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Report

Full-scale field testing of thin oil films from releases of light crude oil at sea

NOFO Oil-on-Water field trial in 2016

Author(s)
Per S. Daling
Alun Lewis, Kristin R. Sørheim and Ingrid Gjesteland

SINTEF Ocean AS
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SINTEF

SINTEF Ocean AS

Address:
Postboks 4762 Sluppen
NO-7465 Trondheim
NORWAY
Switchboard: +47 464 15 000
Telefax: +47 93270701

ocean@sintef.no
www.sintef.no/ocean
Enterprise /VAT No:
NO 937 357 370 MVA

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ABSTRACT

During the 2016 NOFO Oil-on-Water (OOW) field trial at the Frigg field in June 2016, a series of 3 experimental releases with a light crude oil (Åsgard Blend) were conducted. This report summarizes the results of the fate and behaviour of the oil in these experiments and the potential of different methods of oil spill response for reducing the risk for environmental damage of oil films generated in calm sea conditions. The response methods included low dosage dispersant treatment and mechanical dispersion using the Fi-Fi monitors and high-capacity water flush bow boom.

PREPARED BY
Per S. Daling

SIGNATURE
Per S. Daling

CHECKED BY
Ivar Singsaas

SIGNATURE
Ivar Singsaas

APPROVED BY
Mimmi Throne-Holst

SIGNATURE
Mimmi Throne-Holst

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Abbreviations, Acronyms, and Symbols

~	approximately
C	Celsius
m^3	cubic meter
°	degree
>	greater than
h	hour (s)
<	less than
m	meter
µm	micrometre
mL	millilitre
m/s	meter per second
min	minute
mPa.s	millipascal second (= cP, centipoise)
nm	nautical mile
ppm	parts per million
%	percent
s^{-1}	reciprocal second
vmd	volume median diameter
vol.%	volume percent
w/o	water-in-oil
wt.%	weight percent
AIS	Automatic Identification System
ATD	Thermal Desorption Tube
BTEX	Benzene, Toluene, Ethylbenzene and Xylene
BAOAC	Bonn Agreement Oil Appearance Code/Correlation
Black Body IR radiation	Thermal (temperature) radiation emitted by body (here: the oil slick)
COSMO-SkyMed	Constellation of small Satellites for the Mediterranean basin Observation / SAR satellite
CTC	Continuous oil true colour
DCTC	Discontinuous oil true colour
DOR	Dispersant-to-oil Ratio
EO/IR	Electro-Optical/Infrared
Fi-Fi	Fire Fighting
FLIR	Forward Looking Infra-Red
GC-FID	Gas Chromatography-Flame Ionization Detector
HDIR	High-definition Infrared
HDTV	High-definition television
HDZ	High-definition low light television
HISB	Herder In-Situ Burning
HSE	Health, Safety and Environment
IR	Infrared
JSA	Jon Safety Analysis
LEL	Lower Explosive Limit
KSAT	Kongsberg Satellite Services

LD	Low dosage
LISST	Measurements of particle size distribution and concentration
LT	Local Time
MOB	Man Overboard Boat
NCA	Norwegian Coastal Administration
NEA	Norwegian Environmental Agency
NE	Northeast
NNE	North-Northeast
NOFO	Norsk Oljevernforening for Operatørselskap / Eng. Norwegian Clean Seas Association for Operating Companies
NW	Northwest
OSC	On Scene Coordinator
OOW	Oil-on-Water
OWM	Oil Weathering Model
PID	Photoionization Detector
PS	Portside
SB	Starboard
SAR	Synthetic Aperture Radar
SLAR	Side Looking Airborne Radar
SJA	Safety Job Analysis
SW	Southwest
SSW	South-Southwest
RISAT-1, Radarsat-2	Radar Imaging Satellite / SAR satellites
RPAS	Remotely piloted aircraft systems
TBP	True Boiling Point
TOF	Thin Oil Film
TSS	Tromsø Satellite Station
TVOC	Total Volatile Organic Compounds
VHF	Very high frequency
VOC	Volatile Organic Compounds
USV	Unmanned Surface Vehicles
UV	Ultra Violet
UVF	Ultra Violet Fluorescence

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The authors want to thank NOFO for organizing and contributing financially to the Oil-on-Water (OOW) trial in June 2016, the Norwegian Coastal Administration (NCA) for contribution with vessels, and the participating remote sensing aircraft in Norway, Finland and the Netherlands. Jason Engineering AS for response concepts and Maritime Robotics for drone operations. In addition to SINTEF scientists and laboratory personnel. The Research Council of Norway (RCN) and seven oil companies are funding the TOF-project, as referred in executive summary and chapter 1, below.

Executive summary

Background and objectives

The Petromaks 2 Research Program *"Formation and behaviour of thin oil films and evaluation of response methods including HSE"* (hereafter called TOF-project) is a 3–year R&D project (2014-2017) funded by the Research Council of Norway and the oil industry (Aker BP, Centrica, Eni Norge, ENGIE E&P Norge AS, Shell Technology Norway, Statoil, and Total E&P Norge). The TOF-project aims to acquire new knowledge to provide more efficient and safe oil spill response to releases of condensates and light crude oils that may lead to large area of thin oil films on the sea surface, particularly in calm sea conditions.

As an integrated part of the NOFO Oil-on-Water (OOW) field trial at the Frigg field in June 2016, a series of 3 experimental releases (3 x 10 m^3 and designated TOF 3.1, 3.2 and 3.3) using the very light Åsgard Blend crude oil (a blend of light crude oils and condensates) were conducted:

- TOF 3.1: Reference slick without any response treatment (day 1, non-breaking wave conditions).
- TOF 3.2: Release and slick treatment with low dosage dispersant followed by high-capacity bow boom water flushing (day 1, non-breaking wave conditions).
- TOF 3.3: Release and treatment with water flushing from Fi-Fi monitors 3 to 4 hours after release (day 2, breaking wave conditions).

