. The conditions in the MNS test are developed to give as high dispersibility as possible, which include high energy input (breaking waves), optimized oil to dispersant ratio regarding oil film thickness (2.5 mm), homogenous dispersant application method and soaking time, and sampling during dynamic breaking wave conditions.

SINTEF have looked at five weathering reports to check if it is a possibility that the DE measured in the Arctic JIP dispersant testing has been underestimated and if a trend can be indicated for different oil types based on the observations in the weathering reports. The results from flume tests performed in the present project and previous standard weathering studies are not directly comparable, as the DOR and the energy input often were different, dispersants were applied twice in a large number of the flume tests and no ice was present in the standard weathering studies. A summary of the most important oil properties and test parameters, the estimated dispersant efficiencies, and references to the reports are provided in Table 4.5. The flume tests were reported as a part of the weathering studies and an estimated mass balance was given, which included oil on surface, sampled, adsorbed to walls, and evaporated oil. However, a DE of 100% was not reported in any of the flume tests, but was in some of the MNS tests.

The comparisons indicate that DE for the paraffinic oils, Statfjord and Oseberg Sør were higher when tested in the bench scale MNS test than in the flume. The same trend was observed for the waxy crude Norne. Statfjord seems to be completely dispersed in the MNS-tests. For Troll, a naphthenic crude, which is known to be very dispersible, the DE was similar in the flume and MNS-test. Grane, the asphaltenic crude, seems to behave differently in the two flume tests, which could be caused by slightly higher temperature and lower viscosity for the test with shorter weathering time. The DE of the oil weathered for 1 day is similar to the MNS-test, while the DE of Grane weathered for 3 days is lower in the flume than in MNS. According to Strøm and Daling (1997), there was still oil on the surface after second application of dispersant in the 3 days test.

The results indicate that some of the oils that seem to be completely dispersible according to the MNS-test may not disperse as well in the in situ dispersant testing in the flume. With the exception of the test with Grane at 15 ºC, the DE was higher using the MNS protocol than was achieved in the flume tank. Average DE in MNS test was 73%, while that in the flume tank was 52%. The differences in DE ranged from 42% to -7%, with an average of 21%. The naphthenic Troll oil dispersed almost well in the flume as in MNS. Similar results were seen in the tests done in section 4.5 below.

The conditions in the MNS test system cannot be directly compared to the flume test as the MNS is estimated to correspond to a medium to high sea-state condition (simulating breaking waves), whereas the conditions in the flume is estimated to have been gentler. However, the energy dissipation rate in either apparatus have not been measured. The dispersant application to the oil film is optimized to a smaller quantity of oil in the MNS test, while the dispersant spraying in the flume may not dose all of the slick at exactly the same rate. The MNS protocol represents an optimal environment for dispersant use, whereas the flume is intended to represent a more challenging scenario. The MNS test is a more controlled environment, and is likely more repeatable. The absolute standard deviation for DE in the flume tank was estimated to be around 7%.

Table 4.5 Comparing estimated dispersant efficiency of MNS testing and in situ dispersant testing in the meso scale flume.

Oil type	Category	Temp (ºC)	Viscosity (cP)		Water content (%)		Dispersant efficiency (%)		Dispersant application	Weathering time
			MNS	Flume	MNS	Flume	MNS	Flume	Flume	Flume
Statfjord [1)]	Paraffinic	13	3562	3694	50	67	95	61	Two times	3d
Oseberg Sør[2)]	Paraffinic	5	2736	2230	50	61	54	22	Two times	2d 5 hrs
Oseberg Sør[2)]	Paraffinic	13	1880	1990	50	65	41	25	Two times	3 d
Troll[3)]	Naphthenic	13	4790	4380	75	73	100	94	Two times	3 d
Grane[4)]	Asphaltenic	15	16523	9000	50	64	87	94	Two times	1 d
Grane[4)]	Asphaltenic	13	16523	11000	50	62	87	50	Two times	3 d
Norne [5)]	Waxy	3	1990	1400	50	60	42	32	One time	3 d
Norne [5)]	Waxy	13	1070	1639	50	60	83	41	One time	3 d

1) Moldestad et al., 2001
2) Leirvik and Moldestad, 2001
3) Strøm et al., 1995
4) Strøm and Daling, 1997
5) Strøm-Kristiansen and Singsaas, 1996

MNS testing of Troll fresh oil

The energy applied in a standard MNS test is breaking waves, and not directly comparable with the energy in the flume tests. As mentioned above, the conditions in the MNS test are optimized to give as high DE as possible, which is more challenging in the meso scale systems where other parameters than the energy also will have impact on the DE. There are several other laboratory methods for dispersant testing, and no single laboratory test can simulate the range of turbulence and diffusion regimes that exists in different conditions at sea; it is therefore unlikely that one method produces a uniquely correct result. E.g. Clark et al. (2005) have compared four different bench-scale tests to evaluate three dispersants. They concluded the different test methods gave different results, and that laboratory tests with greater mixing energy yielded the highest DE.

In the weathering studies mentioned above, a comparison between standard bench scale dispersant testing (MNS) and amount oil in water after dispersing weathered oil in the flume was done. MNS testing of Troll fresh oil at 0 ºC and 13 ºC was performed in order to compare the dispersant efficiency in the flume with MNS. Standard MNS protocol was followed. A DOR of 1:20 was used in the flume and 1:25 in the bench scale testing. The results given in Table 4.6 show that fresh Troll crude is completely dispersible in the MNS test, at both temperatures (0 ºC and 13 ºC).

In the flume, the DE was measured to be 81% at 0 ºC (with ice) and 88% at 13 ºC (with no ice). No oil was observed on the surface, but there were small amounts of oil on the flume walls and on the ice blocks that was not collected or estimated. It is assumed that this oil possibly account for less than 5 % of the total amount of the Troll oil applied.

Table 4.6 Dispersant efficiency for Troll fresh oil dispersed in bench scale (MNS) and in the meso scale flume.

		MNS	Meso scale flume	
	DOR	Dispersant efficiency (%)	Dispersant efficiency High energy (%)	Comments
TRL-C-80-35-F-0	1:20		81	Temperature 0 ºC, with 80% ice
TRL-C-0-35-F-13	1:20		88	Temperature 13 ºC, no ice
MNS Troll fresh oil	1:25	100		Temperature 2 ºC
MNS Troll fresh oil	1:25	100		Temperature 13 ºC

The results with the Troll oil are similar to what was observed in the review of earlier MNS and flume tank studies (see Section 4.4), with the MNS test giving higher DE. In this case, with a highly dispersible oil, the difference between the MNS and the flume tank DE was lower, averaging 15%.

FACTORS INFLUENCING THE DISPERSANT EFFECTIVENESS

The conclusions are based on the findings from the tests performed under the conditions tested in the SINTEF and SL Ross flumes and may not be directly transferable to realistic conditions in the Arctic. However, flume testing gives repeatable controlled comparisons of relative DE with different oils, dispersants, weathering times, and other "fixed" conditions, which cannot be performed in the field.

Considering the test conditions used and the limitations of these closed system tests (such as DE measured only 30 minutes after applying dispersant and dispersant applied only once), DE in the field could be higher than measured here, given comparable mixing conditions. Experience from field studies have shown that application of dispersants may enhance the more long-term dispersion of the remaining surface oil hours after treatment application (e.g. Lichtenthaler and Daling, 1983; 1985). Also "re-treatment" or even "multi-treatment" of remaining surface oil may be a recommended operative strategy in the field. The DE measured here are conservative estimates given the energy levels applied and the conditions tested in the flume. Any laboratory data should be applied with caution when making decisions for real world oil spill response.

Factors influencing the dispersant effectiveness (DE) in the flume tests:

- As expected, DE varied with both oil type and dispersant type applied
    - All of the crude oils tested were found to have > 50% DE with at least one of the dispersants when tested in 80% ice cover and weathered for 18 hours.
    - Troll Blend (naphthenic) was overall the most dispersible of the tested oils
    - None of the tested dispersants were highly efficient for IFO 80 weathered for 18h (DE 12-28%), but Dasic NS was the most efficient
- Oil weathering time
    - Shorter weathering time resulted in an increase in DE
- Salinity effect
    - The crudes Troll (naphthenic) and Oseberg (paraffinic) were found to have >50% DE with at least one of the dispersants tested in water salinity as low as 5 ppt.
    - Dasic NS and OSR-52 were as good or better in 15 ppt vs 35 ppt water for some, but not all of the oils
    - Corexit 9500 was most influenced by reduced salinity
    - Grane (asphalthenic) seems to be less dispersible in low salinity water (5 ppt)
- Energy levels
    - High energy conditions without propeller wash were sufficient, and applying propeller wash after high energy usually did not significantly enhance the dispersant efficiency
    - Previous results from Faksness et al. (2016) have shown that low energy input did not provide enough energy to mix cause significant dispersion.

Additional tests were performed to get more information about behavior and effectiveness of dispersant testing in the flume:

- Triplicate tests with Troll, Grane, and Alaska North Slope were performed and indicate that some outliers may occur, but that the absolute standard deviation in the DE results for tests, independent of oil type, seems to be 10% or lower.
- Results from previous SINTEF projects have been used to compare DE in MNS-testing with *in situ* dispersant testing in the flume. The DEs measured in the flume are conservative estimates, and cannot be directly comparable with the MNS test, which is optimized to give as high DE as possible (high energy input, homogenous dispersant application, optimized DOR and soaking time, and sampling during dynamic breaking wave conditions).
- Flume testing of fresh Troll crude was done at 0 ºC (with 80% ice) and 13 ºC. DE for Troll Blend were approximately 80% and 90%, respectively, at low and high temperature. This indicate that the total amount of dispersed oil is not limited by the test protocol followed. Potential oil adhesion to the ice blocks and oil sticking to the flume walls are not accounted for here and are assumed higher at 0 ºC than 13 ºC.

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APPENDIX A SINTEF RESULTS AND DISCUSSION

A.1 Test procedure

The test procedure used is described in the main report, and has been documented previously (Faksness and Belore, 2014).

A.2 Background

The original test matrix for this phase of the project called for 23 tests at SINTEF with the commercial dispersants Dasic and OSR-52, and an experimental dispersant. SINTEF tested the oils Troll Blend, Oseberg Blend and Grane crude oil. A detailed test matrix is provided in Table 2.5. No tests with experimental dispersant have been performed so far. For comparison, data for Corexit 9500 are included (from Faksness et al. (2016)).

A.3 Tests conducted

In total 15 tests were performed in the SINTEF flume in this phase of the project. An overview over the tests with Test ID and the test parameters are given in Table A 1. The Test ID is used to identify the different tests, and have been used in tables and figures.

Table A 1 Description of the tests performed at SINTEF with Test ID and test parameters. A dispersant to oil ratio of 1 to 20 was used in all tests (Abbreviations used in Test ID are as follows: TRL: Troll, OSB: Oseberg, GRN: Grane; D: Dasic NS, O: OSR-52, E: Experimental dispersant; 80: Ice coverage; 35, 15 or 05: salinity in seawater).

Test ID	Oil	Dispersant	Salinity	Comments
TRL-D-80-35	Troll Blend	Dasic	35 ppt	
TRL-D-80-15	Troll Blend	Dasic	15 ppt	
TRL-D-80-05-1	Troll Blend	Dasic	5 ppt	Too high intensity applied for high energy input
TRL-D-80-05-2	Troll Blend	Dasic	5 ppt	
OSB-D-80-35	Oseberg	Dasic	35 ppt	
OSB-D-80-15	Oseberg	Dasic	15 ppt	
OSB-D-80-05	Oseberg	Dasic	5 ppt	
GRN-D-80-35	Grane	Dasic	35 ppt	
GRN-D-80-15	Grane	Dasic	15 ppt	
GRN-D-80-05	Grane	Dasic	5 ppt	
TRL-O-80-35	Troll Blend	OSR-52	35 ppt	
TRL-O-80-15	Troll Blend	OSR-52	15 ppt	
OSB-O-80-35	Oseberg	OSR-52	35 ppt	
OSB-O-80-15-	Oseberg	OSR-52	15 ppt	
OSB-O-80-15-	Oseberg	OSR-52	15 ppt	Re-tested
GRN-O-80-35	Grane	OSR-52	35 ppt	
GRN-O-80-15	Grane	OSR-52	15 ppt	
TRL-E-80-35	Troll Blend	Exp disp	35 ppt	Cancelled
TRL-E-80-15	Troll Blend	Exp disp	15 ppt	Cancelled
OSB-E-80-35	Oseberg	Exp disp	35 ppt	Cancelled
OSB-E-80-15	Oseberg	Exp disp	15 ppt	Cancelled
GRN-E-80-35	Grane	Exp disp	35 ppt	Cancelled

Test ID	Oil	Dispersant	Salinity	Comments
GRN-E-80-15	Grane	Exp disp	15 ppt	Cancelled

A.4 Test results and discussion

The physical properties of the oil samples collected after the weathering period, immediately prior to dispersant application, are given in Table A 2. GC chromatograms of the oils prior to dispersant application are provided in Appendix C. For comparison, results from the tests with Corexit 9500 performed in Task 2.2 are included Table A 2 and Table A 3 (from Faksness et al., 2015).

The estimated evaporative loss and measured oil viscosities and densities were consistent in all tests using Troll Blend, indicating that the weathering process was repeatable. In the tests with Oseberg Blend, the density varied from 0.863 to 0.880, which also are reflected in the viscosities and estimated evaporative loss. The variation might be caused by the higher content of the most volatile components in Oseberg Blend. There was observed slush ice in the containment area after 18 hrs of weathering in tests with Grane (GRN-D-80-35 and GRN-O-80-35), which also had the highest viscosities. The water content in these two oil residues were higher than in the others, and measured to 30% and 47%, respective. However, this can also been due to that there was more free water in the oils caused by the slush ice.

Table A 2 Oil properties after in situ weathering and prior to dispersant application. Data for tests with Corexit 9500 are from Faksness et al. (2015). Explanation to Test ID: TRL: Troll, OSB: Oseberg, GRN: Grane; D: Dasic NS, O: OSR-52, 80: Ice coverage; 35, 15 or 05: salinity in seawater, 1 and 2: re-test.

Test ID	Density (15.5 °C) g/mL	Viscosity (2 °C, 100s^{-1}) cP	Water content %	Estimated evap loss (wt%)
TRL-D-80-35	0.891	159	10	26
TRL-D-80-15	0.892	206	11	27
TRL-D-80-05-1	0.894	310	17	29
TRL-D-80-05-2	0.893	246	4	28
TRL-O-80-35	0.893	205	21	29
TRL-O-80-15	0.892	248	4	27
TRL-C-80-35	0.891	187	5	27
TRL-C-80-15	0.891	197	8	26
TRL-C-80-05	0.891	179	6	26
OSB-D-80-35	0.863	124	14	23
OSB-D-80-15	0.880	297	12	37
OSB-D-80-05	0.878	267	11	35
OSB-O-80-35	0.876	216	4	33
OSB-O-80-15-	0.877	290	4	35
OSB-O-80-15-	0.878	310	7	35
OSB-C-80-35	0.868	175	10	32
OSB-C-80-15	0.860	82	8	20
GRN-D-80-35	0.941	4244	30	6
GRN-D-80-15	0.943	2960	8	6
GRN-D-80-05	0.945	3767	19	7
GRN-O-80-35	0.940	4013	47	6
GRN-O-80-15	0.940	2423	16	5
GRN-C-80-35	0.941	2747	6	5

Test ID	Density (15.5 °C) g/mL	Viscosity (2 °C, 100s-1) cP	Water content %	Estimated evap loss (wt%)
GRN-C-80-15	0.938	1855	2	3
GRN-C-80-05	0.937	1490	2	3

Looking at the GC chromatograms in Appendix C, these observations are confirmed, with quite similar evaporative loss in the tests with Troll Blend (Figure C 2) and Grane (Figure C 3), and more varying evaporative loss in the test performed with Oseberg Blend (Figure C 1).

Dispersant effectiveness has been determined using oil-in-water concentration measurements. The data presented in Table A 3 are based on water samples taken at the end of each unique mixing cycle and the oil concentration were determined by extraction the samples followed by UV measurements as described in Faksness and Belore (2014). The dispersant effectiveness is corrected for estimated evaporative loss during oil weathering. The laboratory topping of the batch of Troll Blend used in this project was performed by SINTEF in August, 2015. It showed a higher evaporative loss than in the batch used to estimated evaporative loss in Faksness and Belore (2014) and Faksness et al. (2016). Therefore, the dispersant efficiency using Corexit 9500 data from Faksness et al. (2016) shown in Table A 3 has been corrected to get comparable results for the different dispersants.

Table A 3 Oil concentration in water (from UV measurements) and estimated dispersant efficiency of weathered oil. Estimated evaporative loss is predicted by correlation of density and evaporative loss from artificial weathering performed in previous studies at SINTEF.

			Oil in water from UV (ppm)		Dispersant efficiency (%)	
Test ID	Applied oil (g)	Estimated evap loss (wt%)	High energy	Prop wash	High energy	Prop wash
TRL-D-80-35	833	26	84	81	66	64
TRL-D-80-15	836	27	97	91	76	72
TRL-D-80-05-	844	29	76*	84*	61*	67*
TRL-D-80-05-2	819	26	82	90	65	71
TRL-O-80-35	814	29	95	98	79	80
TRL-O-80-15	812	27	79	82	65	67
TRL-C-80-35	806	27	111	103	90	84
TRL-C-80-15	846	26	85	90	65	69
TRL-C-80-05	809	26	81	71	65	57
OSB-D-80-35	873	23	83	80	60	57
OSB-D-80-15	813	37	82	82	77	77
OSB-D-80-05	819	35	45	57	41	51
OSB-O-80-35	796	33	63	65	57	58
OSB-O-80-15-	771	35	102	49	98	47
OSB-O-80-15-	775	35	78	74	74	70
OSB-C-80-35	802	32	74	72	65	63
OSB-C-80-15	805	20	48	51	36	38
GRN-D-80-35	886	5	79	85	45	48
GRN-D-80-15	872	6	90	86	53	50
GRN-D-80-05	843	7	24	40	14	25
GRN-O-80-35	894	5	54	56	31	32
GRN-O-80-15	886	5	60	58	34	33

			Oil in water from UV (ppm)		Dispersant efficiency (%)	
Test ID	Applied oil (g)	Estimated evap loss (wt%)	High energy	Prop wash	High energy	Prop wash
GRN-C-80-35	898	5	129	121	73	68
GRN-C-80-15	915	3	54	70	29	38
GRN-C-80-05	862	3	29	39	17	22

ND: Not detected; NM: Not measured

**) Too high wave energy was applied during dispersant efficiency testing (34 Hz instead of 21 Hz).*

A.4.1 Dispersant efficiency for the different oils

Dispersant efficiency for the different oils is also illustrated in figures: Troll Blend in Figure A 1, Oseberg Blend in Figure A 2, and Grane in Figure A 3.

Dispersant effectiveness testing of Dasic NS and OSR52 were performed for all oils in 35 ppt and 15 ppt salinity water first. These results showed that Dasic NS seems to have a higher dispersant efficiency in 15 ppt salinity than in 35 ppt salinity for the three oils tested by SINTEF. Therefore, it was decided to include tests of Dasic NS in 5 ppt salinity water.

As shown in Figure A 1, Troll Blend is a relatively dispersible oil, with Corexit 9500 being the most efficient dispersant in high salinity water followed by OSR 52 (approximately 90 and 80 % dispersant efficiency, respectively). The results indicate that the dispersant efficiency of Troll Blend is higher than 50% independently of dispersant or seawater salinity. By mistake, the testing of Dasic NS in 5 ppt water was performed with too high wave energy settings than the other tests, but a re-test using the standardized settings gave similar results (Table A 3). OSR-52 was not tested in 5 ppt water.

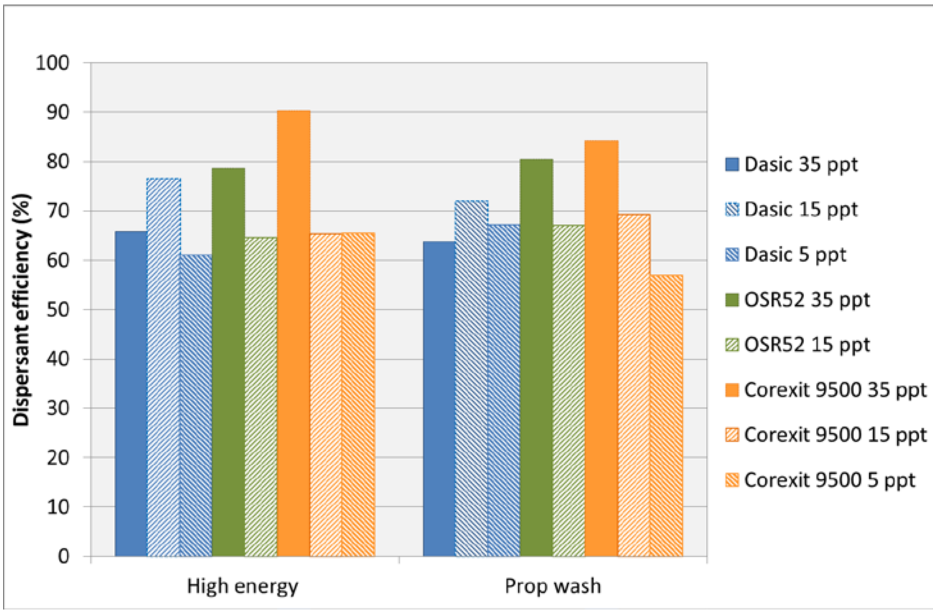


Figure A 1 Dispersant efficiency for Troll Blend

The dispersant efficiency of Oseberg Blend is shown in Figure A 2. The results indicate that the highest effectiveness for Dasic NS and OSR-52 are in water with 15 ppt salinity with more than 70% dispersant efficiency, while the dispersant effectiveness using Corexit 9500 is less than 40%. Corexit 9500 and OSR-52 have not been tested in 5 ppt salinity water.

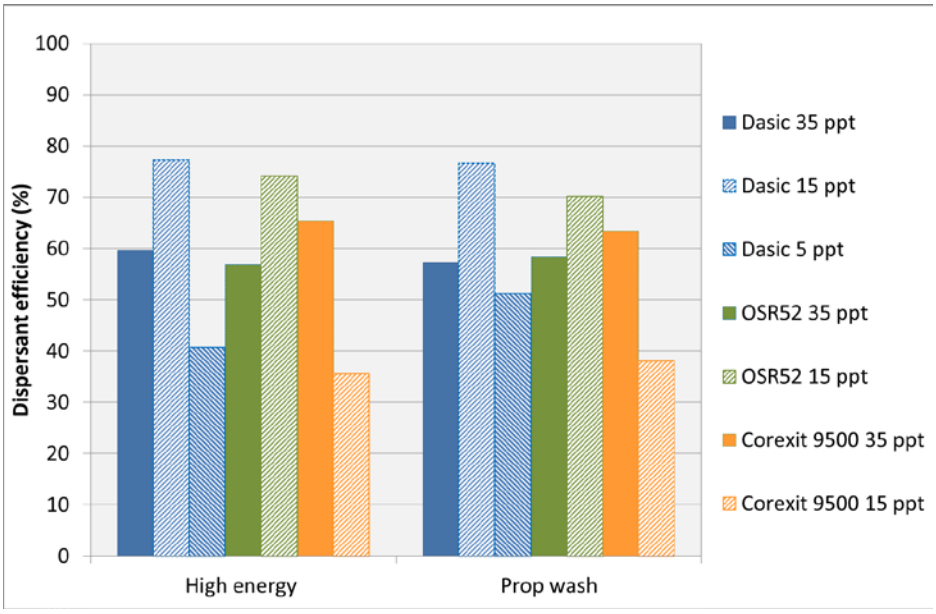


Figure A 2 Dispersant efficiency for Oseberg Blend

Dispersant efficiency for the asphaltenic oil Grane is given in Figure A 3. In 35 ppt seawater, Corexit 9500 was the most effective dispersant for Grane with approximately 70% dispersant efficiency. The dispersant efficiency using Dasic is nearly the same in 35 ppt and 15 ppt water (approximately 50%), while it drops to less to 25 % in 5 ppt water for both Dasic and Corexit 9500. Only about 30% dispersant efficiency was observed in the tests with OSR-52, which seems to be to poorest dispersant for Grane. OSR-52 is not tested in 5 ppt water. Oil residue on the flume walls was collected and weight after test GRN-D-80-05, and it was estimated that it accounted for approximately 15% of the applied oil. If the DE is adjusted for the oil residue on walls, the DE increases from 25% to 29% after prop wash.

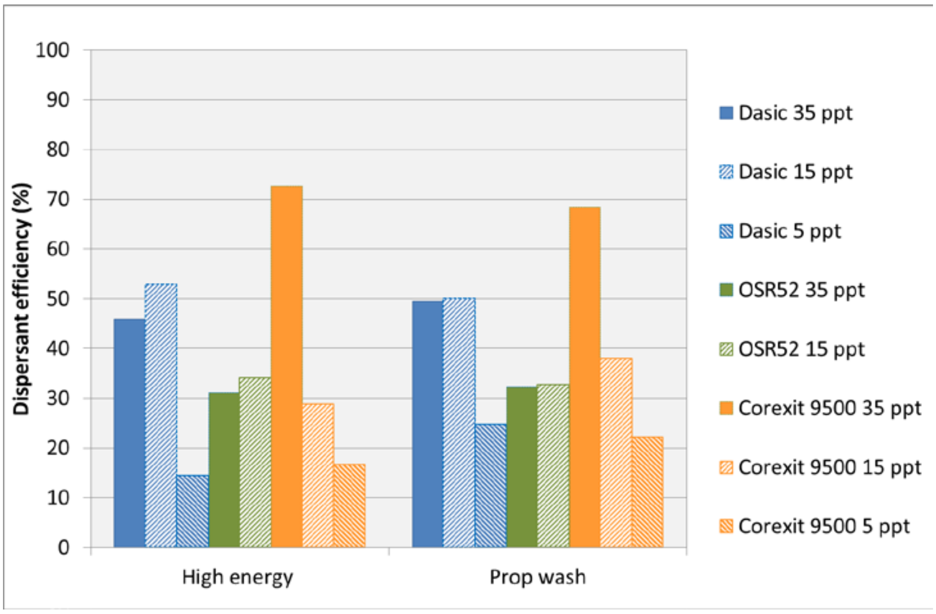


Figure A 3 Dispersant efficiency for Grane

A.4.2 Comparing dispersant efficiency of the dispersants vs oil type and water salinity

The dispersant efficiency for the three oil types in water with different salinities are compared in Figure A 4 to Figure A 6.

Corexit 9500 seems to be the most efficient dispersant for all three oil types in seawater with 35 ppt salinity (Figure A 4). As concluded in Faksness et al. (2015), highest estimated dispersant efficiency using Corexit 9500 was obtained for Troll Blend (mixture of naphthenic and paraffinic oil), followed by the asphaltenic crude Grane and the paraffinic Oseberg Blend. Under the conditions tested here, the results indicate that OSR-52 is a poor dispersant for asphaltenic oils, better for paraffinic oils, and good for more naphthenic oils. Dasic seems to be a slightly better dispersant for naphthenic oils, than for paraffinic oils. Lowest dispersant efficiency was observed when testing the asphaltenic oil, but not as low as OSR-52.

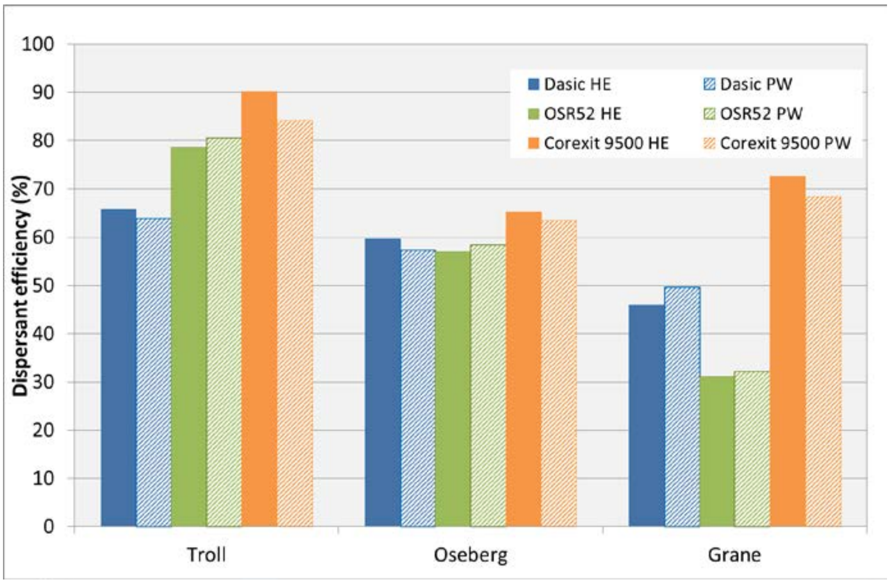


Figure A 4 Comparing dispersant efficiency in 35 ppt salinity water for the three oil types (HE: High energy, PW: prop wash).

Dispersant efficiency in 15 ppt salinity water is shown in Figure A 5. When comparing the different dispersants, Dasic seems to be a slightly better dispersant for the more naphthenic oil and the paraffinic oil, and clearly better for the asphaltenic oil under the tested conditions. All three dispersants seem to work relatively well on the naphthenic oil, with Dasic being slightly better. The dispersant effectiveness for Corexit 9500 is approximately the same as OSR-52 for the naphthenic oil and the asphaltenic oil, but poorer when compared to the other two dispersant on the paraffinic oil. In 15 ppt water, these results indicate that both Dasic and OSR-52 can be used on a naphthenic and paraffinic oil, while Dasic seems to work best if an asphaltenic oil is spilled.

Fewer tests are performed in 5 ppt salinity water (Figure A 6), and only Dasic has been tested on all oils. The results indicate that the dispersant effectiveness is approximately 60% for Corexit 9500 and Dasic on a napthenic oil. Dasic is less effective for the paraffinic oil, and the dispersant effectiveness for both dispersants on an asphaltenic oil is poor, indicating that asphaltenic oils are poorly dispersible in water with low salinity (5 ppt).

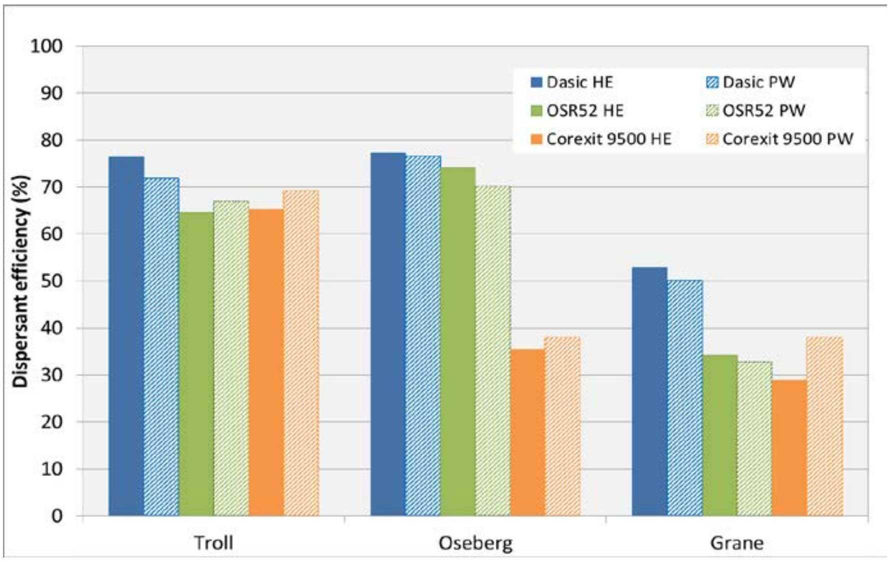


Figure A 5 Comparing dispersant efficiency in 15 ppt salinity water for the three oil types (HE: High energy, PW: prop wash).

There was observed more oil on the flume walls in the test with Grane (GRN-D-80-05) than in previous tests. Therefore, the oil on the flume walls were removed with adsorption pads and quantified. Approximately 15% of the applied oil ended up on the walls here, and if this loss is accounted for, the dispersant efficiency would be about 3% higher in this test.

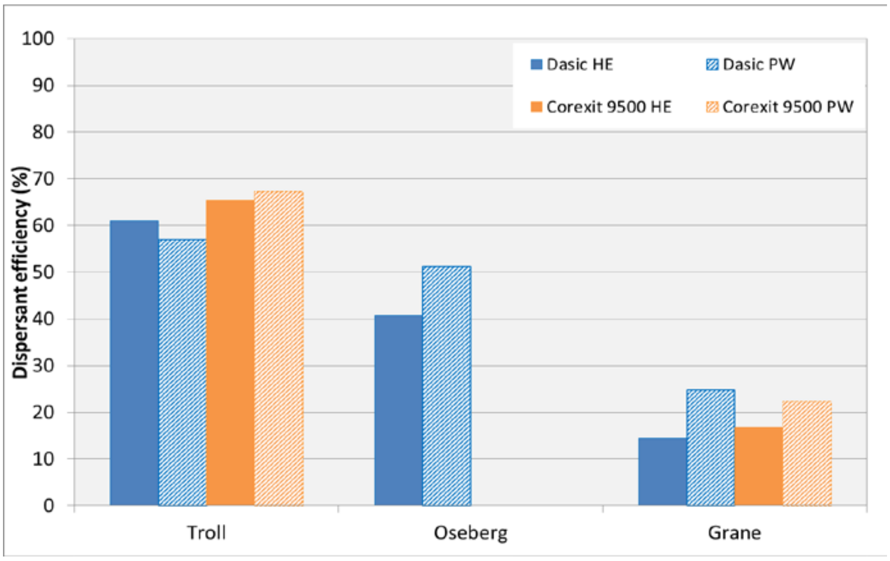


Figure A 6 Comparing dispersant efficiency in 5 ppt salinity water for the three oil types (HE: High energy, PW: prop wash).

A.4.3 Particle size distribution

In addition, oil-in-water concentrations and oil droplet size distribution were measured from in situ LISST monitoring during the entire test period. Data from these measurements are given in Appendix E. As also observed by SL Ross, the concentrations measured from the water samples seem to be higher than the LISST monitoring. During data analysis, contamination of the highest size bin was observed, probably due to a high amount of droplets bigger than 500 µm. Therefor the decision was made to not take this highest size bin into account and stop at the bin mid-size 391 µm. It has earlier been observed that the median oil droplet size was increasing when decreasing the water salinity when using Corexit 9500 as a dispersant (Faksness et al., 2016). However, this trend was not observed in the LISST data collected during the tests using Dasic NS or OSR-52 as dispersants (Table E 1). According to these data, the highest median droplet size was monitored in the natural seawater (35 ppt).

When concentrations are high and droplet sizes are large (mm-scale), existing instrumentation (e.g. LISST-100) is not capable of providing the necessary measurements of oil droplet size distributions. SINTEF has therefore developed a new particle imaging system, designed to quantify high concentrations (in-plume) of suspended particulates within the ranges of 0.056 - 12 mm. The system obtains in-focus images of all particles within the sample volume via the use of telecentric receiving optics and carefully controlled backlighting, producing high-contrast droplet silhouettes which are analyzed using image processing software developed specifically for the system (Davies et al., 2016). SINTEF used a silhouette camera in combination with the LISST in three of the tests in order to measure the particle size distribution of oil during the dispersant testing (Table A 4). The LISST used in the experiments was a LISST-100x type C, which can detect droplets in the range of 5-500 µm. The silhouette camera measurements were added to study the droplets in the range outside of the LISST possibilities. As the size ranges of both instruments are very different, it is not possible to compare the two instruments. Comparison of the two can only be done in a carefully controlled experiment and when using the same size bins for data analysis.

The silhouette camera and LISST instruments were placed after each other in one of the bends of the flume. This positioning was done in order to have the measurements of the silhouette camera and the LISST as close to each other as possible. The SilCam has to be placed in an upright position in the flume, this hindered the ice flow and resulted in congestion of ice blocks. It was also observed that instead of oil droplets moving through the SilCam observation path directly, the droplets moved forth and back while slowly moving out of the camera path. A second challenge was oil sticking and smearing to the window of the camera housing (since the instrument was mounted upright), which got worse over time in the experiment. This position of the SilCam in the plume turned out to be not optimal and led to data showing too large droplets and too high concentrations. It was therefore decided to not include the SilCam data.

Table A 4 Overview of the experiments performed in the flume combining the LISST and silhouette camera.

Test ID	Date	Oil	Dispersant
TRD-80-D-05	18.08.2015	Troll	Dasic NS
GRN-80-D-05	26.08.2015	Grane	Dasic NS
OSB-18-O-15	17.09.2015	Oseberg	OSR-52

A.5 Summary

Boundaries for dispersant efficiency testing using three commercial dispersants (Corexit 9500, Dasic NS, and OSR-52) and three North Sea crude oils (Troll Blend (naphthenic and paraffinic), Oseberg Blend (paraffinic), and Grande (asphaltenic) were estimated using the flume-based experiments. The water salinity did impact the results with the poorest dispersant efficiencies found in the 5 ppt salinity water. As expected, the dispersant effectiveness varied with both oil type and dispersant type applied.

Summary of the results are based on the findings from the tests performed under the conditions applied in the SINTEF and flume and may not be directly transferable to realistic conditions in the Arctic:

- Troll Blend (naphthenic) was overall the most dispersible of the tested oils
- Corexit 9500 was most influenced by reduced salinity for the tested North Sea crudes
- Dasic was as good or better in 15 ppt vs 35 ppt water for the three tested North Sea
- OSR-52 was as good or better for Oseberg Blend and Grane, but not for Troll Blend.
- In low salinity water (5 ppt), Grane was less dispersible then Troll and Oseberg

APPENDIX B SL ROSS RESULTS AND DISCUSSION

B.1 Test procedure

The same test procedure described in the main report (Faksness and Belore, 2014) was used.

B.2 Background

The original test matrix for this phase of the project called for 22 tests at SL Ross with the commercial dispersants Dasic and OSR-52, and an experimental dispersant. SL Ross tested Alaska North Slope and Grane crude oils, and Intermediate Fuel Oil (IFO) 80. One test was performed with Troll Blend crude oil for the purposes of comparing the results between the SINTEF and SL Ross flumes. A detailed test matrix is given in Table 2.6. No tests with experimental dispersant have been performed. For comparison, data for Corexit 9500 are included (from Faksness et al. (2016)).

B.3 Tests conducted

In total, 21 unique tests were performed in the SL Ross flume in this phase of the project with three additional tests conducted that were duplicate or repeated tests. Of the 21 unique tests conducted, two were completed for inter-laboratory comparison and three were completed to fill in the data set for Corexit 9500 and IFO 80 that was not available during the phase 2 component of the work. An overview of the tests with Test ID and the test parameters is provided in Table B 1. The Test IDs are used to identify the different tests, and have been used in subsequent tables and figures, below.

Table B 1 Description of the tests performed at SL Ross with Test ID and test parameters. Dispersant to oil ratio of 1 to 20 (by volume) was used in all tests. Test ID codes as follows: ANS: Alaska North Slope, GRN: Grane, IFO 80: IFO; D: Dasic, O: OSR-52; 80 or 50: Ice coverage; 35 or 15: salinity in seawater; 18 or 6: weathering time in hours.

Test ID	Oil	Dispersant	Salinity	Weathering	Ice Coverage	Comments
ANS-D-80-35-6	ANS	Dasic	35 ppt	6 hr	80%	
ANS-D-80-15-6	ANS	Dasic	15 ppt	6 hr	80%	
ANS-D-80-35-18	ANS	Dasic	35 ppt	18 hr	80%	
ANS-D-80-15-18	ANS	Dasic	35 ppt	18 hr	80%	
GRN-D-50-35-6	Grane	Dasic	35 ppt	6 hr	50%	
GRN-D-50-15-6	Grane	Dasic	15 ppt	6 hr	50%	
IFO-D-80-35-18	IFO	Dasic	35 ppt	18 hr	80%	
IFO-D-80-35-6	IFO	Dasic	35 ppt	6 hr	80%	
ANS-O-80-35-6	ANS	OSR-52	35 ppt	6 hr	80%	
ANS-O-80-15-6	ANS	OSR-52	15 ppt	6 hr	80%	

Test ID	Oil	Dispersant	Salinity	Weathering	Ice Coverage	Comments
ANS-O-80-35-18	ANS	OSR-52	35 ppt	18 hr	80%	
ANS-O-80-15-18	ANS	OSR-52	15 ppt	18 hr	80%	
GRN-O-80-35-6	Grane	OSR-52	35 ppt	6 hr	80%	
GRN-O-80-15-6	Grane	OSR-52	15 ppt	6 hr	80%	
IFO-O-80-35-18	IFO	OSR-52	35 ppt	18 hr	80%	This test was duplicated
IFO-D-80-35-6	IFO	OSR-52	35 ppt	6hr	80%	
IFO-C-80-35-18	IFO	Corexit 9500	35 ppt	18 hr	80%	Task 2.2 fill-in
IFO-C-80-35-6	IFO	Corexit 9500	35 ppt	6 hr	80%	Task 2.2 fill-in
ANS-C-80-35-18	ANS	Corexit 9500	35 ppt	18 hr	80%	Duplicate of Task 2.2 test
ANS-C-80-15-18	ANS	Corexit 9500	15 ppt	18 hr	80%	Task 2.2 fill-in. Test was duplicated
TR-C-80-35-18	Troll	Corexit	35 ppt	18 hr	80%	
GRN-C-80-35-18	Grane	Corexit	35 ppt	18 hr	80%	Interlab comparison
	ANS	Exp	35 ppt	18 hr	80%	Cancelled
	ANS	Exp	15 ppt	18 hr	80%	Cancelled
	ANS	Exp	35 ppt	18 hr	80%	Cancelled
	ANS	Exp	15 ppt	18 hr	80%	Cancelled

B.4 Test results and discussion

The density and viscosity of the oil samples collected after the weathering period, immediately prior to dispersant application, are provided in Table B 2. The evaporative loss (by mass was calculated from the density, based on weathering curves generated by previous laboratory tests. GC chromatograms of the oils prior to dispersant application are provided in Appendix D. For comparison, results from the tests with Corexit 9500 performed in Task 2.2 are included Table B 2 and Table B 3 (from Faksness et al., 2016).

Table B 2 Oil properties after in situ weathering and prior to dispersant application.). Explanation of Test ID codes is as follows: ANS: Alaska North Slope, GRN: Grane, IFO 80: IFO; D: Dasic, O: OSR-52; 80 or 50: Ice coverage; 35 or 15: salinity in seawater; 18 or 6: weathering time in hours.

Test ID	Density (20 °C) g/mL	Viscosity (0 °C, 100s^{-1}) cP	Water content %	Estimated evap loss (wt%)
ANS-D-80-35-6	0.907	260	0%	17%
ANS-D-80-15-6	0.909	271	0%	18%
ANS-D-80-35-18	0.922	798	3%	24%
ANS-D-80-15-18	0.913	625	0%	20%
ANS-O-80-35-6	0.909	314	0%	18%
ANS-O-80-15-6	0.904	236	0%	15%
ANS-O-80-35-18	0.918	586	0%	22%

Test ID	Density (20 °C) g/mL	Viscosity (0 °C, 100s^{-1}) cP	Water content %	Estimated evap loss (wt%)
ANS-O-80-15-18	0.920	1011	4%	23%
ANS-C-80-35-6	0.910	474	6%	18%
ANS-C-80-35-18	0.915	474	0%	21%
ANS-C-80-15-18	0.925	1447	1%	26%
GRN-D-50-35-6	0.934	2441	0%	5%
GRN-D-50-15-6	0.935	2153	0%	5%
GRN-O-80-35-6	0.936	3498	0%	6%
GRN-O-80-15-6	0.936	2191	0%	6%
GRN-C-50-35-18	0.937	2129	0%	6%
GRN-C-50-15-18*	0.938	2853	0%	6%
IFO-D-80-35-6	0.947	9674	1%	0%
IFO-D-80-35-18	0.948	12787	0%	0%
IFO-O-80-35-6	0.948	7454	1%	0%
IFO-O-80-35-18	0.948	10171	9%	0%
IFO-C-80-35-6	0.949	7968	0%	0%
IFO-C-80-35-18	0.948	11268	0%	0%
TR-C-80-35-18	0.883	285	0%	16%
GRN-C-80-35-18	0.938	1921	4%	6%

**Test GRN-C-50-15-18 was run with prop wash only (i.e., there was no high energy waves only period)*

The measured oil viscosities and densities, and estimated evaporative losses, were generally consistent between tests with the same oils and weathering periods. Evaporative loss varied between 15 and 18% after 6 hours, and between 20 and 26% after 18 hours for ANS crude oil. Higher densities and viscosities were noted with later tests (i.e., ANS-D-80-35-18, ANS-C-80-35-6 and ANS-C-80-15-18), which may have been due to not heating and mixing the bulk oil container sufficiently prior to obtaining the test samples. Limited emulsification was measured with the 18-hour tests. Inspection of the GC results (see Figures D 2 and D 3) showed significant similarities between the samples taken after the 6-hour weathering periods, and between the samples taken after the 18-hour weathering periods. The traces from the 18-hour samples showed lower concentrations of light ends, as expected.

Evaporative loss varied between 5 and 6% for the 6-hour tests with Grane crude oil, reaching 7% for the one 18-hour test. Viscosity varied between 2153 and 3498 cP at 0°C. Emulsification was negligible for all tests, and were significantly less than measured during the tests conducted by SINTEF. Inspection of the GC results for the tests with Grane crude oil (see Figure D 5) showed only slightly lower concentrations of light ends in the samples taken after 18 hours of weathering, compared to the samples taken after 6 hours.

No significant evaporative loss was detectable using oil densities measured in the tests with IFO 80. Viscosities varied between approximately 7500 and 9500 cP for the 6-hour tests, and 10,000 and 12,750 cP for the 18-hour tests indicating that there was a change in the oil characteristics during the weathering periods. No significant differences were noted between the GC results for the tests with IFO 80 (see Figure D 1).