The main objectives for the full-scale field testing of the TOF project were:

- To verify the findings from laboratory testing with supplementary documentation from field observation of the properties, fate and behaviour of oil films generated by spills of light crude oils and condensates. If weather conditions were suitable, it would be possible to study the formation of bands /windrows of thick oil, which can be an important factor of the behaviour and persistence at sea of spilled condensates or light crude oils.
- To test and document the operative efficacy and capabilities of response options based on recommendations and findings from concept testing in the laboratory. Laboratory and field testing of response concepts was also conducted as a part of the "Oljevern 2015 program *"Mechanical Dispersion of Thin oil films"* funded by NOFO.
- To characterize personal exposure to airborne hydrocarbons by stationary and personal (biological) monitoring of volatile oil components (VOCs) under relevant oil spill response conditions.

Selection of test oil used for the field experiments

During the 3–year TOF-project, eight different light crude oils and condensates, all in production on the Norwegian Continental Shelf, were studied; Alve, Atla, Marulk, Ormen Lange and Skarv (all condensates), Gjøa and Vale (light crude oils) and Statfjord crude oil (as a reference oil). These oils were characterized and tested in laboratory experiments during the TOF-project. The residues generated after weathering in the laboratory under simulated calm sea conditions exhibited a wide span of physicochemical properties.

It was decided that only one test oil could be used for the field experiments. Åsgard Blend was selected on the basis of logistically accessibility and as being reasonably representative for some of the oils tested in the TOF-project. The relatively high content of volatiles in Åsgard Blend is typical of many Norwegian condensates and light crude oils and this made it suitable for studying the potential for exposure to VOCs for personnel involved in oil spill response.

The properties of the Åsgard Blend residues remaining after different degrees of evaporation are similar to those of Skarv, Alve, and Vale. These oils have the potential to produce residues that are semi-solid after 1 to 2 days at sea under calm conditions. Such semi-solid residues will not be naturally dispersed by wave action as small oil droplets into the water column. Semi-solid residues on the sea surface will be broken up into lumps or flakes, with sizes depending on sea conditions and residue rheological properties. This behaviour will pose challenges for detection, monitoring and for effective oil spill response (including use of dispersants).

The more volatile and lower wax content condensates, Atla, Ormen Lange and Marulk, produce residues with much lower pour points and no measurable yield stress at typical sea temperatures. The weathered residues will be low viscosity liquids that will be naturally dispersed as small oil droplets in the water column and these will be rapidly biodegraded. Gjøa light crude oil formed "loose"/semi-stable emulsions during simulated weathering on the sea surface. Due to its low pour-point and no yield stress Gjøa will have a longer operative "time-window" for use of dispersants compared to many of the other light oils and condensates tested.

General observations of the slick behaviour, air measurements and risk for human exposure

A lot of good data was acquired from various monitoring platforms during the two-day field trial. Comprehensive planning and good prevailing weather conditions permitted three of the four planned TOF experiments to be performed. Good documentation on the spreading, fate and behaviour of the spilled oil in both non-breaking (< 5 m/s wind speed) and in breaking wave conditions (> 5 m/s wind speed) was obtained.

Measurements of the total VOC (TVOC) concentrations in the air above the slicks were made at sea, and the volatile compounds were also detected by IR sensors on the aircraft and the Aerostat. It is believed that this is the first time that this has been achieved at a field trial.

Compared to the heavier Grane crude oil released for herder / in-situ burning experiments, the Åsgard Blend slicks produced five times higher concentrations of TVOC in the air, as measured in the sampling boats when they were operating close and downwind from the slick shortly after release. However, the TVOC concentrations rapidly declined within 30 min after the release of oil, and to zero after 1 hour. The personal exposure to VOCs, particularly benzene, close to and downwind of the slick, was therefore relatively high, but only for a short period. Based on these findings, it is recommended that response personnel responding to releases of light crude oils / condensates should not initiate response action during the first 1 hour after release. For continuous releases, this indicates that the response should allow for a drifting time of > 1 hour, i.e. typically 0.5 - 1 km downwind to the release source.

The experimental slicks of Åsgard Blend were released onto the sea surface in a way that produced the intended thin oil layer with an average thickness of approximately 0.2 mm to 0.5 mm. The initial spreading behaviour of the oil was in accordance with the modelled spreading behaviour. A small area of sheen spread out from the periphery of the released oil, but this had minimal effect on the overall average oil layer thickness. The average oil layer thickness then decreased by approximately 25% in 30 minutes to 1 hour as the more volatile components evaporated into the air. The oil remaining on the sea surface became re-distributed as areas of relatively thin oil (approximately 0.1 mm thick or less) and smaller areas of relatively thick oil (approximately 1 mm thick). After about one hour on the sea surface, the reference slick (TOF 3.1) had ceased spreading and formed a narrow band of thick oil residue (1-2 mm thick) containing > 80% of the oil volume within < 20 % of the IR detectable slick area. The shape of the narrow band of thick oil was distorted by the prevailing wind and currents, but the same area was maintained for many hours on the sea. The relatively thin oil (IR black detectable) spread and appeared to produce an increasing area of visual and UV detectable sheen. This sheen (< 1 µm,) is considered not to cause any harmful environmental effect e.g. on seabirds (French et al., 1997).

Low-dosage dispersant application and high-capacity water boom flushing
Low-dosage dispersant spraying followed by high-capacity water flushing 0.5 to 1 h after the dispersant treatment was an effective operative strategy for dispersing the TOF 3.2 slick. The aerial IR images and water-column measurements taken just after the dispersant spraying indicated that the majority of the area of thick oil had been broken up and rapidly dispersed as small droplets (70-100 µm VMD (Volume Median Diameter)) into the water column. This indicates that even very low dispersant–to-oil ratios (DOR 1:300 to 1:400 for the thickest oil) were sufficient to disperse this light crude oil. Only a thin oil film remained after the dispersant treatment. Effective dispersion was achieved by combining the low-dosage dispersant treatment followed by the artificial turbulence introduced using the bow boom water flushing from MS Strilborg moving at a speed of 8 – 12 knots through the slick. This strategy has a high encounter rate and significantly reduced the persistence of the light crude oils /condensates on the sea surface in calm conditions.

The high-capacity water flushing bow-boom system was not tested as a stand-alone / independent response technology. However, experiments from laboratory basin testing (during the Oljevern 2015 project) with similar nozzles and test conditions as in the field, indicates that this system has the potential to be an effective response for dispersing weathered oil residues with viscosities of < 150 to 250 mPa.s without using dispersants.

Fi-Fi monitors water-flushing
Although not tested under optimal conditions, the Fi-Fi monitor water-flushing response was effective. The test oil had weathered on the sea for 3 to 4 hours under breaking wave conditions before treatment. The oil had started to form a "loose" (semi-stable) emulsion with a viscosity of about 330 mPa.s and this was considered to be a higher viscosity than is optimal for effective water-flushing. Nevertheless, the testing clearly demonstrated the potential for reducing the persistence on the sea surface of spilled light crude oils /condensate. The narrow bands of relatively thick "loose" emulsion were broken up by the impact of water from the Fi-Fi into small pieces, or granules. Additionally, light-brown plumes of dispersed oil were observed in the water. The concentration of dispersed oil in the water column measured in transects 10-15 min. after the water flushing was measured to 10-30 ppm with oil droplet diameters of 100-120 microns.

The testing demonstrated that the operational time-window for water-flushing is limited. If the water-flushing had been carried out earlier at 1 to 1.5 h after the release, the oil /emulsion viscosity would, according to weathering prediction, have been lower and approximately 150 to 200 mPa.s. The lower viscosity would have been more optimal for the water-flushing and would have produced, according to modelling estimates, smaller oil droplet diameters in the range of 70-100 microns.

Further documentation / recommendations
Extensive experimental data were gained through this field trial using the Åsgard Blend light crude / condensate. However, the planned test program was not entirely accomplished for various reasons. There is still the potential for extending the documentation of the fate and behaviour of different condensates, light crude oils or light refined products. Further documentation could be obtained by:

- Laboratory experiments
  - Extend the test matrix for water-flushing with the test method designed during the "Oljevern 2015".Testing a larger range of oils and weathering degrees with a wider variation in viscosity would establish more robust and fundamental documentation as a basis for estimating the precise time-window for water-flushing.
- Field testing
  - Field testing (in 2017): Use existing offshore oil production sites where, during periods with calm weather, areas of thin oil on the sea surface are formed due to produced water discharge. These areas could be used to systematically test the operative aspects of Fi-Fi and

the high-capacity water flow boom use. Such tests would need to be planned and accomplished in close cooperation with remote sensing aircraft.

- Field testing (in 2018): The promising demonstration of these response concepts during the 2016 NOFO OOW field trial should be extended at the future NOFO OOW trials planned for 2018. It is recommended that similar experiments be conducted, but using less persistent condensates or a surrogate such as a marine gas oil.

1 Background

The Petromaks 2 Research project *"Formation and behaviour of thin oil films and evaluation of response methods including HSE"* (hereafter called the TOF-project) is a 3-year R&D project (2014-2017) funded by the Research Council of Norway (RCN), and by the oil industry (Aker BP, Centrica, ENGIE E&P Norge, Eni Norge, Shell Technology Norway, Statoil, and Total E&P Norge). The companies are all producers of condensates and / or light crude oils that have been included as test oils in laboratory studies from this project, and summarized in Ramstad et al., 2016. As a part the oil producers release approval for operating the oil fields, the Norwegian Authorities are expecting documented routines for evaluating, planning and if needed, strategies for responding to acute releases of condensates and other petroleum products that may form thin oil films on the sea surface. It is therefore important to have a good understanding and documentation of the properties, fate and behaviour of such oils when spilled at sea producing thin oil films under calm sea conditions and the potential of response methods modified or customized to deal with such spilled oils. In this context, we have defined thin oil films as spill scenarios leading to initial releases of oil slicks in thicknesses range of > 5- < 200-300 micron i.e. film thicknesses that may have potential for environmental effects on e.g. sea birds (e.g. French et al., 1997). This thickness range corresponds to codes 3 and 4 of the Bonn Agreement Oil Appearance Correlation (BAOAC, Lewis, 2007).

The TOF-project aims to acquire new knowledge to provide more efficient and safe oil spill response to releases of condensates and light crude oils that may lead to thin oil films on the sea surface. In order to fulfil this objective, the following goals were identified:

- Obtain an increased understanding through laboratory studies and supplementary documentation from full-scale field trial of the formation and behaviour of thin oil films, the potential for water-in-oil (w/o) emulsion formation and possible solidification of condensates and light crude oils with different physicochemical properties. This includes the assessment of novel oil spill response concepts and countermeasure strategies in treatment of oil films generated under calm sea conditions.
- Assess the potential human exposure to volatile compounds during oil spill response operations in order to characterize the risk as a function of oil composition, weathering time and sea temperature (temperate versus Arctic conditions).
- Refine algorithms in oil trajectory models in order to give more reliable predictions of the lifetime and behaviour of thin oil films and formation of "bands/windrows" consisting of semi-solidified (wax-enriched) oil residues and to assess the efficacy of response options for various spill scenarios.