Grab samples of tank water were obtained prior to dispersant application, and at the end of the high energy and prop wash periods. The oil-in-water concentration was determined by extracting the grab samples with dichloromethane and comparing the absorbance of the extracts to prepared calibration curves, as described in Faksness and Belore (2014). Dispersant effectiveness was calculated by comparing the amount of oil in the water column with the amount of oil applied initially, accounting for losses from evaporation and sampling. The dispersant effectiveness results are provided in Table B 3.

Table B 3 Oil concentration in water (from UV measurements) and estimated dispersant efficiency of weathered oil. Estimated evaporative loss is predicted by correlation of density and evaporative loss from artificial weathering performed in previous studies at SL Ross.

			Oil in water from UV (ppm)		Dispersant efficiency (%)	
Test ID	Applied oil (g)	Estimated evap loss (wt%)	High energy	Prop wash	High energy	Prop wash
ANS-D-80-35-6	874.0	17%	99.2	96.9	71%	69%
ANS-D-80-15-6	871.0	18%	39.2	47.7	29%	35%
ANS-D-80-35-18	878.3	24%	70.1	75.1	55%	59%
ANS-D-80-15-18	871.0	20%	14.2	34.0	11%	25%
ANS-O-80-35-6	868.9	18%	103.5	87.0	76%	64%
ANS-O-80-15-6	870.7	15%	82.6	89.3	58%	63%
ANS-O-80-35-18	875.9	22%	103.0	91.6	79%	70%
ANS-O-80-15-18	867.2	23%	89.4	81.1	70%	64%
ANS-C-80-35-6	873.3	18%	63.0	70.8	46%	52%
ANS-C-80-35-18	872.2	21%	59.0	62.4	45%	47%
ANS-C-80-15-18	928.8	26%	8.7	16.0	7%	12%
GRN-D-50-35-6	901.6	5%	77.4	108.2	47%	66%
GRN-D-50-15-6	906.2	5%	85.9	66.0	52%	40%
GRN-O-80-35-6	907.4	6%	99.5	97.7	61%	60%
GRN-O-80-15-6	918.3	6%	83.9	84.1	50%	51%
GRN-C-50-35-18	914.3	6%	101	104	61%	63%
GRN-C-50-15-18*	909.6	6%	NM	69	NM	42%
IFO-D-80-35-6	922.8	0%	99.7	110	56%	62%
IFO-D-80-35-18	914.5	0%	48.0	46.1	27%	26%
IFO-O-80-35-6	921.6	0%	81.0	90.2	46%	51%
IFO-O-80-35-18	926.1	0%	27.0	24.5	15%	14%
IFO-C-80-35-6	920.5	0%	61.4	53.5	35%	30%
IFO-C-80-35-18	918.0	0%	27.7	24.3	16%	14%
TR-C-80-35-18	844.3	16%	60.9	65.4	45%	48%
GRN-C-80-35-18	909.5	6%	66.9	143.5	41%	88%

**Test GRN-C-50-15-18 was run with prop wash only (i.e., there was no high energy waves only period)*

B.4.1 Dispersant efficiency for the different oils

Dispersant efficiency for the ANS and Grane crude oils, and IFO 80 is presented in Figure B 1 through Figure B 3, respectively.

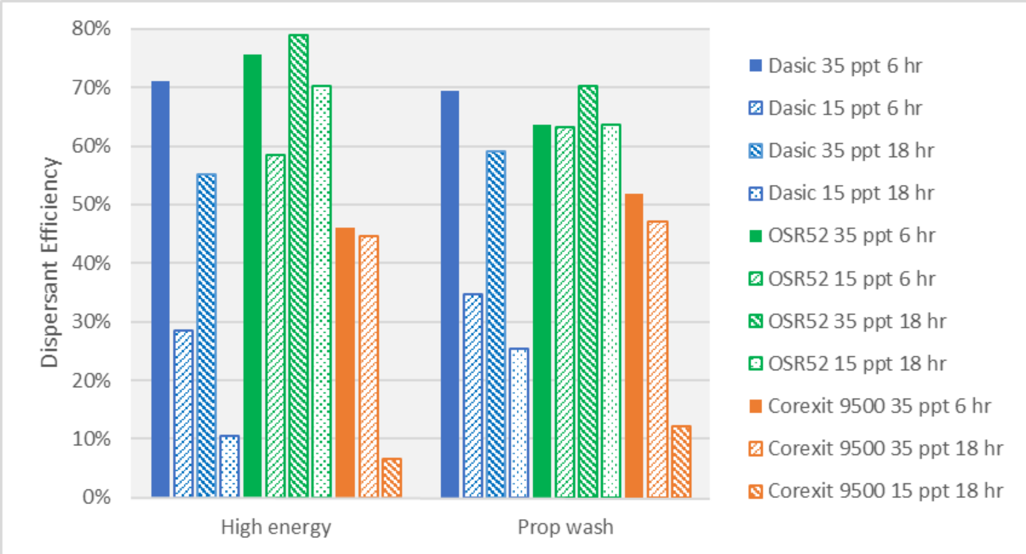


Figure B 1 Dispersant efficiency for Alaska North Slope crude oil

Dasic performed well on ANS in 35 ppt salinity water, but showed significantly lower effectiveness in 15 ppt water. Efficiency was lower by 15 to 20% when the 18-hour weathering tests are compared to the 6-hour tests. Prop wash generally improved efficiency by only a small margin of approximately 5%.

OSR-52 performed consistently well on ANS. Efficiency varied between 58 to 79%. The highest efficiencies were achieved in 35 ppt water, averaging 8% more efficient than the tests in 15 ppt water. Prop wash did not significantly affect efficiency.

Corexit 9500 showed similar, but consistently lower, performance to Dasic on ANS. The highest effectiveness was achieved with 6-hour weathering in 35 ppt water. Performance decreased at 18 hours of weathering, and decreased further in 15 ppt water. Prop wash did not significantly affect efficiency.

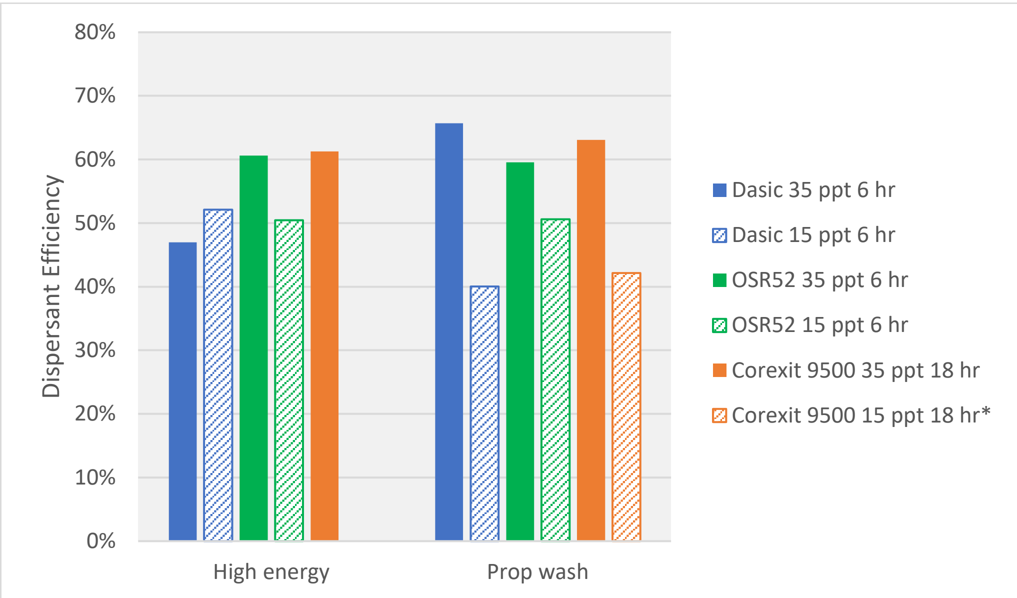


Figure B 2 Dispersant efficiency for Grane crude oil

Efficiency was in a much narrower range for Grane crude oil, with all dispersants performing between 40 and 69%. Prop wash generally had only a small effect on efficiency. Salinity had a negligible effect on efficiency over the range tested, with the exception of Dasic with prop wash, which was 25% more effective in 35 ppt water. It should be noted that the tests with Finasol OSR-52 were done in 80% ice coverage, while the tests with Corexit 9500 and Dasic Slickgone were done in 50% ice coverage. The test with Corexit 9500 in 15 ppt water was performed using only the prop wash energy regime (i.e., the high wave energy period was not applied).

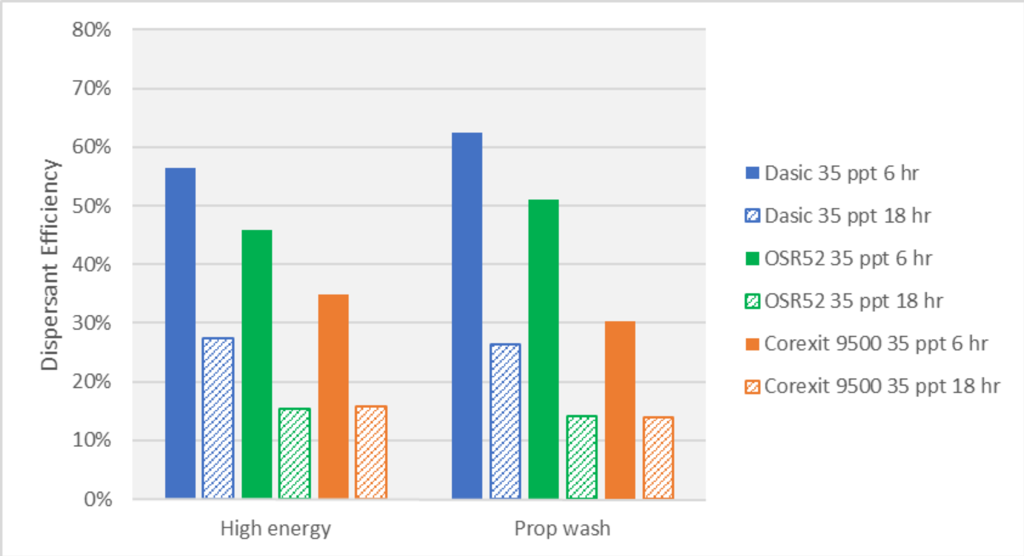


Figure B 3 Dispersant efficiency for IFO 80

IFO 80 showed a similar pattern to ANS crude oil, but with generally lower efficiencies. Tests weathered for 18 hours had lower efficiency than those weathered for 6 hours by around 20 to 40%. Prop wash had a negligible effect on efficiency.

B.4.2 Comparing dispersant efficiency of the dispersants vs oil type and water salinity

The dispersant efficiency for the three oil types in water with 35 and 15 ppt salinities are compared in Figure B 4 and Figure B 5, respectively.

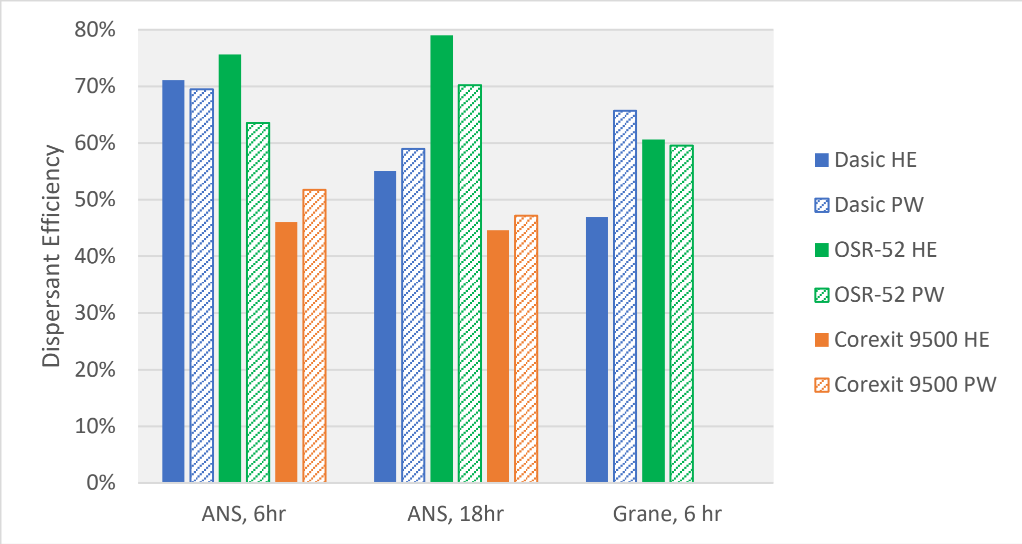


Figure B 4 Dispersant efficiency in 35 ppt salinity water for ANS and Grane crude oils (HE: High energy, PW: prop wash).

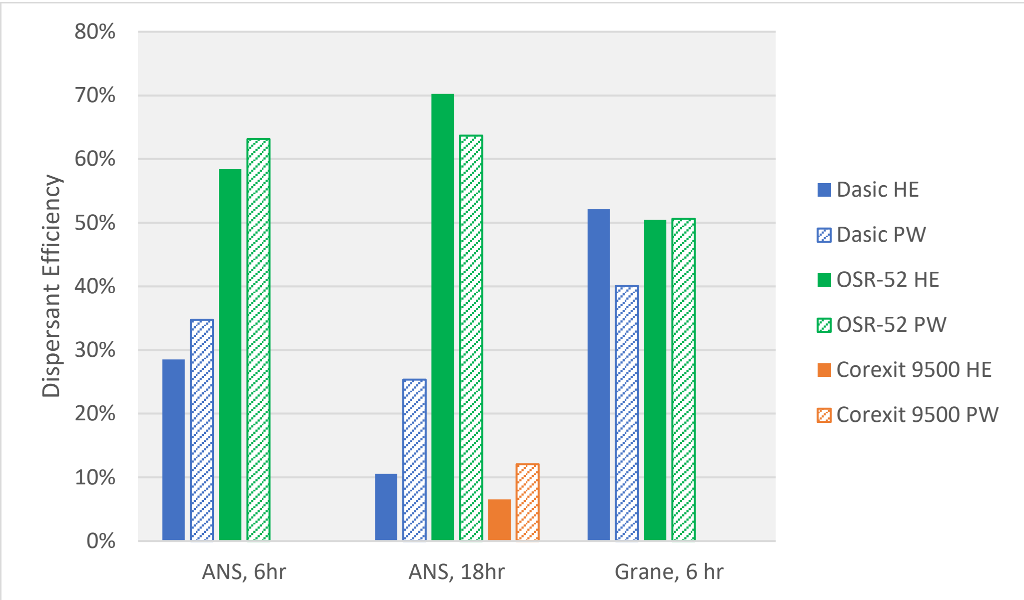


Figure B 5 Dispersant efficiency in 15 ppt salinity water for ANS and Grane crude oils (HE: High energy, PW: prop wash).

OSR-52 dispersant was the least affected by changing salinity, with an average difference of 9% between the tests in 35 ppt and 15 ppt water. Dasic was the most affected, with an average difference of 29% between the tests in 35 ppt and 15 ppt water. Corexit 9500 was only tested at two salinities with the 18 hour weathered ANS; the average difference between the tests in 35 ppt and 15 ppt water was 14%.

Corexit 9500 had the lowest effectiveness of the three dispersants with ANS crude oil. All three dispersants performed similarly with Grane crude oil.

B.4.3 Particle size distribution

In addition, oil-in-water concentrations and oil droplet size distribution were measured from in situ LISST monitoring during the entire test period. Data from these measurements are provided in Appendix F.

As also observed by SINTEF, the concentrations measured from the water grab samples were generally higher than recorded using the LISST. It was observed that the volume median oil droplet size increased when the salinity in the water decreased. This is consistent with a reduced dispersant efficiency in lower salinity water as larger oil drops are not as easily retained in the water column.

B.5 SL Ross Result Summary Highlights

The dispersant effectiveness values summarized in the following refer to the values recorded at the end of each test after the application of prop wash. The addition of prop wash after the use of high energy waves did not increase the dispersant effectiveness significantly or consistently throughout the testing so the following results generally apply to the high wave results as well. Refer to the main results section for additional details.

Tests were conducted on three oils: ANS, Grane and IFO 80, with two degrees of oil weathering: 6hrs and 18 hrs and with two water salinities: 35 ppt and 15 ppt. A complete test matrix including all of these variables was not possible within the budget allocated. Table B 4 summarizes the results discussed below.

Table B 4 Summary of SL Ross Dispersant Effectiveness Results

Oils and Dispersants Tested	Dispersant Effectiveness (%) at End of Prop Wash Period			
	6 hr Weathered Oil		18 hr Weathered Oil	
	35 ppt	15 ppt	35 ppt	15 ppt
ANS				
Corexit 9500	52		47	12
Dasic Slickgone NS	69	35	59	25
OSR-52	64	63	70	64
IFO 80				
Corexit 9500	30		14	
Dasic Slickgone NS	62		26	
OSR-52	51		14	
Grane				
Corexit 9500			63*	42* **
Dasic Slickgone NS	66*	40*		
OSR-52	60	51		

** The tests with Grane using Dasic and Corexit 9500 dispersants were conducted with 50% ice coverage*

***The test with Grane and Corexit 9500 dispersant in 15 ppt water was conducted with the prop energy only (i.e., no high energy wave period was applied).*

ANS results:

Corexit 9500 had the lowest effectiveness on ANS crude oil in 35 ppt water of the three dispersants (27 % with18 hr weathering and 52% with 6hr weathered oil). Dasic performed well in 35 ppt water (59% with 18 hr weathering and 69% with 6 hr weathered oil) but showed significantly lower effectiveness (25 and 35%, respectively) in 15 ppt water. OSR-52 performed consistently well on ANS over the range of weathered oils and water salinities tested. Efficiency varied between 63 to 70%.

IFO 80 Results:

Dispersant effectiveness on IFO 80 in both 35 and 15 ppt water showed similar patterns to ANS crude oil, but with generally lower efficiencies. Corexit 9500 was again the least effective product (30% in 35 ppt water and 14% in 15 ppt). Dasic and OSR-52 both performed reasonably well in 32 ppt water (62 and 51 %, respectively) but both were less effective in 15 ppt water (26 and 5%, respectively).

Grane Results:

All three dispersants performed similarly (between 56 and 66%) on 6 hour weathered Grane crude in 35 ppt water. Effectiveness dropped to between 40 and 51% on 6 hour weathered Grane in 15 ppt water.

Salinity effect:

OSR-52 dispersant was the least affected by changing salinity, with an average difference of -9% between the tests in 35 ppt and 15 ppt water. Dasic was the most affected, with an average difference of 29% between the tests in 35 ppt and 15 ppt water. Corexit 9500 was only tested at two salinities with the 18 hour weathered ANS; the average difference between the tests in 35 ppt and 15 ppt water was 14%.

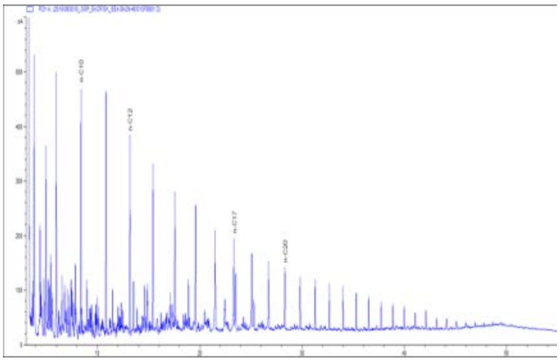
Oil Weathering Time Effect:

Weathering ANS to 18 hr resulted in an average decrease in dispersant efficiency of about 10% in the 35 ppt tests and 5% in the 15 ppt tests. In the 18 hr weathered IFO 80 tests the dispersants were on average about 30% less effective than on the 6 hr weathered oil.

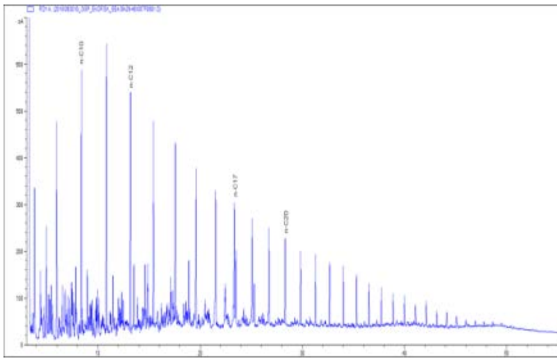
Measure Oil Drop Sizes:

The measured volume median oil droplet sizes increased when the salinity in the water decreased. This is consistent with a reduced DE in lower salinity water as larger oil drops are not as easily retained in the water column.

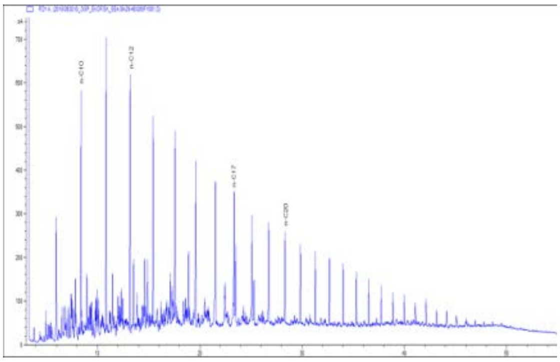
APPENDIX C GC CHROMATOGRAMS FROM SINTEF



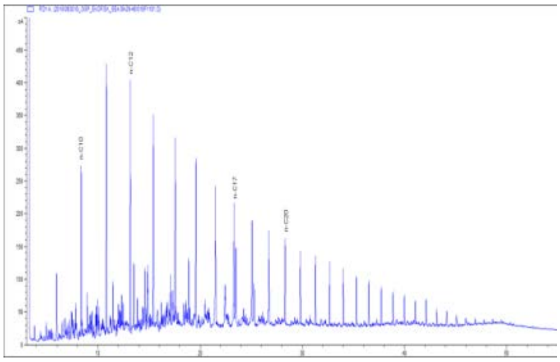
Oseberg Blend crude oil (SINTEF ID 2015-0060)



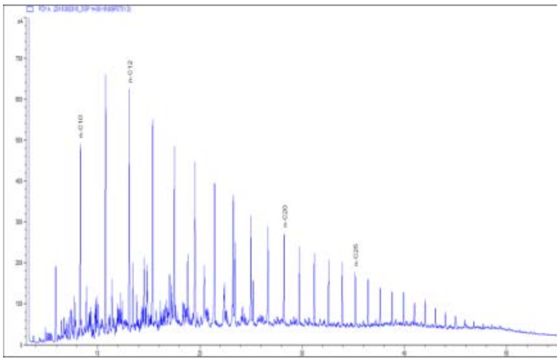
OSB-D-80-35



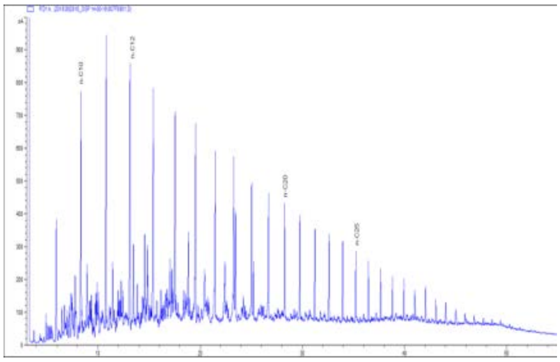
OSB-O-80-35



OSB-D-80-15

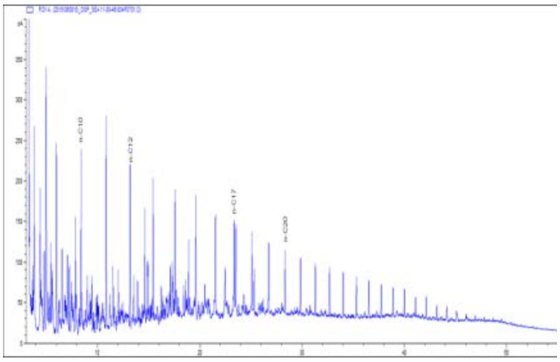


OSB-O-80-15

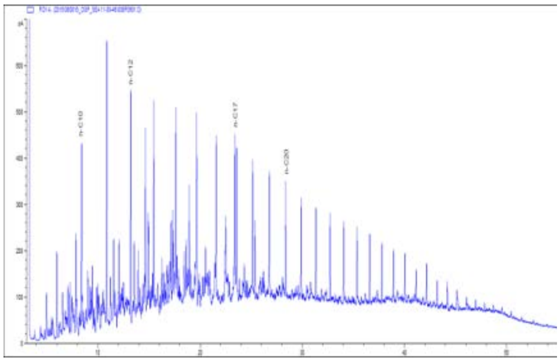


OSB-D-80-5

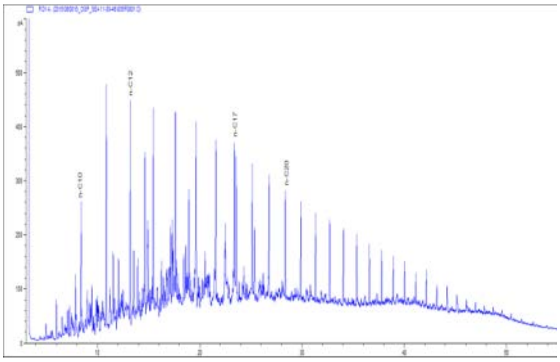
Figure C 1 GC chromatograms of Oseberg Blend weathered for 18 hrs in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.5.