SINTEF has participated in many full-scale field trials over the past 30 years, both in experimental design and monitoring of the oil in the marine environment. These experiments have covered a wide range of objectives, including validation of efficacy of response techniques and to study the fate and weathering of different oils released under different conditions (surface and subsurface releases) with different environmental conditions such as open sea, in ice, and onshore. The full-scale testing from the TOF-project was a part of the NOFO Oil-on-Water (OOW) field trial conducted at the Frigg field in June 14-16, 2016. This report summarizes the results of a series of three experimental releases with the light crude oil/condensate Åsgard Blend to study the fate and behaviour of the oil film and to test and document the potential of different response methods for reducing the risk for environmental damage of oil films generated in calm sea conditions.

The original plan was to perform two series of field experiments in 2015 and 2016 with dedicated releases of 2 different oils selected from the laboratory studies (TOF-project). However, it was not logistically possible to include TOF experiments in conjunction with the NOFO OOW field trial in 2015. The release application in 2016 from NOFO to the Norwegian Environmental Agency (NEA) in 2016 included releases of one single oil. The Åsgard Blend light crude oil/condensate (hereafter called Åsgard Blend) was chosen as the most suitable and available oil at time for the field trial.

2 Objectives for the field experiments

The main objectives for the full-scale field testing of the TOF project (refers to experiment 3 of the NOFO 2016 OOW field trials) were:

- To verify the findings from laboratory testing with supplementary documentation from field observation of the properties, fate and behaviour of oil films generated from light crude oils and condensates. If weather conditions were suitable, it might also be possible to study the formation of "bands /windrows" which can be an important parameter related to the behaviour and lifetime at sea of spilled condensates or light crude oils.
- To test and document the operative efficacy and capabilities of response options based on recommendations and findings from the concept testing in the laboratory.
- To characterize personal exposure to airborne hydrocarbons with focus on benzene by stationary and personal (biological) monitoring of volatile oil components (VOCs) under relevant oil spill response conditions. To test the effect of personal protection equipment (PPE) including gloves and mask. This is covered by the PhD-work as a part of the TOF-project, and is described in a separate papers (in progress) and is therefore only briefly described in this report.

3 Release permit, test-site area and documentations

On February 11th 2016, NOFO sent an application to Norwegian Environmental Agency (NEA) for permission for scientific releases of oil to be included in the NOFO OOW field trials scheduled for in week 24/25, 2016. The application included the following four categories of experiments:

"Traditional" testing of mechanical equipment (total: 150 m^3 weathered crude oil emulsion):

1. Integrated pump-system for NOFI Current Buster 6
2. DESMI "Perforated boom"

TOF and HISB experiments:

3. Thin Oil Films (TOF) - 4 releases (total 40 m^3, Åsgard Blend light crude oil)
4. Herder and in situ burning (HISB) - 3 releases (total 18 m^3, Grane Blend crude and total 17 L of Herder- ThickSlick 6535)

SINTEF contributed to the application with a detailed description of the justification, goals, experimental plans, monitoring, in addition to criteria limitations for the TOF experiments. After a hearing period, NOFO received the approval from the NEA 19th of April 2016. No specific requirements or comments were made on the planned releases with Åsgard Blend.

The release site area for the experiments specified in the application to the Norwegian Environmental Agency (NEA) to was an area of 20 x 20 nautical mile (nm) at the Frigg field. Position: N59º 59' E002º27', see also the red square in the map in Figure 3-1.

Figure 3-1 Map showing release site area (red square) for the NOFO OOW 2016.

Prior the field trial, the following documentations were worked out:

- Operational Order (NOFO, 2016) including
  - HSE-plan
  - Risk assessment
- Field plan for the TOF releases included detailed time schedule (Daling and Sørheim, 2016). See also chapter 6.1.

4 Laboratory characterization of Åsgard Blend

Content of Åsgard Blend (blend of light crude oils and condensates)
Åsgard Blend consists of a blend of paraffinic light crude (LC) oils and paraffinic condensates (Con) from Haltenbanken in the Norwegian Sea. Production from fields: Åsgard A (LC), Åsgard B (Con) & Kristin (Con/LC), Smørbukk (Con/LC), Mikkel (Con), Morvin (LC) and Tyrihans (LC) is comingled. The relative contribution from the fields can vary slightly depending on the daily production from the individual fields. However, available data from laboratory analysis indicates only small variations in relevant physicochemical properties of Åsgard Blend during the last two years (Statoil Mongstad laboratory; Haustveit, personal comments). According to available information, the Åsgard Blend that came into to Mongstad 4th of June 2016 consisted of about 30 % Åsgard A from storage tank (50% Åsgard A and 50 % Åsgard B, Morvin, Mikkel) and about 70 % Åsgard C from storage vessel (50% Kristin, Tyrihans and 50 % Åsgard B). This indicates that the majority of the Åsgard Blend was coming from condensate fields. 40 m^3 of this blend was dedicated as test oil in the full-scale field testing.

Evaporation, viscosity, yield stress and pour point
In December 2016, SINTEF received 40 L of a representative sample of Åsgard Blend from Statoil Mongstad for a limited laboratory study to characterize weathering properties according to the standard SINTEF weathering methodology (Daling et al., 1999). The characterization of Åsgard Blend indicated that the oil was a mixture of paraffinic condensates and light crude oils compared with the condensates and light crude oils characterized during laboratory studies from this TOF-project (Ramstad et al., 2016). The standard SINTEF weathering methodology consists of preparing a series of oil residues by distillation to simulate evaporative loss from oil on the sea and preparation of a series of w/o-emulsions from these residues. The different levels of evaporative loss, as defined by the distillation temperatures, approximately equate to time of the oil on the sea surface required to achieve this evaporative loss (
Table *4-1*). This is based on previous field experiences with crude oil spills. However, based on the experiences from this field experiments, this "rule of thumb" seem to be valid for the rate of evaporative loss for Åsgard Blend.

Table 4-1 Distillation temperature of residues prepared in laboratory vs. representative weathering time at the sea surface.

Residue	**Approximate representative time on the sea surface**
Fresh	None
150°C+	0.5 - 1 hour
200°C+	0.5 - 1 day
250°C+	2 - 5 days

Table 4-2 summarizes the main physicochemical properties of Åsgard Blend as input to the SINTEF Oil Weathering Model (OWM) for prediction of the oil weathering properties at sea. The predictions were conducted both prior and after the field trial with sea temperatures of 10 and 13°C and with terminal film thicknesses of 0.2 and 1 mm for comparison (see Appendix A).

Table 4-2 Physicochemical properties of Åsgard Blend used as input to the SINTEF OWM

Oil type	Residue	Evap. (vol. %)	Residue (wt. %)	Density (g/mL)	Flash point (°C)	Pour-point (°C)	Wax (wt.%)	Visc. (mPa.s) 13°C ($10s^{-1}$)	Yield stress (Pa)
Åsgard Blend	Fresh	0	100	0.780	-	-36	3.9*	1	0.2
	150°C+	50	55	0.845	35	6	7.1	16	0.3
	200°C+	63	41	0.866	75	15	9.5	132	-
	250°C+	72	32	0.883	122	24	12	707	3

** Crude Assay of Åsgard Blend -. No applicable measurement*

The viscosity of a fluid is a measure of its resistance to gradual deformation by shear stress. A fluid that behaves according to Newton's law, with a viscosity that is independent of the stress, is said to be *Newtonian*. The oil residues produced by weathering exhibit *non-Newtonian* flow behaviour, with the measured viscosity decreasing with increased shear rate, because of the wax that has precipitate within the oil. Table 4-3 shows the decreasing viscosities of the 200°C+ and 250°C+ residues of Åsgard Blend with increasing shear rates of 10, 100 and 1000 s^{-1}. Further, the 200°C+ and 250°C+ residues are increasingly semi-solid at typical sea temperatures and is evident from their pour point. Pour point is the temperature at which the oil just flows under very low shear conditions in a standard laboratory test method. The pour point increases from +6°C for the 150°C+ residue to +24°C for the 250°C+ residue. The weathered residues possess increasingly high yield stress. The yield stress is the applied stress that must be exceeded for the oil residue to flow. Oil residues on the sea at temperatures significantly below their pour point will behave as solids at the low shear rate exerted by non-breaking wave action and will not flow and spread.

Table 4-3 Viscosity of fresh oil and residues of Åsgard Blend with different shear rates (s^{-1}).

Oil type	Residue	Visc. (mPa.s) 13°C ($10s^{-1}$)	Visc. (mPa.s) 13°C ($100s^{-1}$)	Visc. (mPa.s) 13°C ($1000s^{-1}$)
Åsgard Blend	Fresh	1	1	2
	150°C+	16	13	11
	200°C+	137	59	34
	250°C+	707	228	104

Åsgard Blend in comparison with the TOF-project oils from laboratory studies

Figure 4-1 shows the true boiling point curve (TBP, or distillation curve) for the light crude oil and condensates used in the laboratory studies (Ramstad et al., 2016) including Åsgard Blend. Åsgard Blend has a high composition (65 vol. %) of volatiles with boiling point less than 200ºC, which corresponds approximately to the fraction of oil components that will evaporate from an oil slick within the first 0.5-1 day at sea. This is in the same range as the proportion of volatiles in several of the condensates such as Marulk and Skarv. 20 vol. % of Åsgard Blend are residual components with boiling point > 300ºC, will not be lost by evaporation. The low density (0.78 g/mL) of fresh Åsgard Blend reflects the high proportion of condensate and is in the middle range of the TOF oils (Figure 4-2). The high pour point of the Åsgard Blend 250ºC+ residue (Figure 4-3) are in the same range as the paraffinic condensates of Skarv and Alve, the paraffinic light crude oil (Vale), and reference oil Statfjord C Blend.