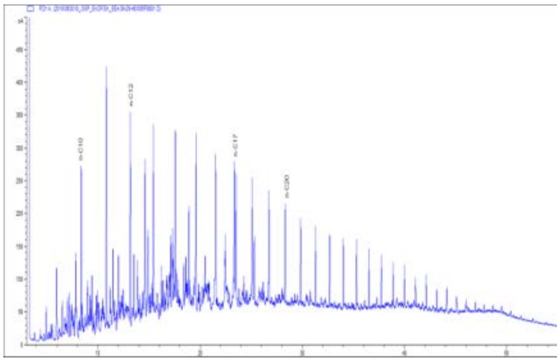
Troll Blend crude oil (SINTEF ID 2014-0335)



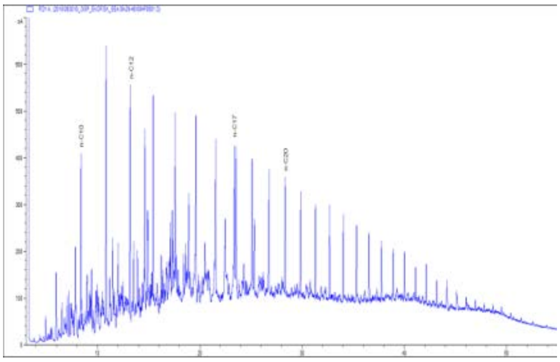
TRL-D-80-35



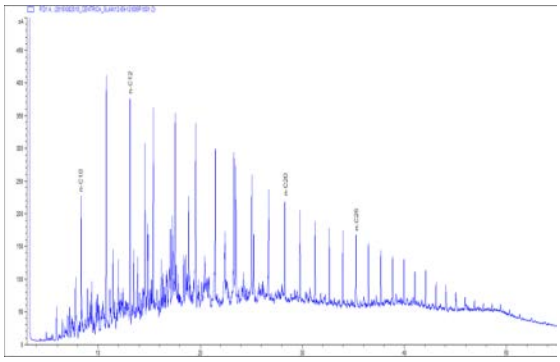
TRL-O-80-35



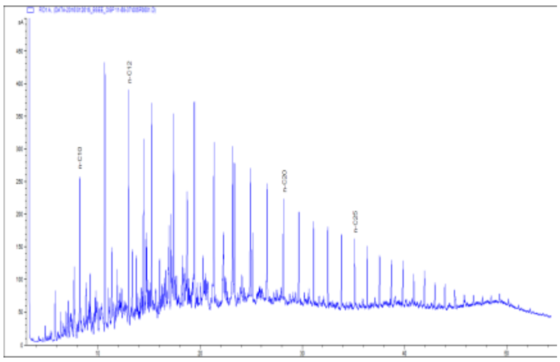
TRL-D-80-15



TRL-O-80-15

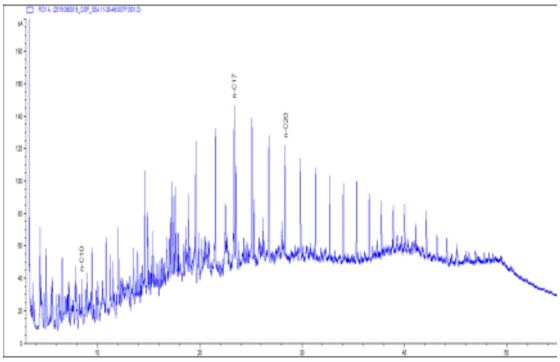


TRL-D-80-5-1

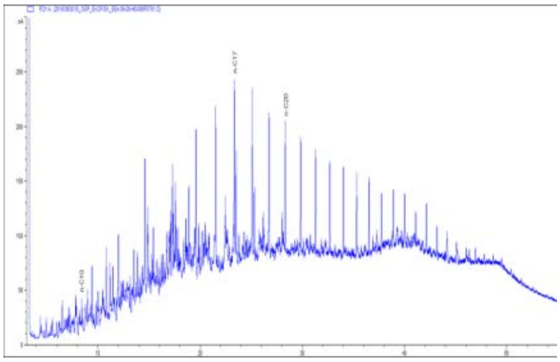


TRL-D-80-5-2 (analyzed under slighly different conditions)

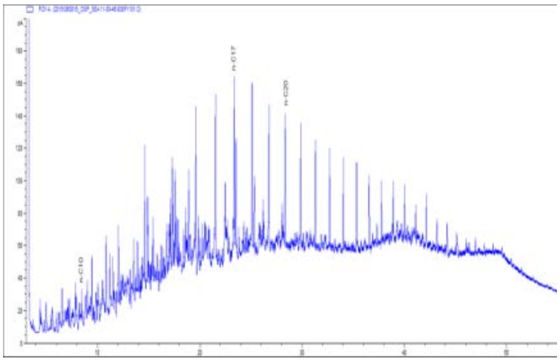
Figure C 2 GC chromatograms of Troll Blend weathered for 18 hrs in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.5.



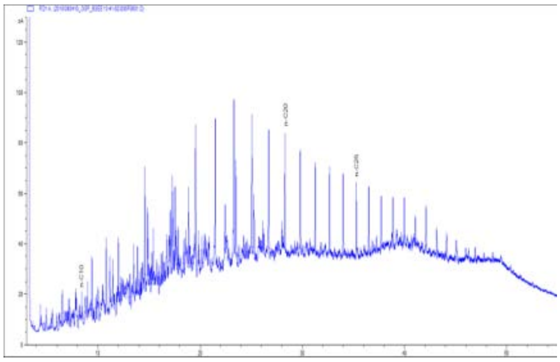
Grane crude oil (2015-0061)



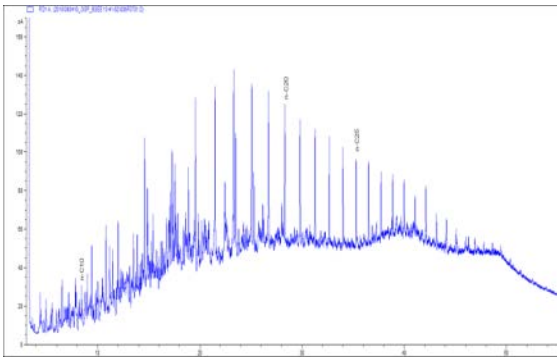
GRN-D-80-35



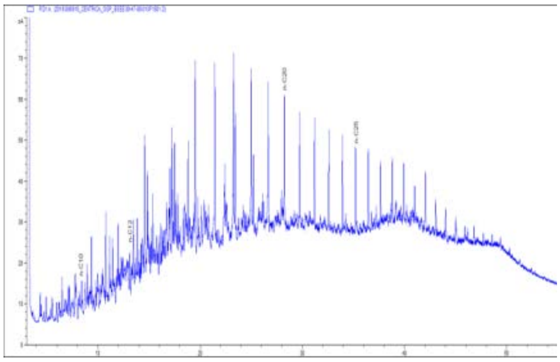
GRN-O-80-35



GRN-D-80-15

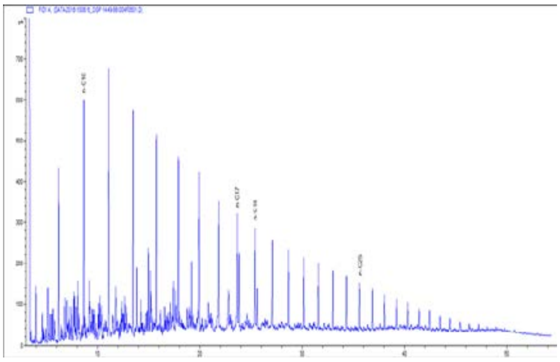


GRN-O-80-15

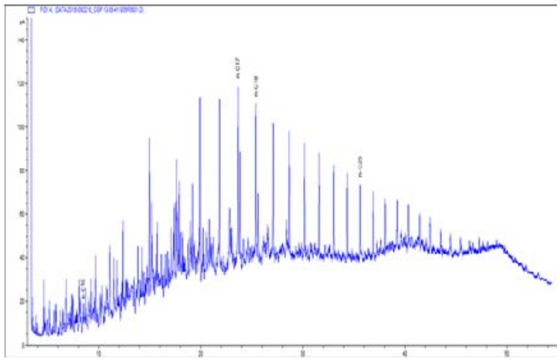


GRN-D-80-5

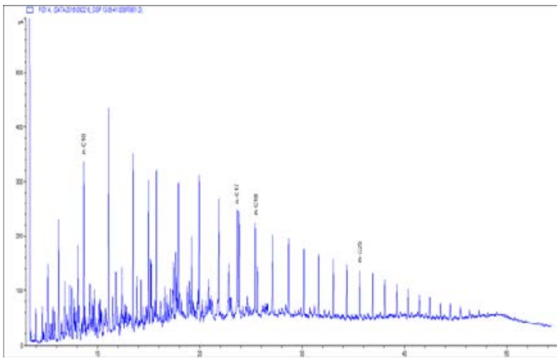
Figure C 3 GC chromatograms of Grane crude oil weathered for 18 hrs in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.5.



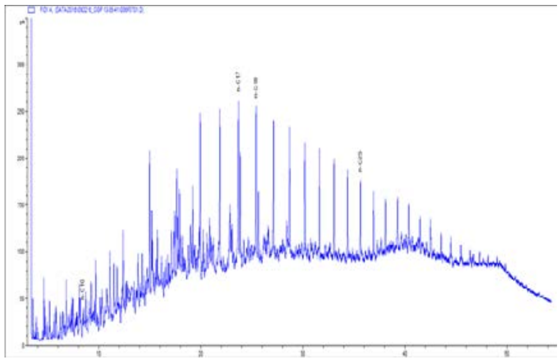
OSB-C-0-35-L



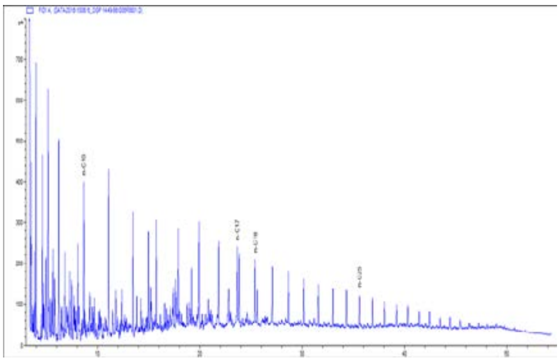
GRN-C-0-35-L



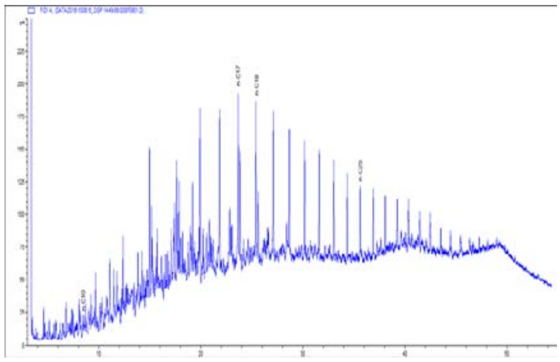
TRL-C-0-35-L



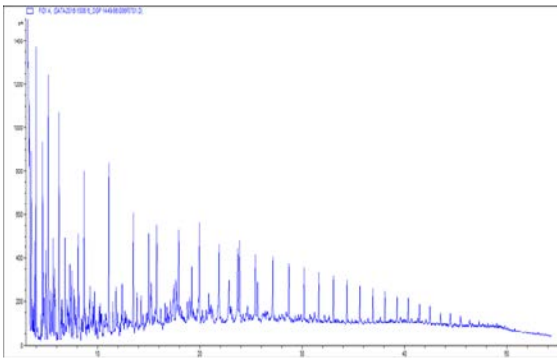
GRN-C-80-35-A



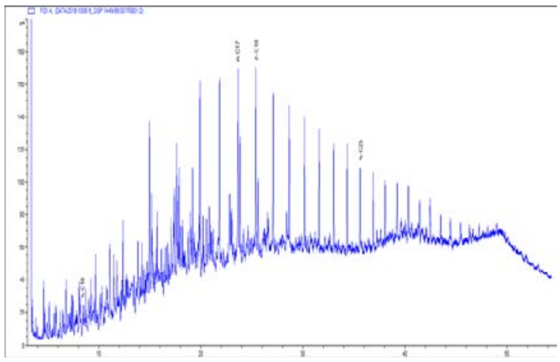
TRL-C-80-35-F-0



GRN-C-80-35-B



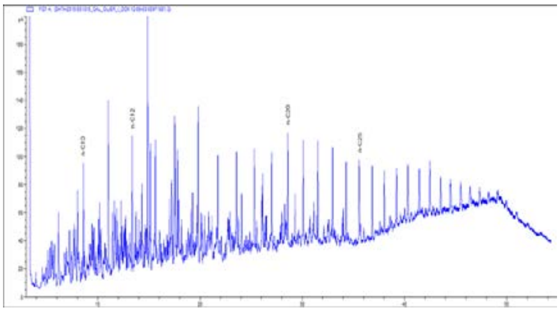
TRL-C-0-35-F-13



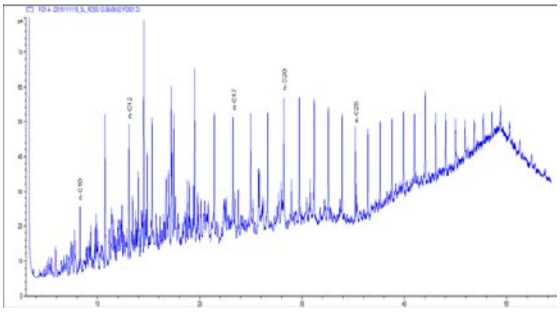
GRN-C-80-35-C

Figure C 4 GC chromatograms of the oils prior to dispersant application. Explanation of test identifications is provided in Table 4.1.

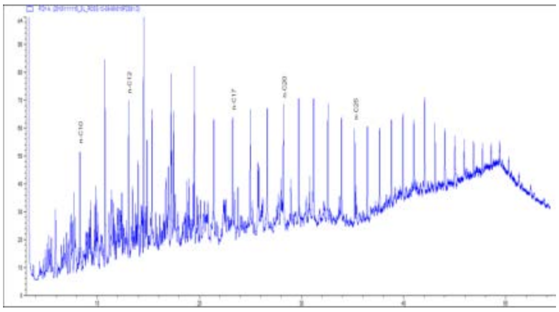
APPENDIX D GC CHROMATOGRAMS FROM SL ROSS



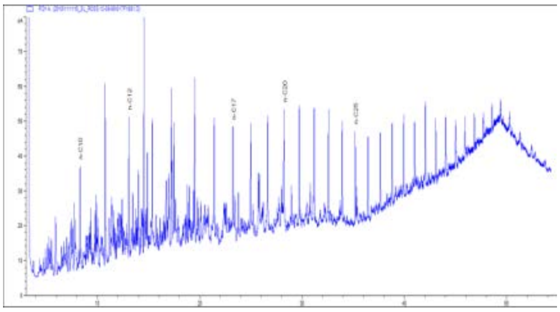
IFO 80 fresh oil (2015-0466)



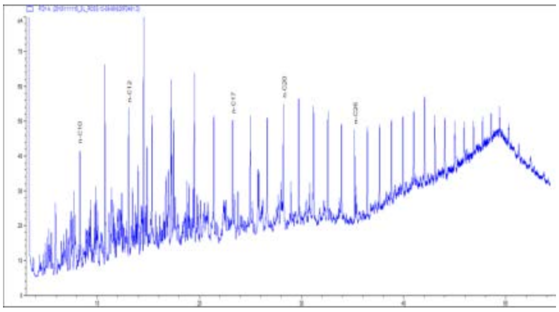
IFO-O-80-35-18



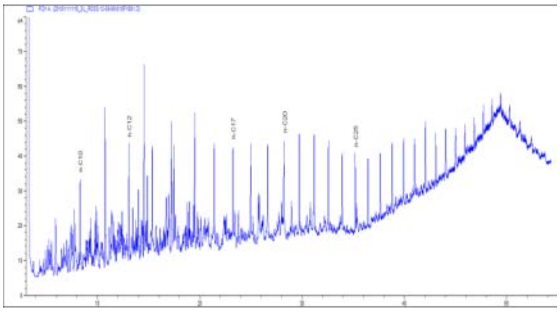
IFO-O-80-35-6



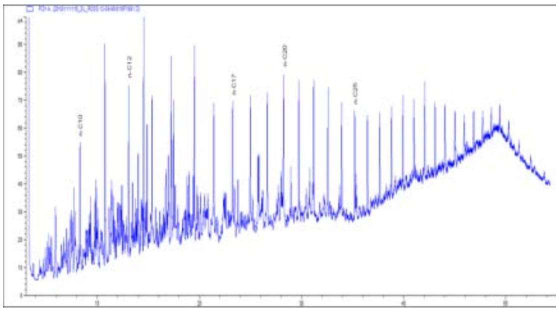
IFO-D-80-35-18



IFO-D-80-35-6

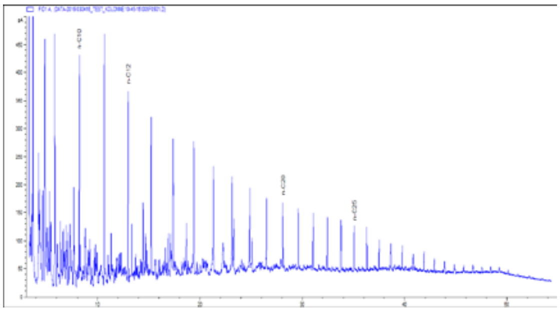


IFO-C-80-35-18

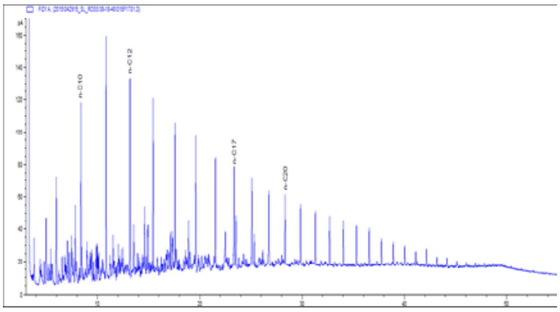


IFO-C-80-35-6

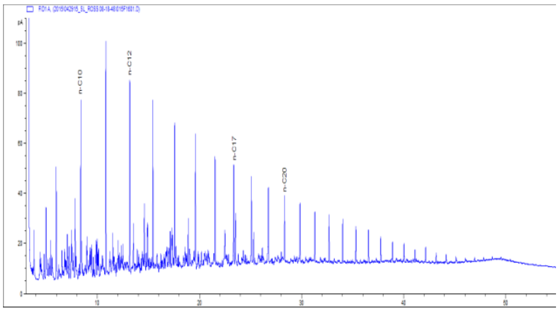
Figure D 1 GC chromatograms of IFO 80 weathered in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.6



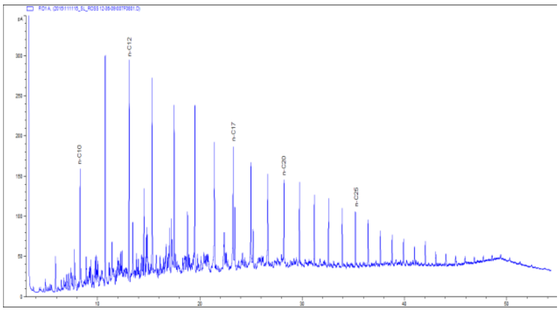
ANS crude oil (2014-BSEE)



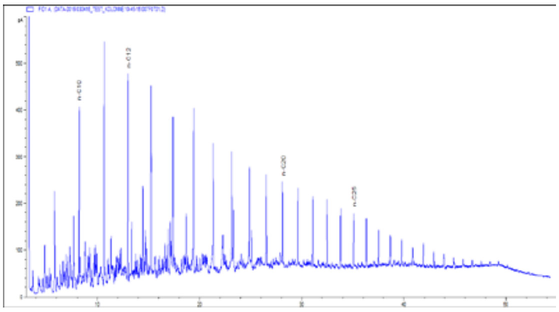
ANS-D-80-35-6



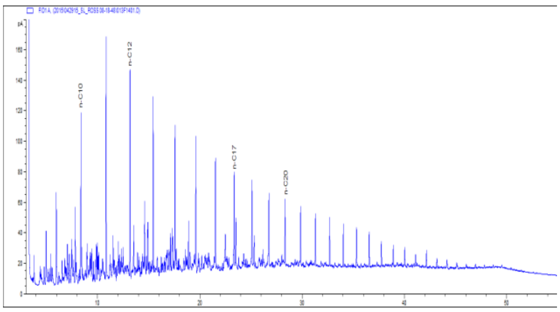
ANS-D-80-15-6



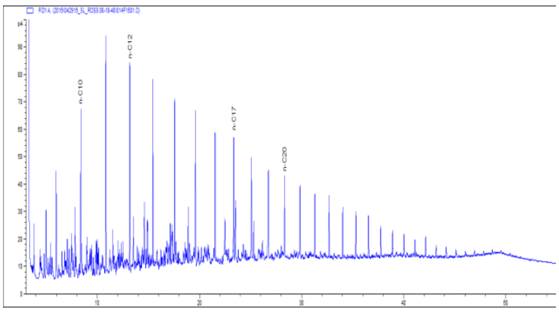
ANS-D-80-35-18



ANS-D-80-15-18

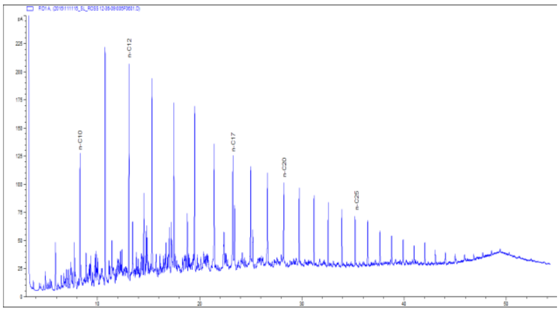


ANS-O-80-35-6

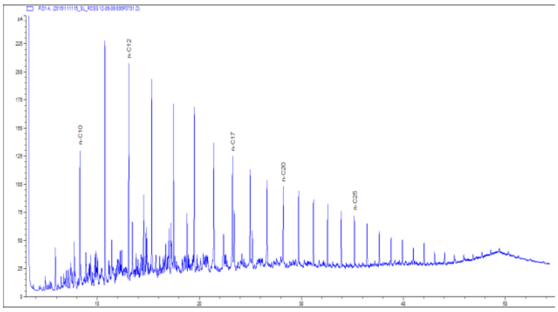


ANS-O-80-15-6

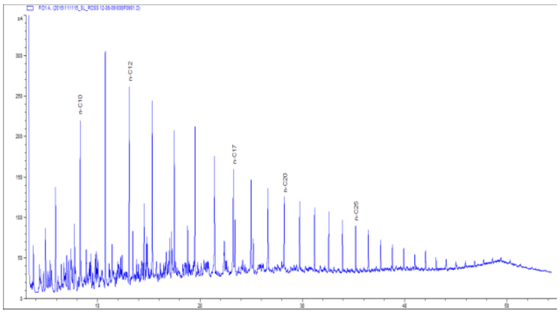
Figure D 2 GC chromatograms of ANS crude oils weathered in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.6.