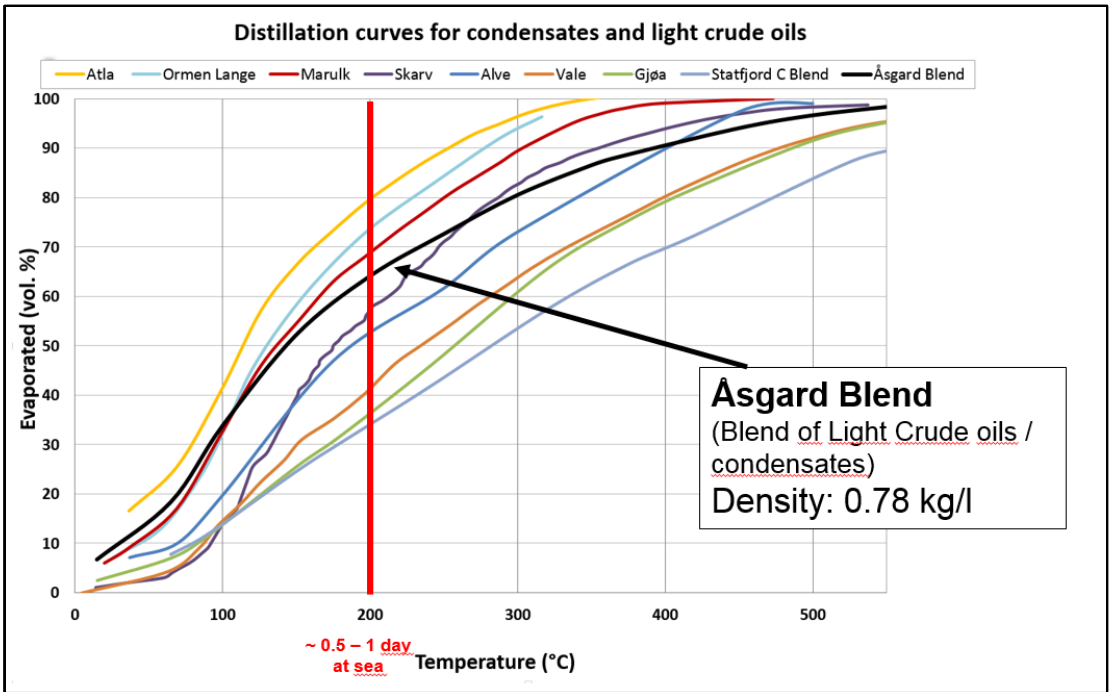

Figure 4-1 True boiling point curve (TBP) of condensates and light crude oil from the TOF-project, including Åsgard Blend.

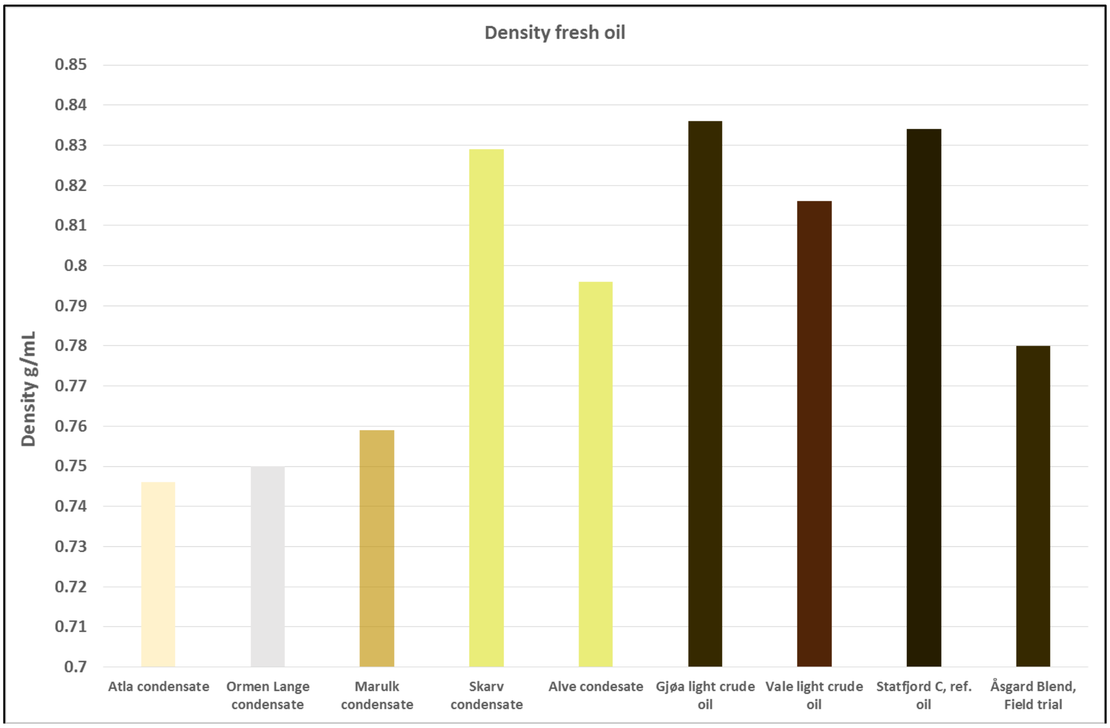

Figure 4-2 Variation of densities of the TOF-project oils (fresh oils) of condensates and light crude oils, including Åsgard Blend.

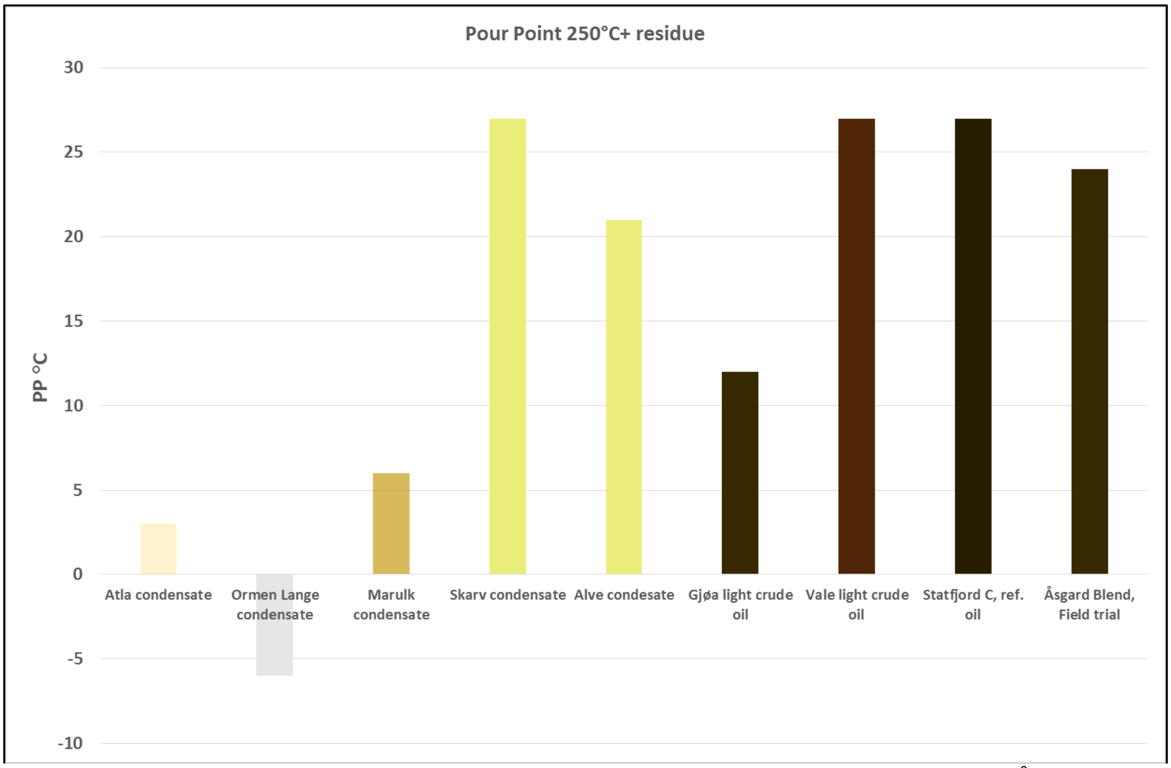

Figure 4-3 Pour point of the TOF-project oils of the 250°C+ residue, including Åsgard Blend.

Figure 4-4 below compares the predicted lifetime at sea by running the SINTEF OWM for Åsgard Blend and other condensates and light crude oils characterized from the TOF-project (Ramstad et al., 2016). It should be emphasized that these predictions were based on a standard set scenario (underwater release) to simulate an initial thin film thickness lower than 250 µm.

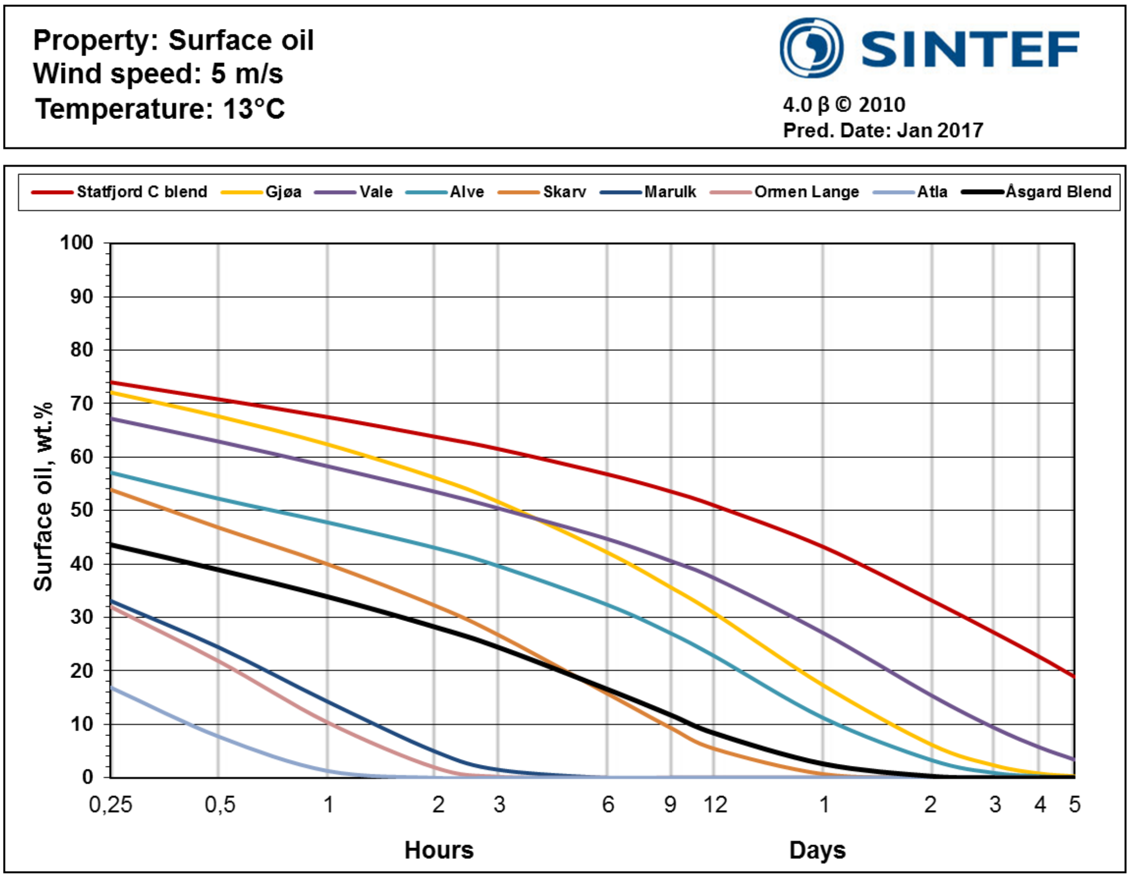

Figure 4-4 Predicted lifetime at sea surface for Åsgard Blend (black line) compared with the other condensates and light crude oils characterized in the TOF-project. Predictions based on underwater release.

Summary

In light of the decision to include only one test oil in the NOFO OOW field trial in 2016, the limited laboratory characterization of Åsgard Blend indicated that this oil is reasonably representative of the wide span of properties among the condensates and light crude oils from laboratory studies in the TOF-project. Åsgard Blend is also representative of the typical range of volatiles for Norwegian condensates and light crude oils with respect to study the potential for exposure to personnel dealing with oil spill response from releases of condensates and light crude oils.