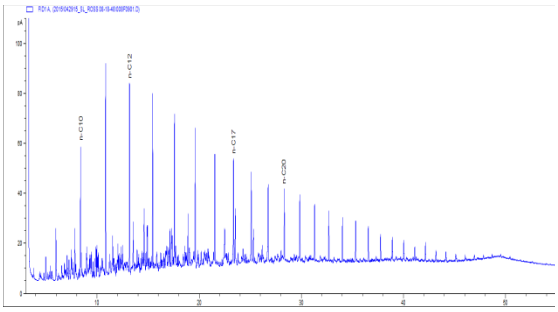
ANS-O-80-35-18



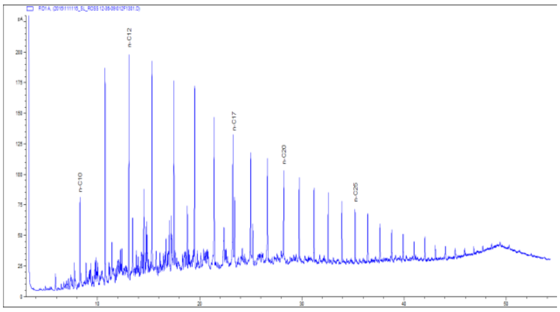
ANS-O-80-15-18



ANS-C-80-35-6

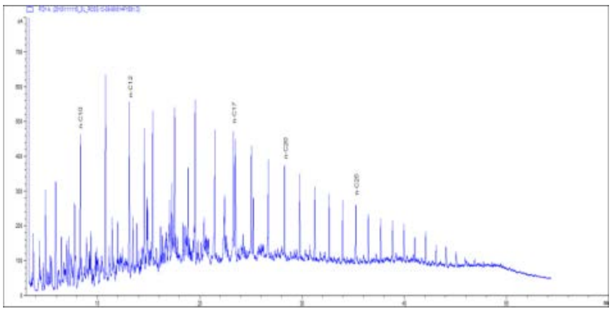


ANS-C-80-35-18



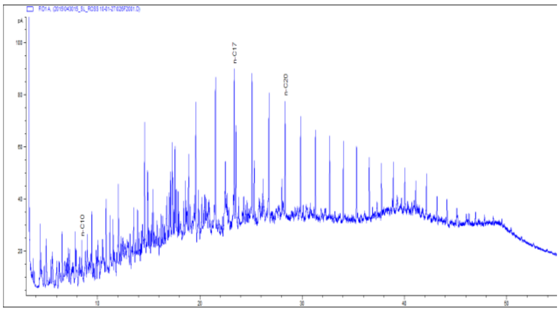
ANS-C-80-15-18

Figure D 3 GC chromatograms of ANS crude oils weathered in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.6.

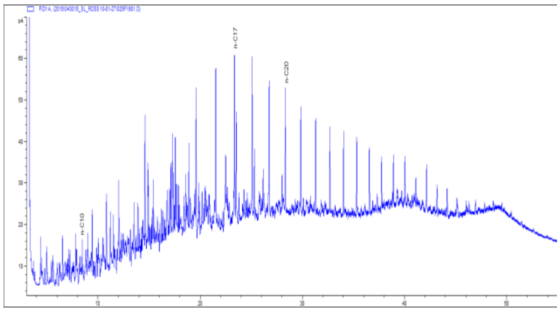


TR-C-80-35-18

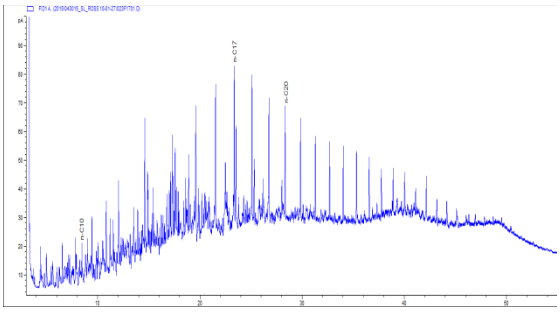
Figure D 4 GC chromatograms of Troll crude oil weathered for 18 hrs in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.6.



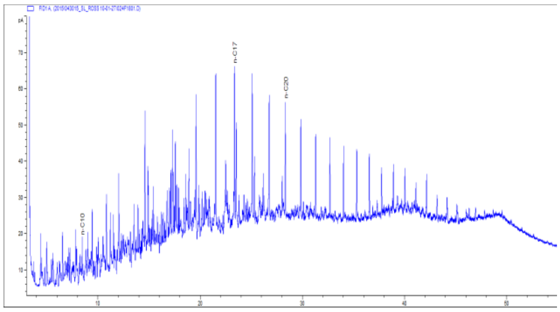
GRN-D-50-35-6



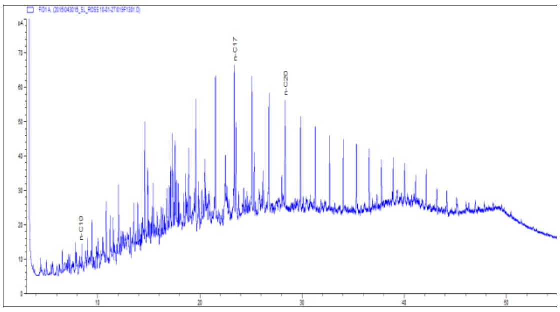
GRN-D-50-15-6



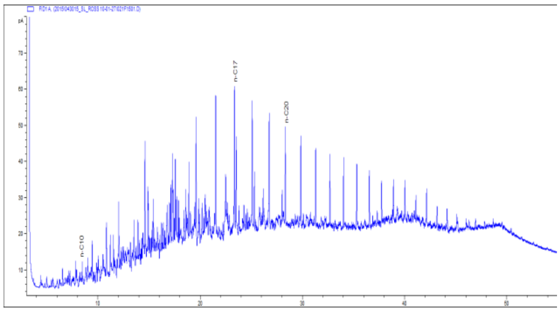
GRN-O-80-35-6



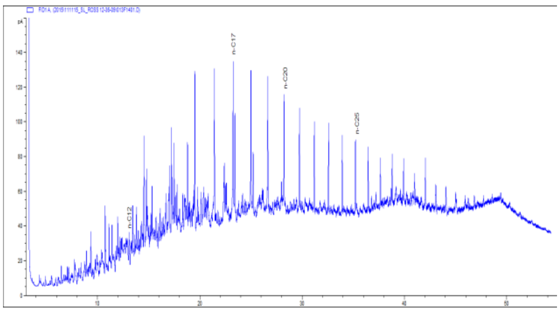
GRN-O-80-15-6



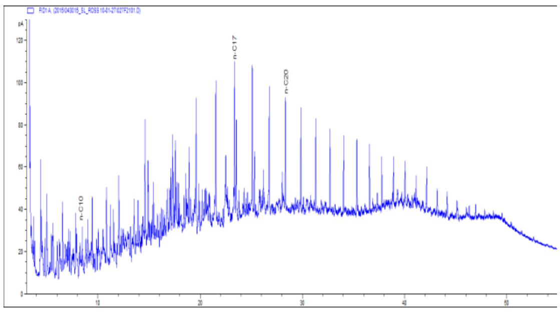
GRN-C-50-35-18



GRN-C-50-15-18*



GRN-C-80-35-18



Grane Crude Oil

Figure D 5 GC chromatograms of Grane crude oil weathered in the flume prior to dispersant testing. Explanation of test identifications is provided in Table 2.6.

APPENDIX E DATA ON PARTICLE SIZE DISTRIBUTION FROM SINTEF

The LISST is a system based on laser diffraction. The LISST used in the experiments was a LISST-100x type C, which can detect droplets in the range of 5-500 µm.

Data shown in Table E 1 (and Figure E 1 to Figure E 13) and Table E 2 (and Figure E 14 to Figure E 21) are obtained from an average of one minute of readings immediately prior to the time of water sampling. The largest size class (bin 32) has been discarded for all figures data shown and in calculations of concentration and d50. This is due to concerns regarding possible contamination from particles exceeding 500 µm.

The data were collected in conditions in which Schlieren may be present (i.e., possible temperature gradients over the sample volume). Caution should therefore be applied to the interpretation of high concentrations of apparently large particles reported by the LISST-100 (see Mikkelsen et al., 2008).

The d50 is calculated from the 50th percentile of the cumulative sum of the volume distribution for the first 31 size classes. The concentration is calculated from the sum of volume concentration over the first 31 size classes.

Table E 1 Summary of LISST data and oil concentration in water grab samples from SINTEF.

	High energy			Propeller wash			Comment
Test ID	LISST d50 µm	LISST conc ppm	Water grab ppm	LISST d50 µm	LISST conc ppm	Water grab ppm	
TRL-D-80-35	135	80	84	209	352	81	Ice particles in water might influenced d50
TRL-D-80-15	85	56	97	134	172	91	
TRL-D-80-05	86	46	76	109	67	84	Higher energy input
TRL-O-80-35	150	41	95	185	126	98	Slush in water
TRL-O-80-15	88	37	79	127	77	82	
TRL-C-80-35	29	66	111	29	65	103	
TRL-C-80-15	51	49	85	102	134	90	
TRL-C-80-05	134	37	81	106	28	71	
OSB-D-80-35	91	57	83	164	212	80	Ice blocking the LISST
OSB-D-80-15	31	21	82	58	34	82	
OSB-D-80-05	88	27	45	100	37	57	
OSB-O-80-35	154	43	63	140	53	65	
OSB-O-80-15	98	67	78	81	58	74	High background LISST
OSB-C-80-35	42	47	74	41	45	72	
OSB-C-80-15	162	83	48	97	36	51	
GRN-D-80-35	203	81	79	208	202	85	Switch LISST (not calibrated?)
GRN-D-80-15	90	45	90	216	62	86	
GRN-D-80-05	96	20	24	151	34	40	
GRN-O-80-35	192	38	54	196	53	56	Offline data from LISST
GRN-O-80-15	No LISST data collected		60	No LISST data collected		58	
GRN-C-80-35	67	77	129	67	77	121	

	High energy			Propeller wash			Comment
	LISST d50	LISST conc	Water grab	LISST d50	LISST conc	Water grab	
Test ID	µm	ppm	ppm	µm	ppm	ppm	
GRN-C-80-15	166	61	54	221	213	70	
GRN-C-80-05	128	13	29	191	33	39	

Table E 2 Summary of LISST data and oil concentration in water grab samples from SINTEF. Test parameters for these additional tests are provided in Table 4.1

	Low energy			High energy			Prop wash		
	LISST d50	LISST conc	Water sample	LISST d50	LISST conc	Water sample	LISST d50	LISST conc	Water sample
Test ID	µm	ppm	ppm	µm	ppm	ppm	µm	ppm	ppm
GRN-C-0-35-L	53	65	74						
TRL-C-0-35-L	101	23	31						
OSE-C-0-35-L	237	13	6						
GRN-C-80-35-A				31	96	127	27	84	109
GRN-C-80-35-B				60	80	111	63	85	124
GRN-C-80-35-C				71	65	85	90	76	92
TRL-C-0-35-F-13				22	111	128	22	121	135
TRL-C-80-35-F-0				35	126	134	57	195	168

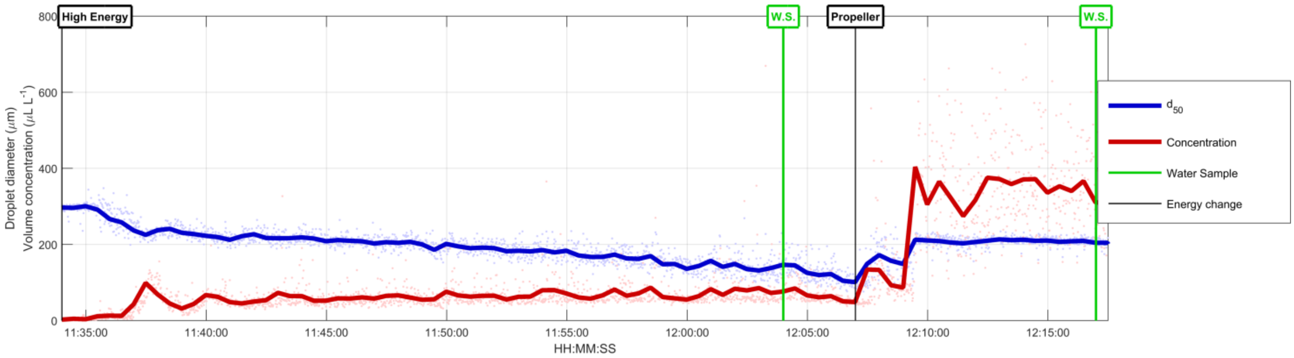


Figure E 1 TRL-D-80-35

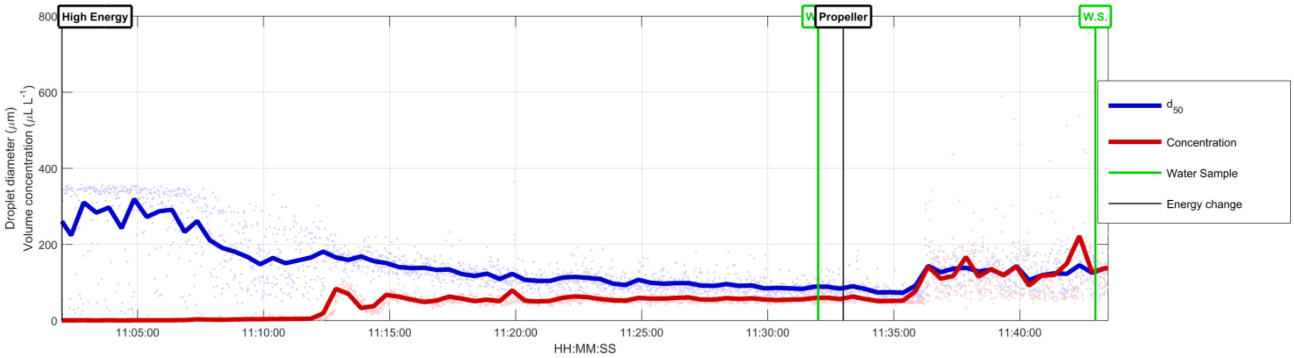


Figure E 2 TRL-D-80-15

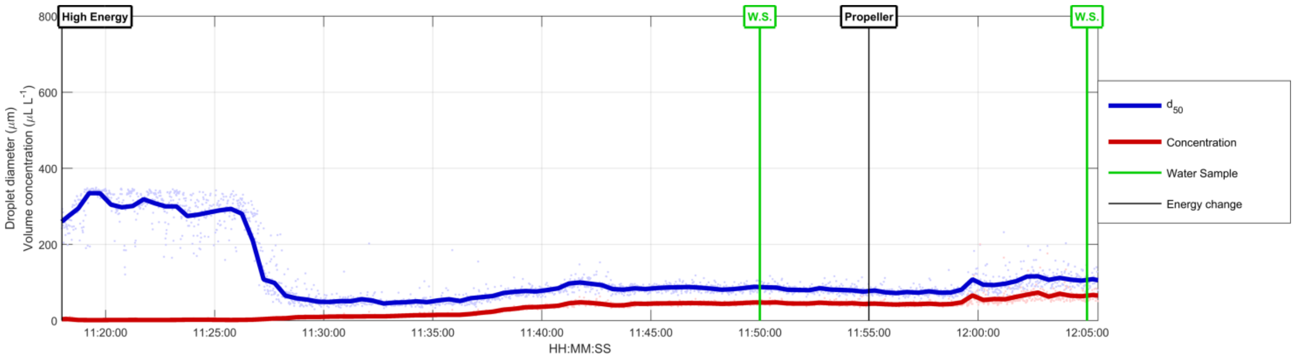


Figure E 3 TRL-D-80-05

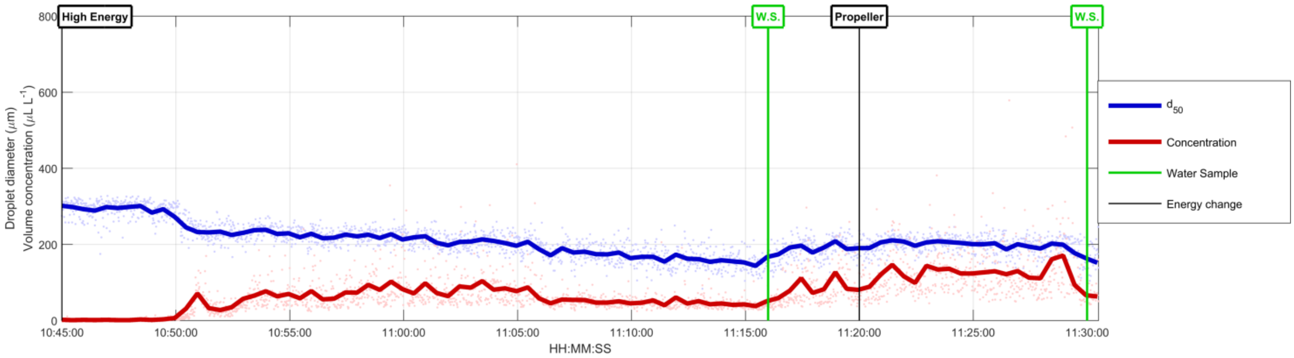


Figure E 4 TRL-O-80-35

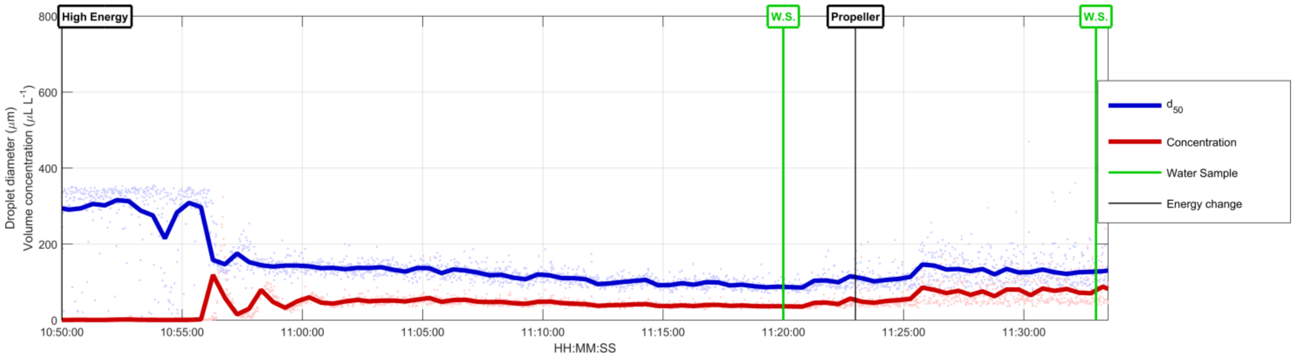


Figure E 5 TRL-O-80-15

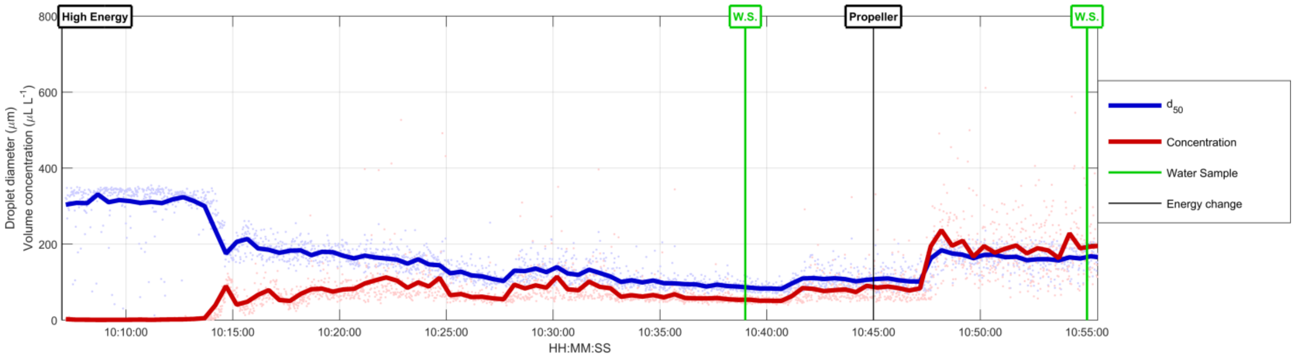


Figure E 6 OSB-D-80-35

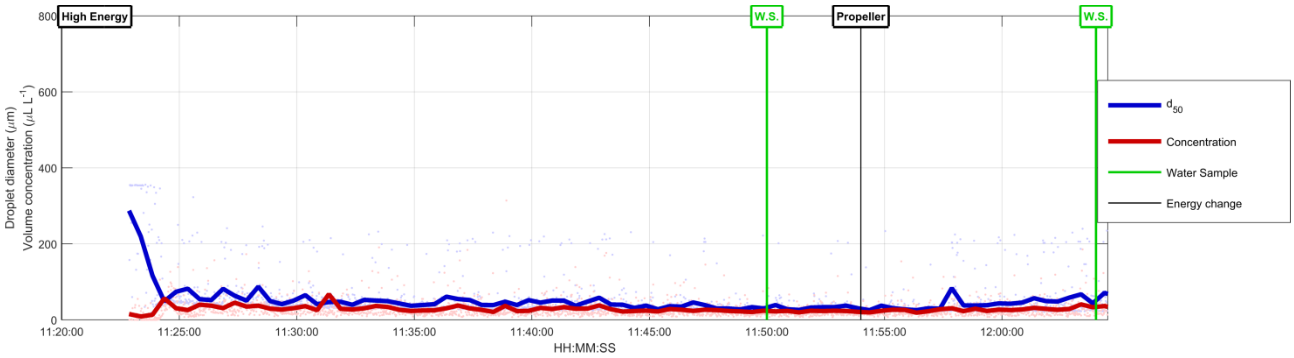


Figure E 7 OSB-D-80-15

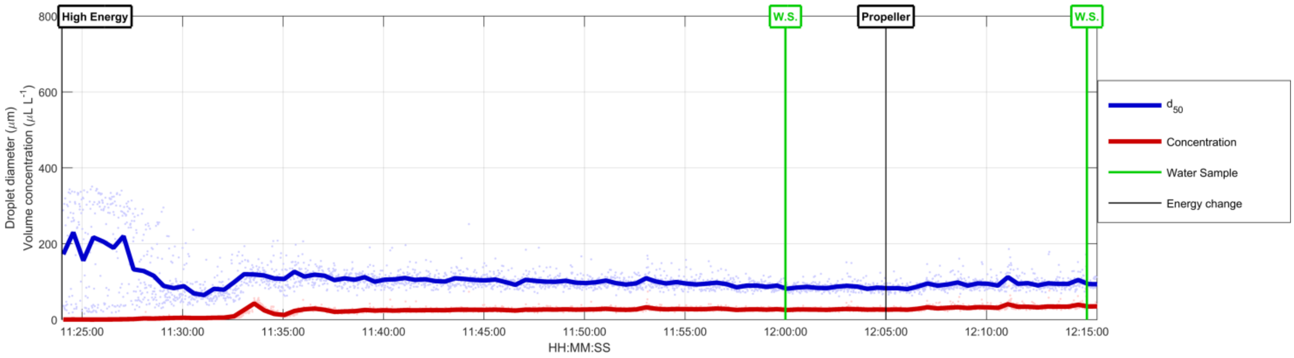


Figure E 8 OSB-D-80-05

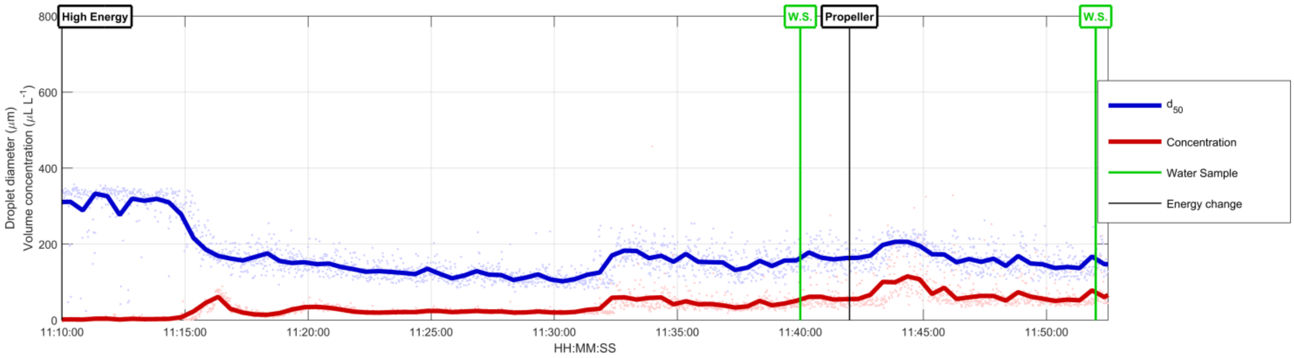


Figure E 9 OSB-O-80-35

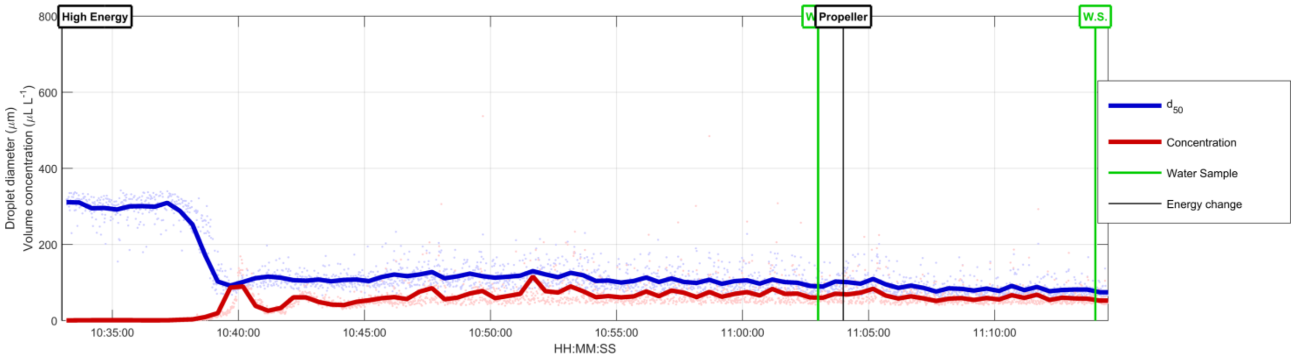


Figure E 10 OSB-O-80-15

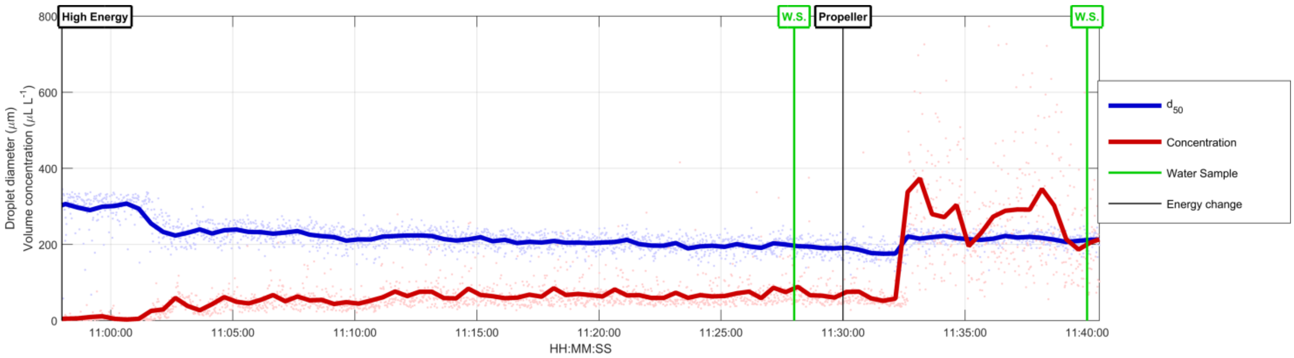


Figure E 11 GRN-D-80-35

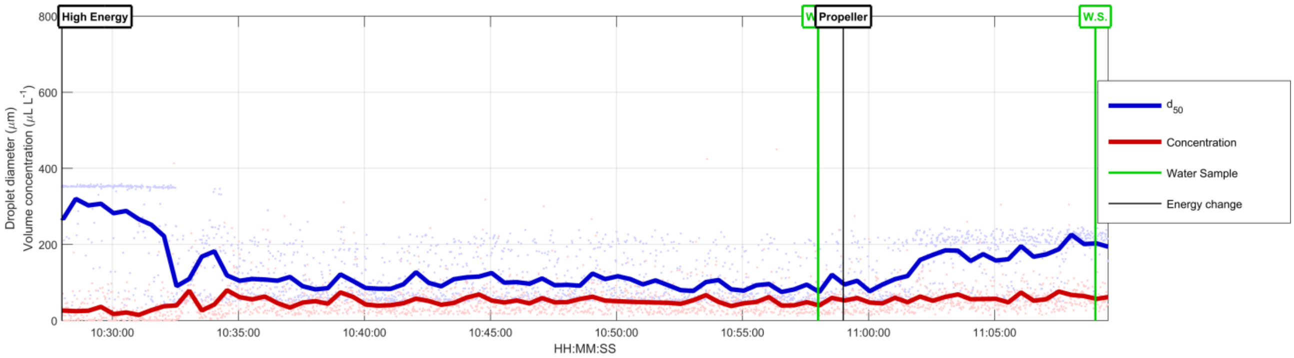


Figure E 12 GRN-D-80-15

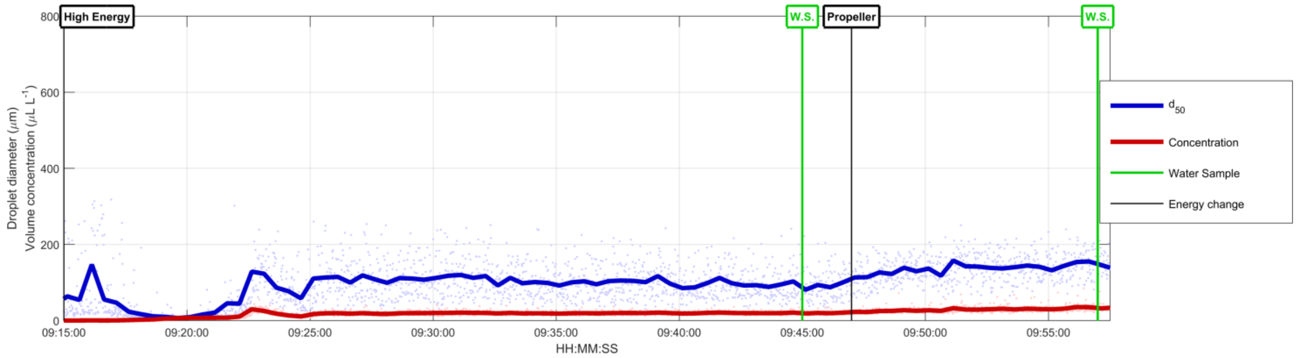


Figure E 13 GRN-D-80-05

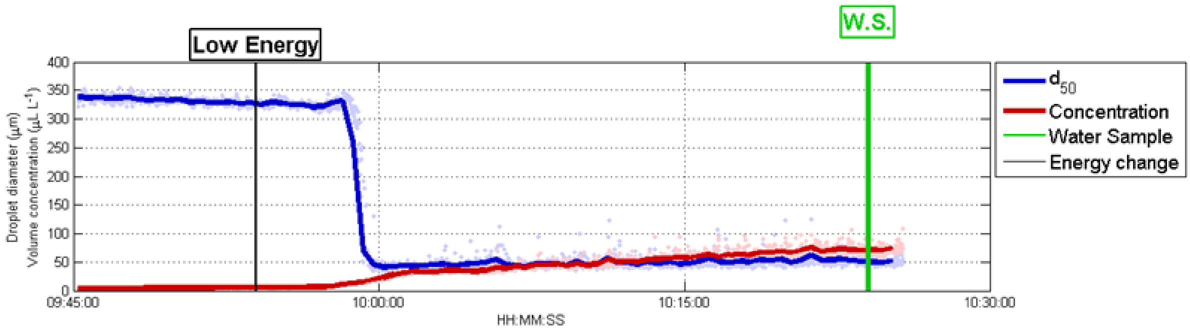


Figure E 14 GRN-C-0-35-L

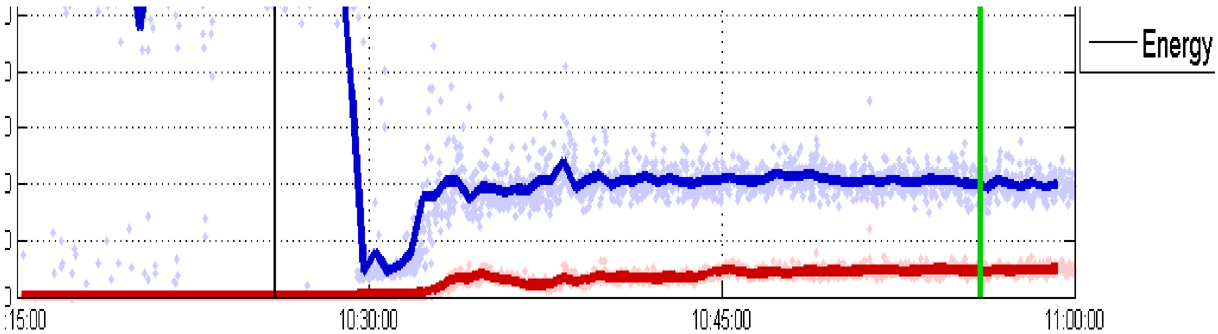


Figure E 15 TRL-C-0-35-L

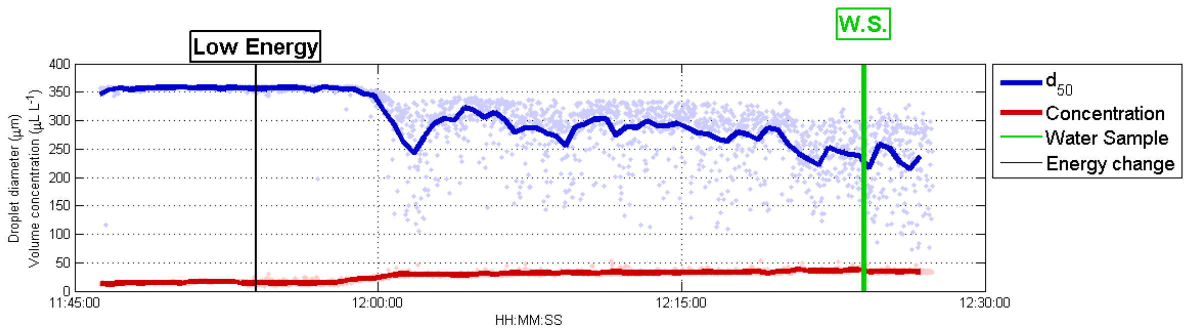


Figure E 16 OSE-C-0-35-L

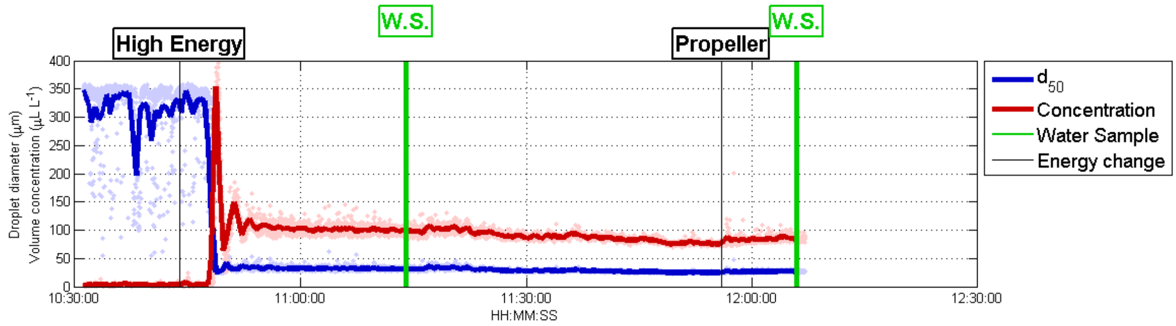


Figure E 17 GRN-C-80-35-A

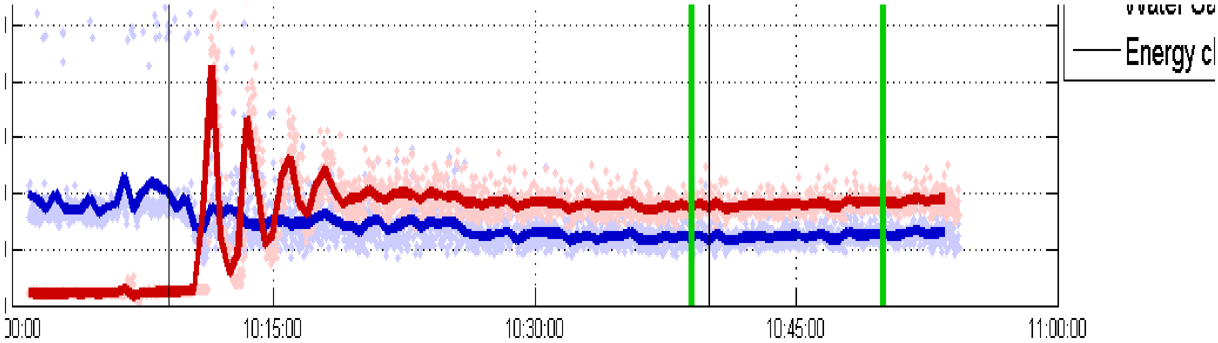


Figure E 18 GRN-C-80-35-B

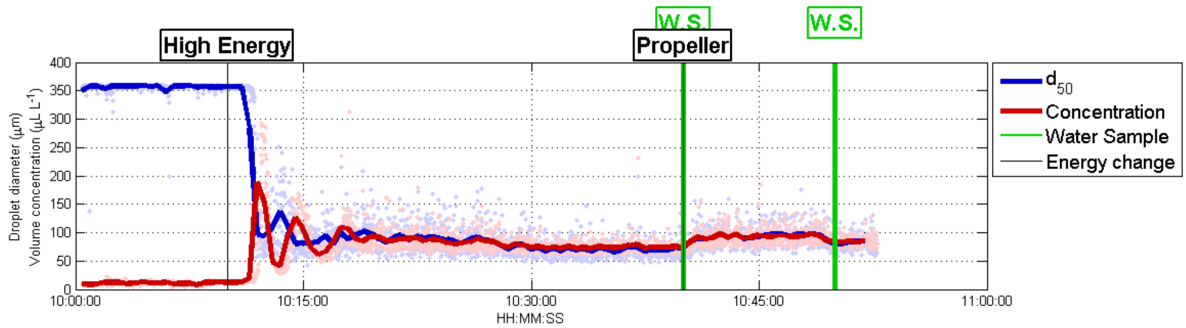


Figure E 19 GRN-C-80-35-C

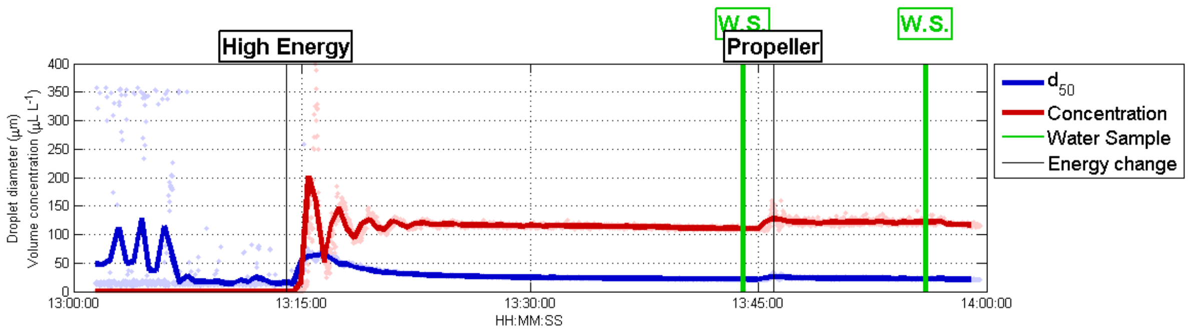


Figure E 20 TRL-C-0-35-F-13

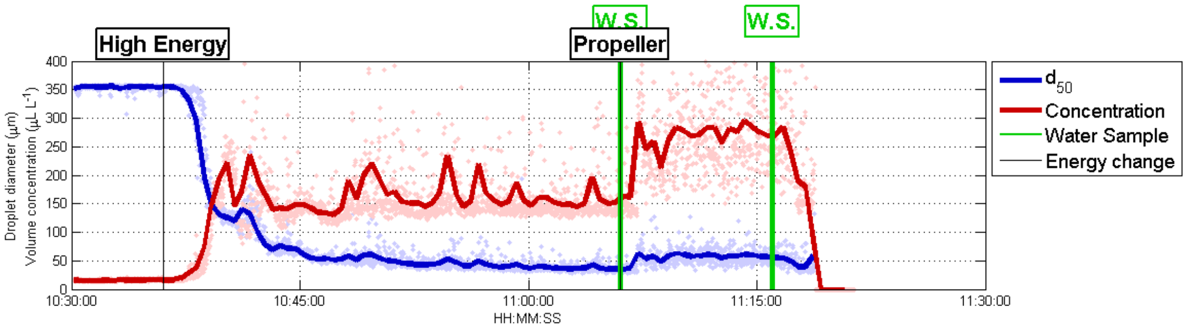


Figure E 21 TRL-C-80-35-F-0

APPENDIX F DATA ON PARTICLE SIZE DISTRIBUTION FROM SL ROSS

SL Ross measured droplet size distribution in the water column with a LISST 100-X, type C, which can detect droplets in the range of 5-500 µm.

Data shown in Table F 1 and Table F 2 was obtained from an average of a minimum of 100 LISST samples in the vicinity of the time of water sampling.

The d50 is calculated from the 50th percentile of the cumulative sum of the volume distribution for the 32 size classes measured by the LISST. The concentration is calculated from the sum of volume concentration over the 32 size classes.

Table F 1 Summary of LISST data and oil concentration in water grab samples from SL Ross.

	High energy			Propeller wash		
	LISST d50	LISST conc	Water grab	LISST d50	LISST conc	Water grab
Test ID	µm	ppm	ppm	µm	ppm	ppm
ANS-D-80-35-6	33.4	75.9	99.2	33.2	76.4	96.9
ANS-D-80-15-6	67.4	33.7	39.2	69.7	34.6	47.7
ANS-D-80-35-18	48.0	56.0	70.1	45.8	57.1	75.1
ANS-D-80-15-18	53.8	16.8	14.2	116.1	30.3	34.0
ANS-O-80-35-6	38.5	75.1	103.5	37.7	72.8	87.0
ANS-O-80-15-6	37.1	57.8	82.6	37.0	57.4	89.3
ANS-O-80-35-18	46.3	75.0	103.0	47.3	80.2	91.6
ANS-O-80-15-18	46.6	61.1	89.4	47.5	63.7	81.1
ANS-C-80-35-6	45.1	47.4	63.0	52.9	53.9	70.8
ANS-C-80-35-18	88.5	21.7	24.5	97.3	26.0	34.4
ANS-C-80-15-18	93.1	8.6	8.7	115.8	21.5	16.0
GRN-D-50-35-6	26.6	109.7	77.4	25.6	107.8	108.2
GRN-D-50-15-6	66.4	64.7	85.9	61.9	59.8	66.0
GRN-O-80-35-6	40.8	72.1	99.5	39.8	70.3	97.7
GRN-O-80-15-6	58.3	54.3	83.9	33.0	96.0	84.1
GRN-C-50-35-6	52.0	58.6	100.8	53.5	60.2	103.8
GRN-C-50-35-18	154.0	39.3	68.6	138.1	37.0	56.2
IFO-D-80-35-6	78.5	69.4	99.7	76.6	65.4	110.4
IFO-D-80-35-18	78.0	42.2	48.0	69.6	39.9	46.1
IFO-O-80-35-6	68.4	56.6	81.0	68.4	57.1	90.2
IFO-O-80-35-18	84.4	14.7	8.9	73.4	9.5	9.6
IFO-C-80-35-6	75.0	42.1	61.4	74.3	40.4	53.5
IFO-C-80-35-18	102.0	29.3	27.7	94.8	27.8	24.3
TR-C-80-35-18	63.5	45.4	60.9	62.8	46.2	65.4
GRN-C-80-35-18	63.4	48.5	3.8	62.7	47.6	66.9

Table F 2 Summary of LISST data and oil concentration in water grab samples for Task 4 tests from SL Ross

	Low energy			High energy			Prop wash		
	LISST d50	LISST conc	Water sample	LISST d50	LISST conc	Water sample	LISST d50	LISST conc	Water sample
Test ID	µm	ppm	ppm	µm	ppm	ppm	µm	ppm	ppm
ANS-C-0-35-L	70.4	16.2	16.0						
ANS-C-80-35-A				53.4	58.1	35.0	54.6	81.9	42.0
ANS-C-80-35-B				81.2	44.3	36.8	88.7	61.3	39.3
ANS-C-80-35-C				66.8	13.4	13.9	136.0	59.7	57.5

Figures F 1 through F 29, below, show the water concentration and 50th percentile droplet size for the tests conducted at SL Ross.

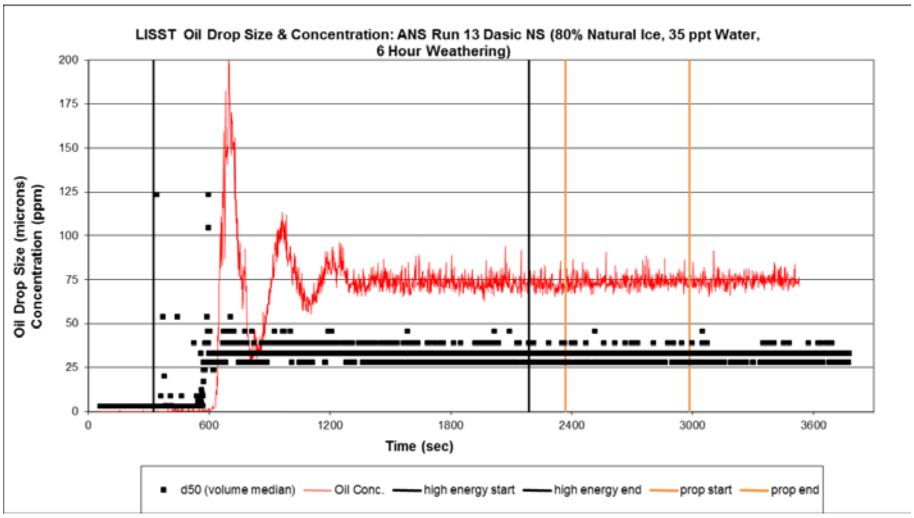


Figure F1 ANS-D-80-35-6

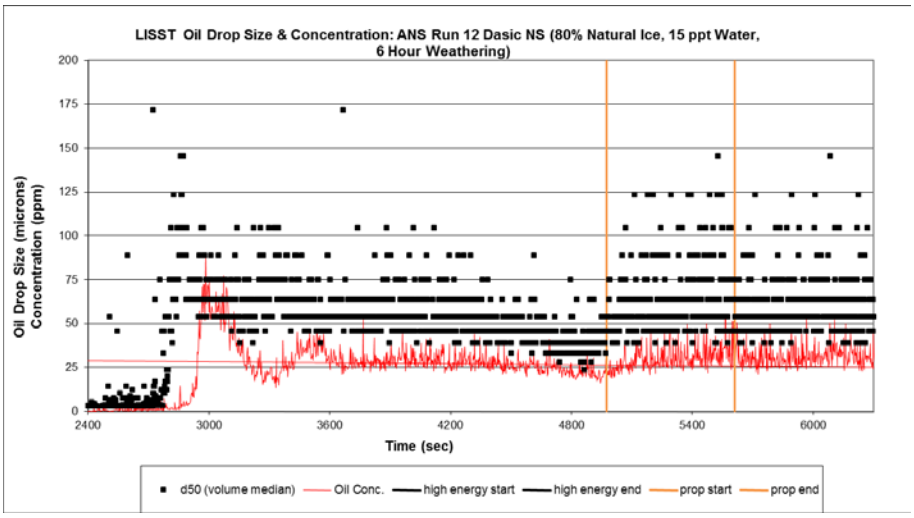


Figure F2 ANS-D-80-15-6

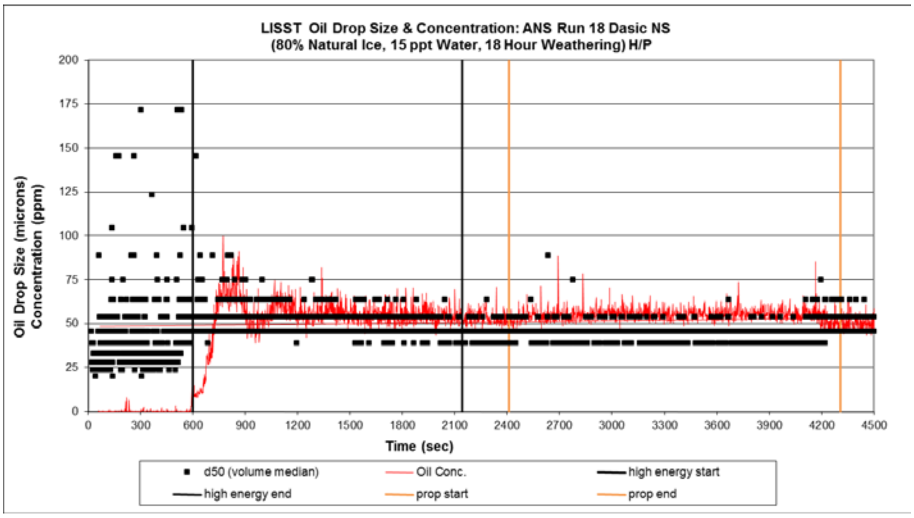


Figure F3 ANS-D-80-35-18

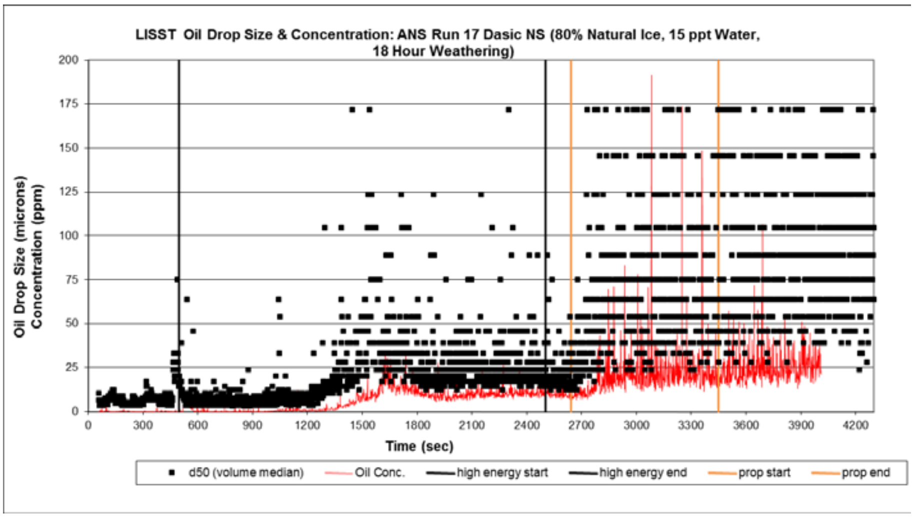


Figure F4 ANS-D-80-15-18

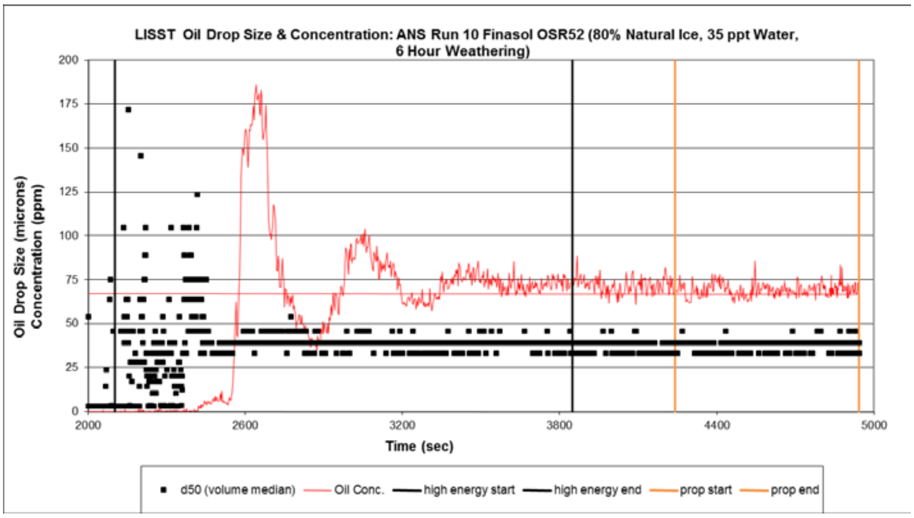


Figure F5 ANS-O-80-35-6

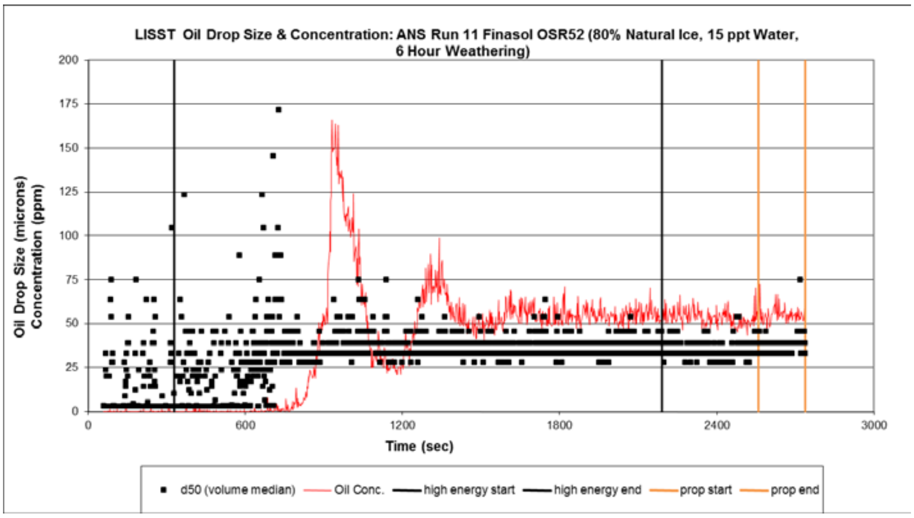


Figure F6 ANS-O-80-15-6

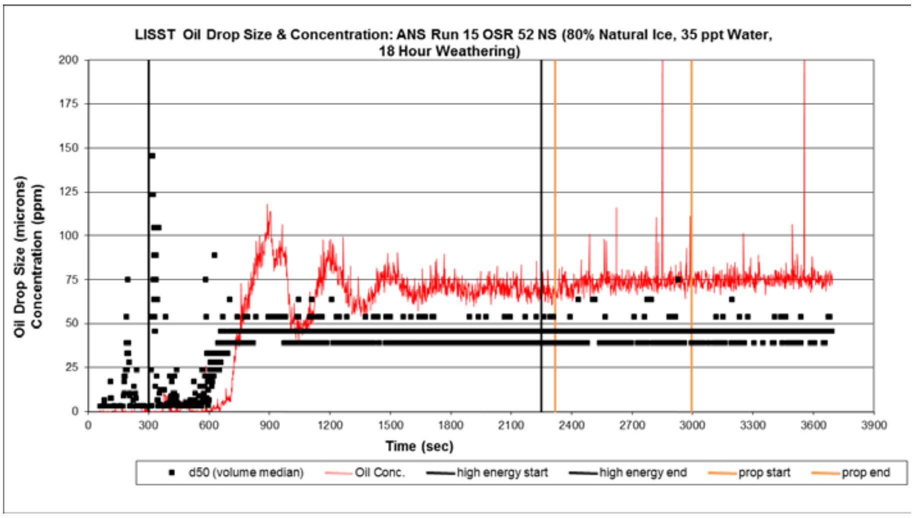


Figure F7 ANS-O-80-35-18

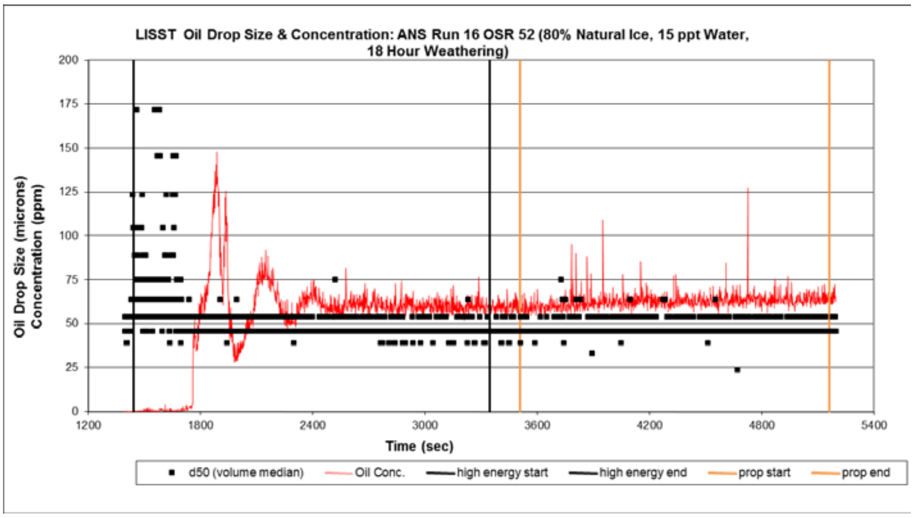


Figure F8 ANS-O-80-15-18

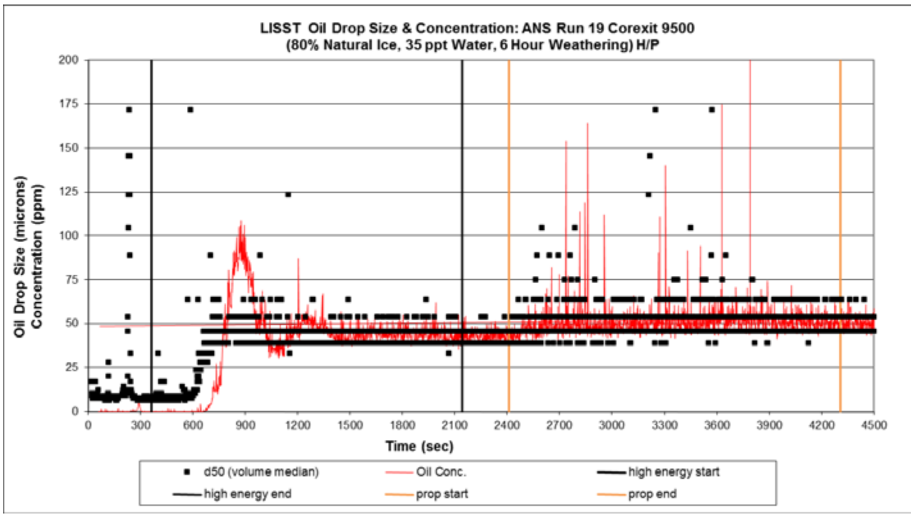


Figure F9 ANS-C-80-35-6

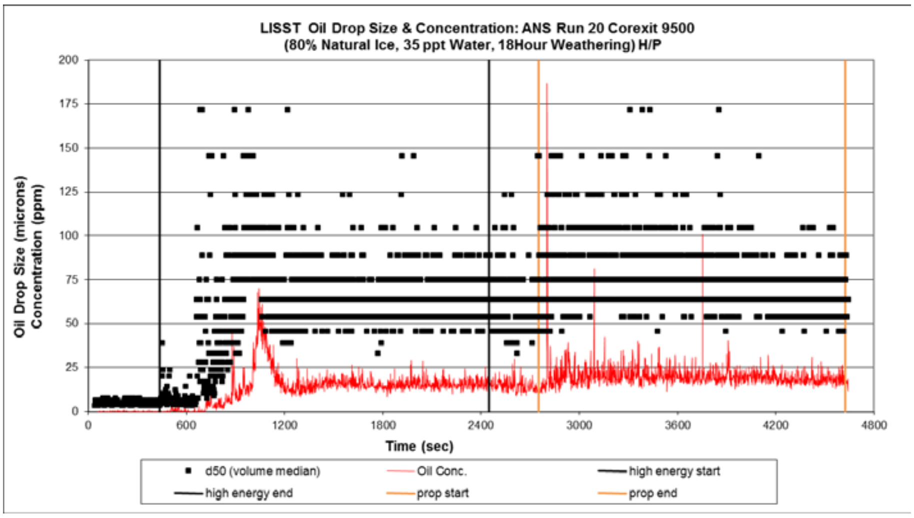


Figure F10 ANS-C-80-35-18

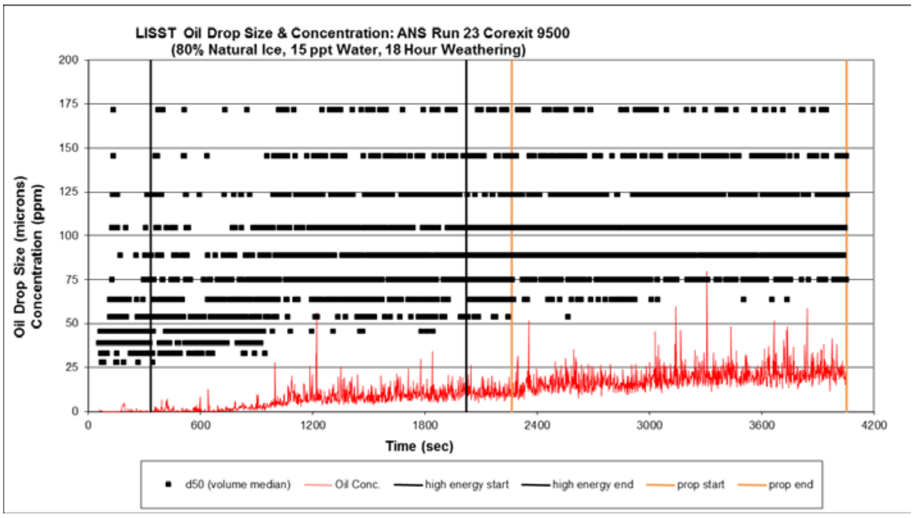


Figure F11 ANS-C-80-15-18

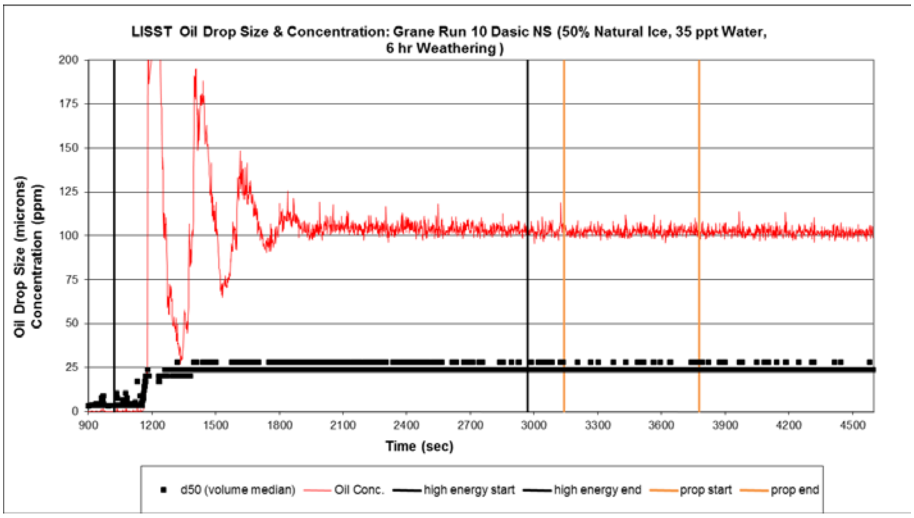


Figure F12 GRN-D-50-35-6

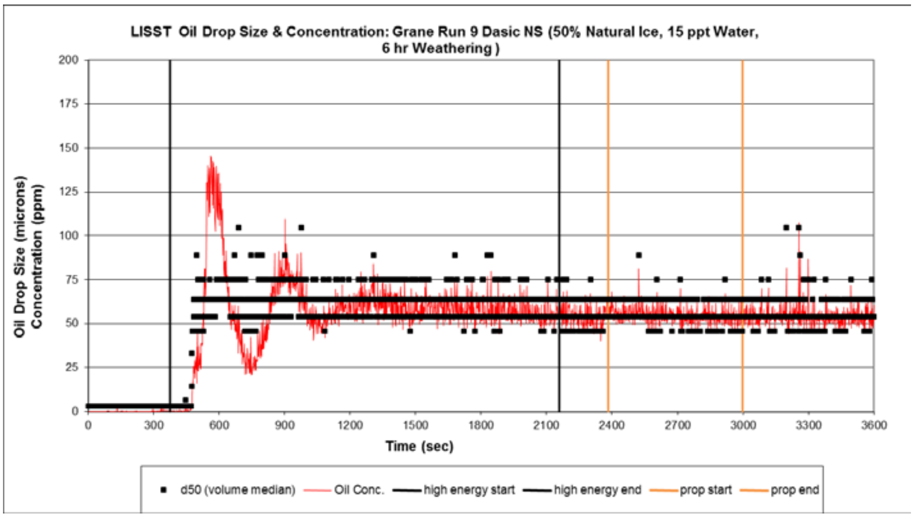


Figure F13 GRN-D-50-15-6

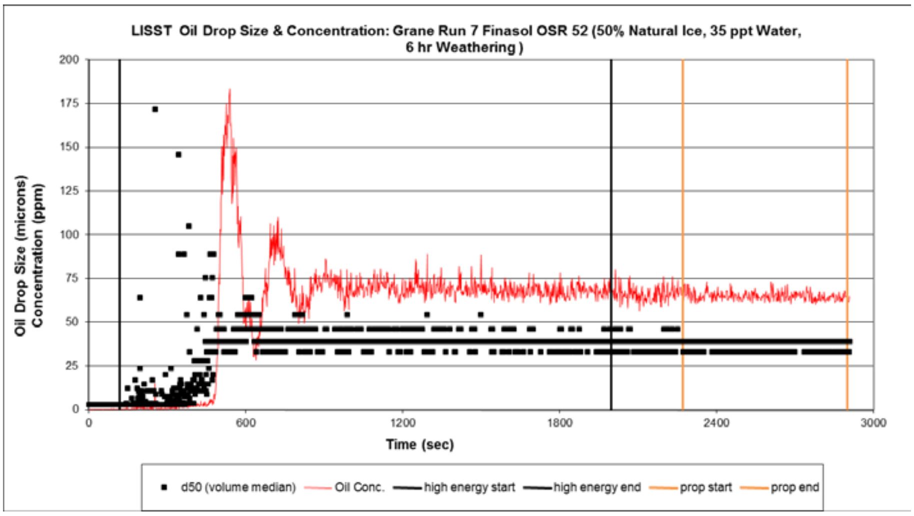


Figure F14 GRN-O-80-35-6

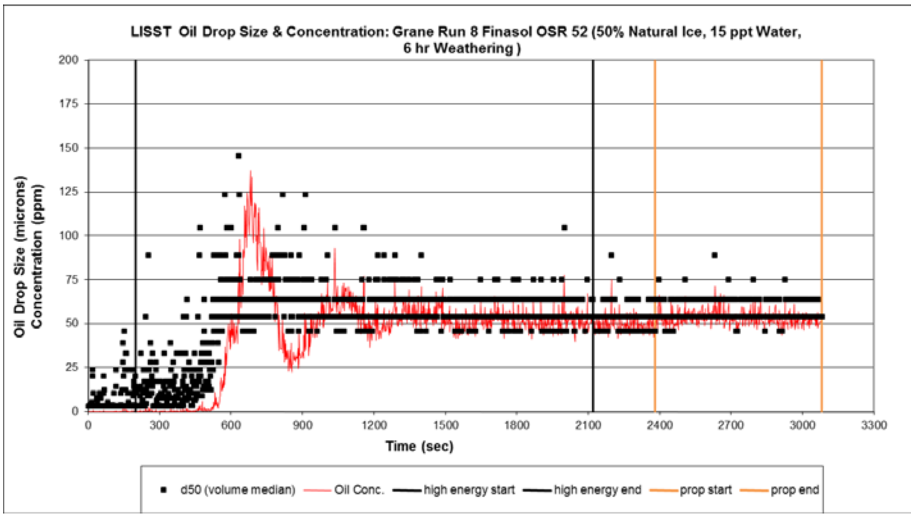


Figure F15 GRN-O-80-15-6

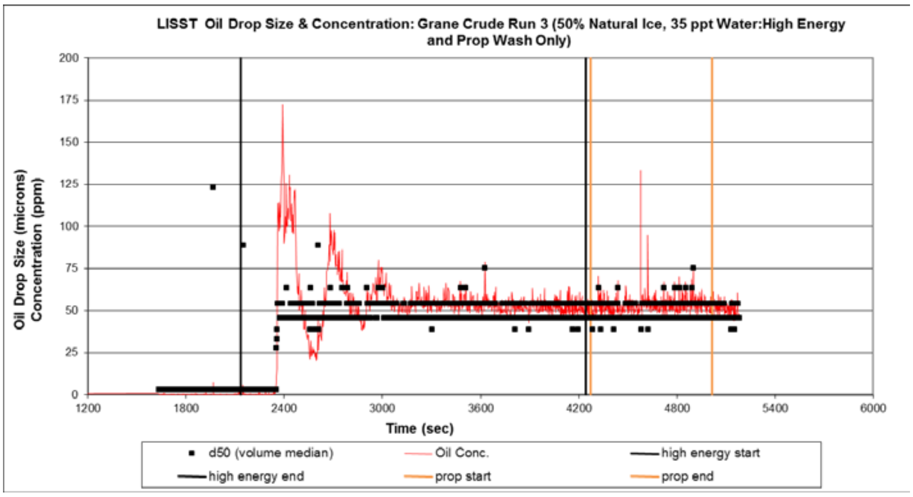


Figure F16 GRN-C-50-35-18

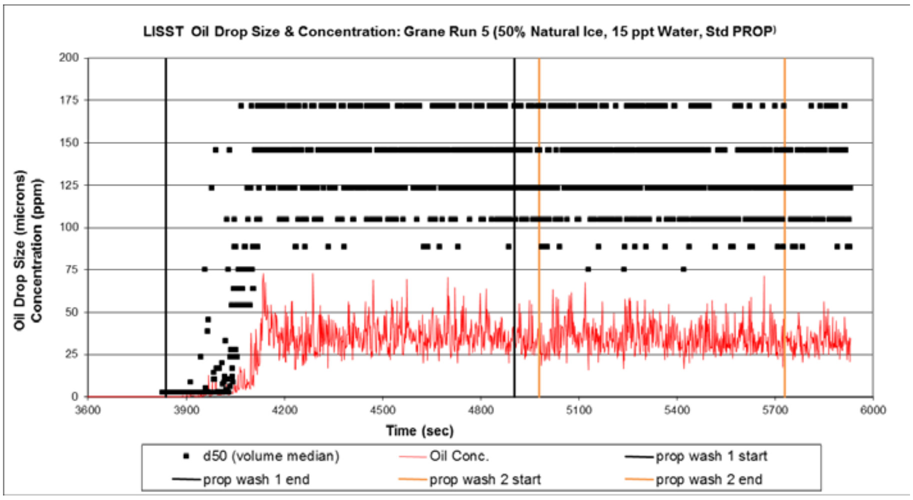


Figure F17 GRN-C-50-15-18

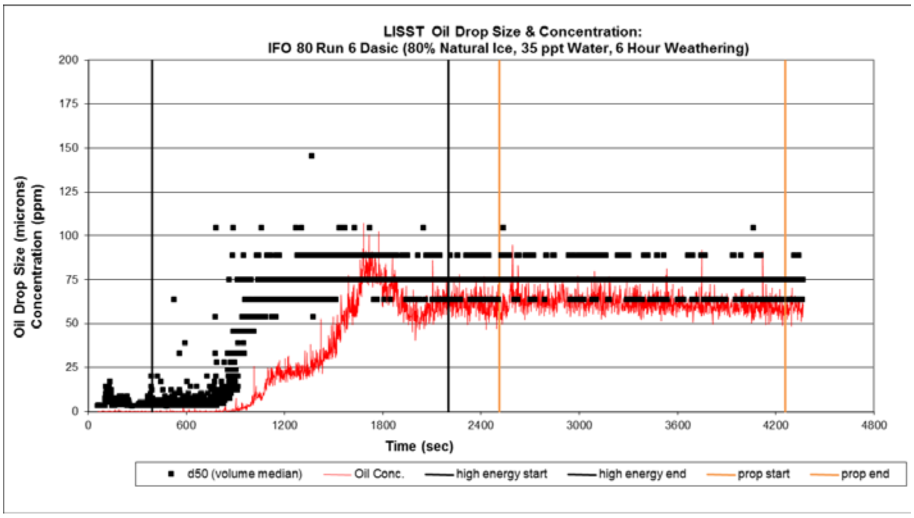


Figure F18 IFO-D-80-35-6

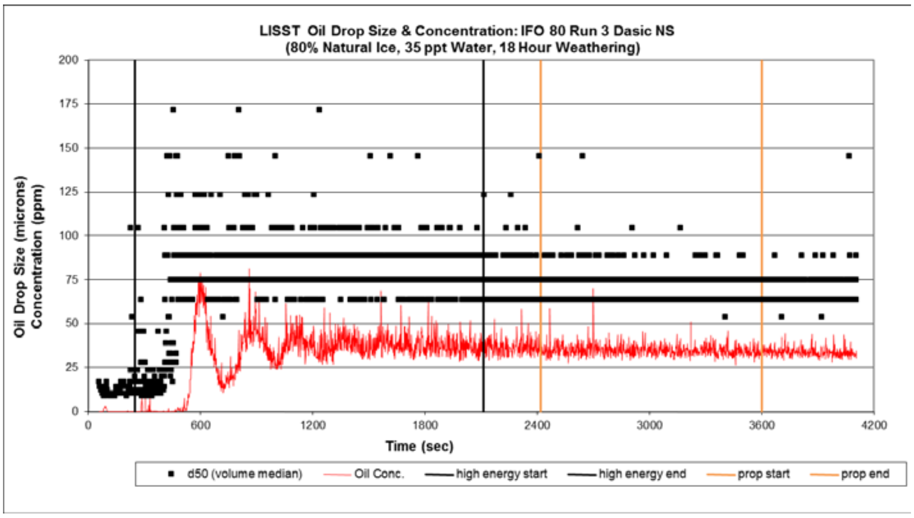


Figure F19 IFO-D-80-35-18

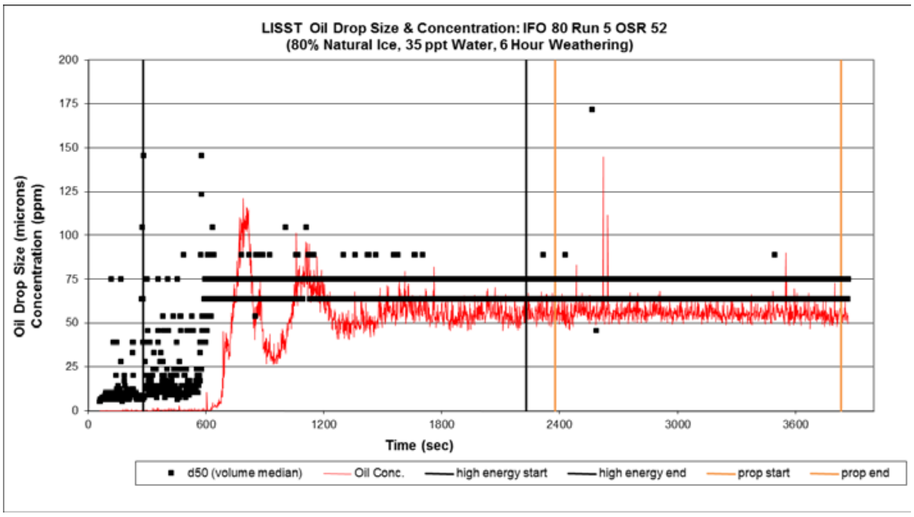


Figure F20 IFO-O-80-35-6

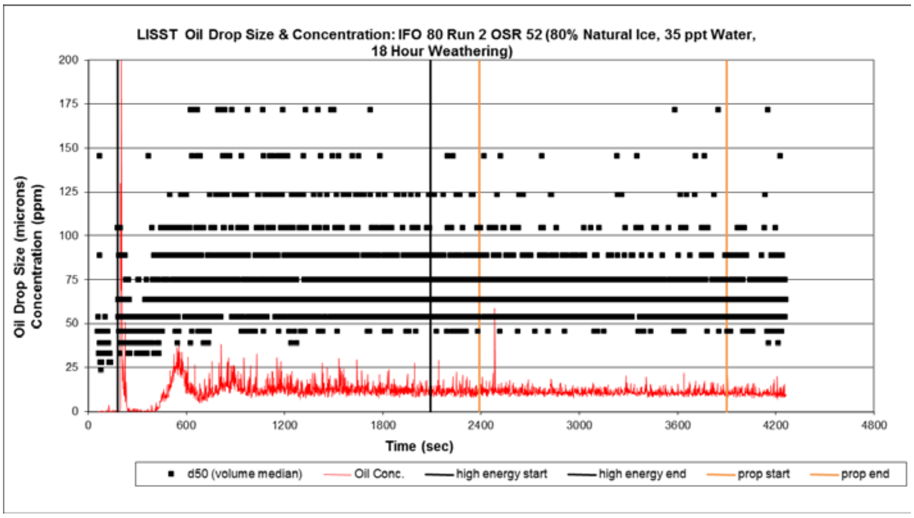
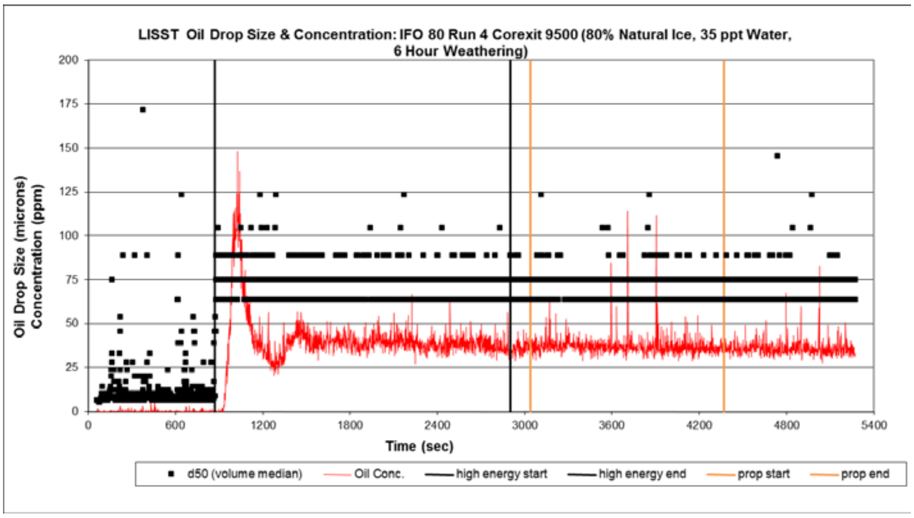


Figure F21 IFO-O-80-35-18



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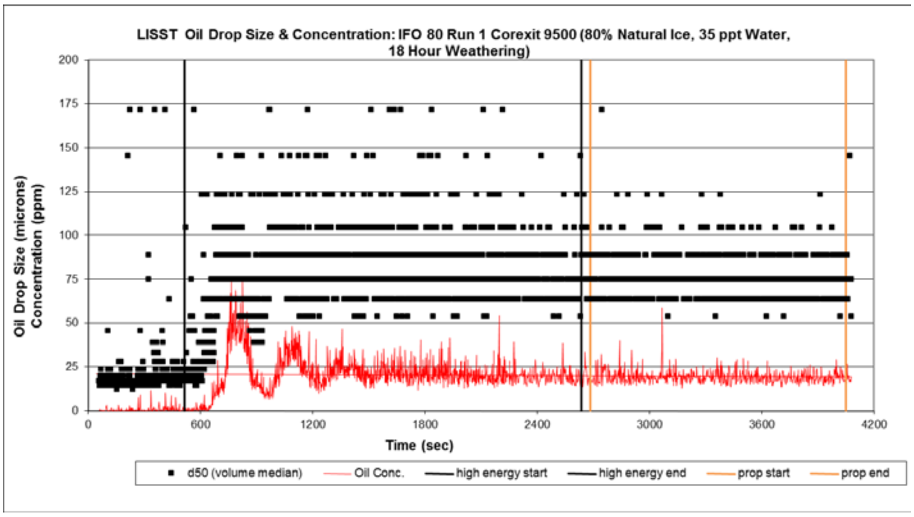

Figure F23 IFO-C-80-35-18

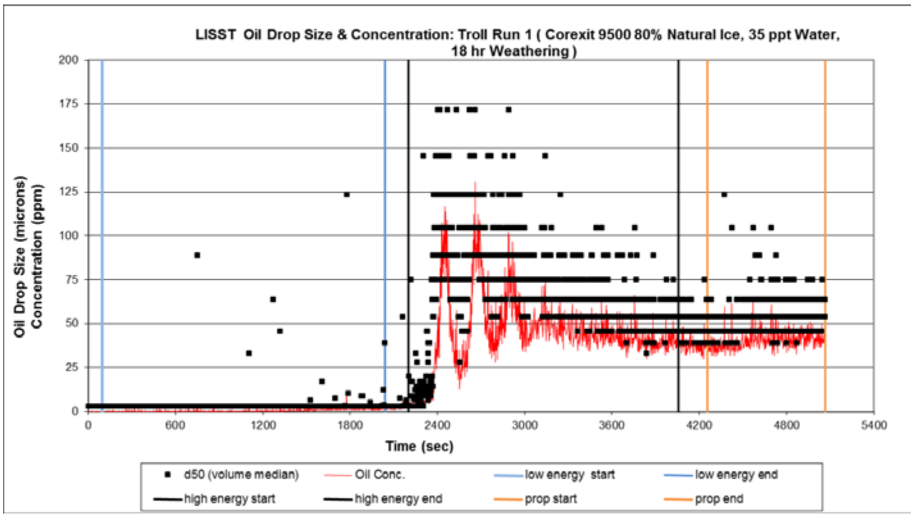

Figure F24 TR-C-80-35-18

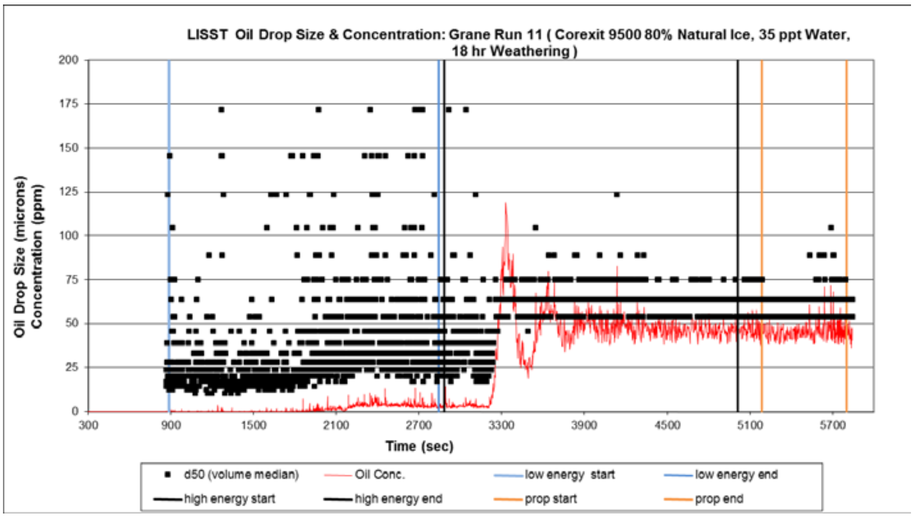

Figure F25 GRN-C-80-35-18

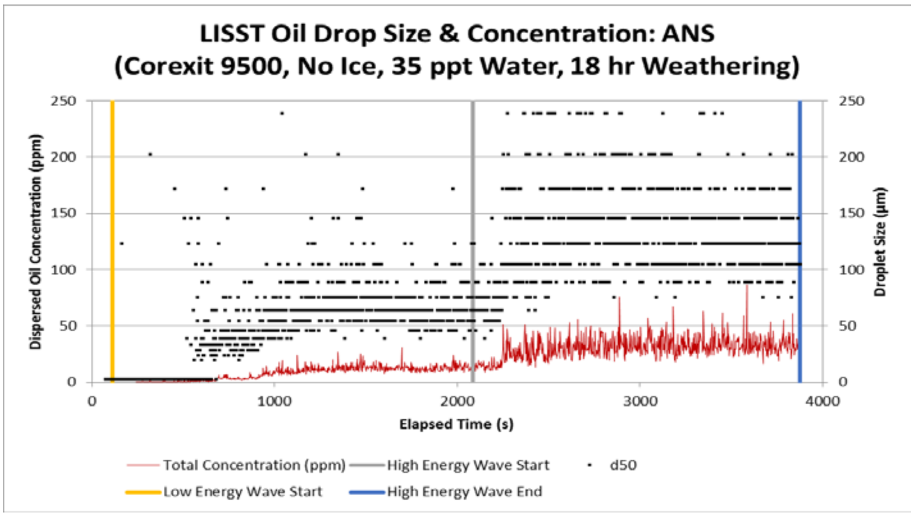

Figure F26 ANS-C-0-35-L

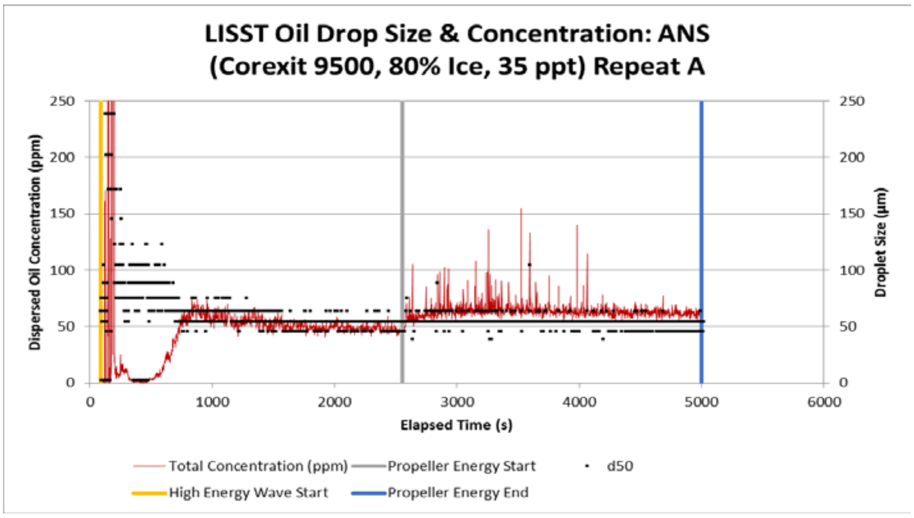

Figure F27 ANS-C-80-35-A

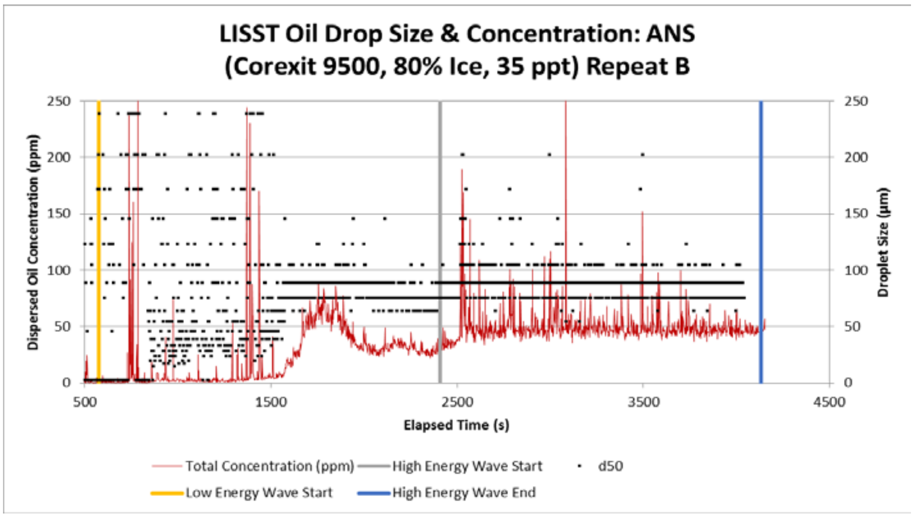

Figure F28 ANS-C-80-35-B

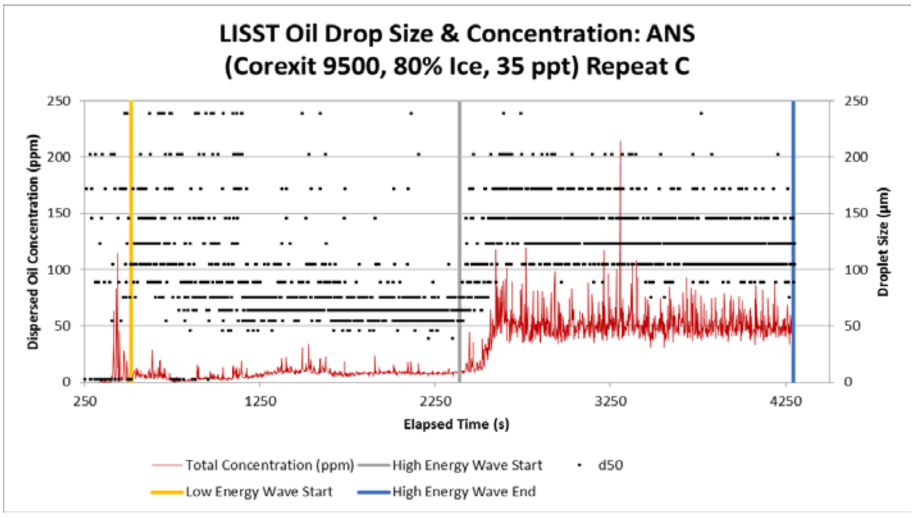

Figure F29 ANS-C-80-35-C