The properties of the residues of Åsgard Blend remaining after different degrees of evaporation are similar to those of Skarv, Alve, and Vale. These oils have the potential to produce residues that are semi- solid after 1-2 days at sea under calm weathering conditions. Such semi-solid residues will not be naturally dispersed by wave action as small oil droplets in the water column. Semi-solid surface residue may start to break up into lager lumps or flakes (with sizes depending on sea conditions and residue rheological properties) and may therefore be challenging both for detection, monitoring and effective oil spill response. Studies have shown that emulsified lumps do not have the same potential for biodegradation compared to dispersed oil with oil droplets less than 50-70 micron, where the rate and degree of biodegradation of oil in the water column are highly dependent on the oil droplets size (Brakstad et al., 2014 and 2015). The more volatile and low-waxy condensates characterized and tested in the laboratory during the TOF project (*i.e*. Atla, Ormen Lange and Marulk, see Ramstad et al., 2016) are generating residues with much lower pour point and no measurable yield stress. Those residues will more easily form small, liquefied oil droplets during wave actions. This will give relative shorter lifetime on the sea surface (Figure 4-4) and will also be more rapidly degraded by microorganisms in the water column (e.g. Brakstad et al., 2014 and 2015). Gjøa is another light crude oil characterized and tested in the laboratory during the TOF project. Gjøa residues may form "loose" /semi-solid emulsions during weathering on the sea surface. However, due to its low pour-point and no yield stress the oil will have a longer operative "time-window" for using dispersants (up to several days) to enhance the dispersion of the surface oil/emulsion as small oil droplets into the water column.

5 Equipment and methods

This chapter describes the equipment and methods used for the TOF experiments during the NOFO OOW field trial in 2016 (June 14-16th.)

5.1 Observation and remote sensing

5.1.1 Satellites

During the field trial period, Kongsberg Satellite Services (KSAT) located at Tromsø Satellite Station (TSS) treated SAR data from a total of 11 acquisitions from the "RISAT-1, Radarsat-2, Cosmo-SkyMed" satellites, that covered the relevant area during the field trial. See overview of the SAR satellites in Table 5-1.

Table 5-1 Overview of SAR satellites acquisitions during the field test period.*

Oil discharges are detected in X of 11 SAR acquisitions

KONGSBERG

Sensor	Mode	Date	Time (UTC)	Pol.	# detections
RISAT-1	FRS-1	06/14/2016	06:22	CP	0
RISAT-1	FRS-2		17:16	QP	4
Cosmo-SkyMed	WR#04		19:18	VV	5
Cosmo-SkyMed	WR#02	06/15/2016	05:16	VV	3
Radarsat-2	FQ21		06:07	QP	1
RISAT-1	FRS-1		06:14	CP	2
RISAT-1	FRS-1		17:07	CP	1
Radarsat-2	FQ22		17:35	QP	3
Cosmo-SkyMed	WR#02		17:59	VV	7
Cosmo-SkyMed	WR#00		18:48	HH	2
RISAT-1	FRS-1	06/16/2016	06:07	CP	0

/ 6 / 30-Jun-16 ©KSAT 2015

**SAR = Synthetic Aperture Radar*

5.1.2 Remote sensing aircraft

Three remote sensing aircraft from three countries participated during the field trial, see specifications in Table 5-2. The participating remote sensing aircrafts are shown in Figure 5-1.

Table 5-2 Specifications of participating remote sensing aircraft.

Country	Aircraft type	Registration
Norway	King Air B350ER	LN-KYV
The Netherlands	Dornier 224	PH-CGN
Finland	Dornier 224	OH-MVO

Figure 5-1 Participating remote sensing aircraft from three countries (Norway, Netherlands and Finland).

Sensors in aircraft

A range of sensors (Table 5-3) available in the aircraft was used in monitoring the spreading of the oil slicks and in documenting effects of the response treatment of the slicks.

<u>SLAR (Side Looking Airborne Radar)</u>

The radar detects oil on the sea surface by wave damping. It has a good range; 20 km on either side of aircraft, but low resolution about 20 m per pixel. SLAR is used operationally to locate spilled oil at sea, but has limited use for experimental work.

EO/IR (Electro Optical / IR) also known as a FLIR (Forward Looking Infra-Red)
Camera and thermal imaging IR camera with high zoom capability. The gyro-stabilised and steerable turret on underside of aircraft can auto-track; lock onto 'target' and follow, irrespective of aircraft movements. Produces images taken at oblique angle, not straight-down, vertical images.

IR/UV (Infrared/Ultraviolet) Line scanner
This is not a camera, but a line scanner. Images are built up as aircraft flies straight and level above the oil slick. Aircraft height determines coverage and resolution. The system produces two vertical images one IR and one UV of exactly the same 'target'. These systems are not so useful for operational oil spill response, but are very useful for field experiments. Appendix C gives an overview of the surveillance monitoring performed by the remote sensing aircraft

*Table 5-3 Sensors in remote sensing aircraft**

Countries	SLAR	EO/IR (FLIR)	IR/UV Line scanner
Norway	YES	HDIR + HDTV + HDZ	NO
Netherlands	YES	FLIR + TV	NO
Finland	YES	FLIR or TV	YES

**Additionally, all aircraft were equipped with hand-held HR (High Resolution) photo-/video-cameras*

5.1.3 Interpreting remote sensing images

Interpretation of images

Still images taken from the various cameras and sensors of the surveillance aircraft are used in this report to document how the oil slicks spread and how they were affected by the various response treatments used.

Visual images

The visual images produced by video, HDTV (High Definition TV) and HDZ (High Definition Low Light TV) are a visual record of the scene observed. The visual appearance of oil can be an indication of the oil layer thickness according to the Bonn Agreement Oil Appearance Correlation (BAOAC) (see Table 5-4).

Table 5-4 The Bonn Agreement Oil Appearance Correlation (BAOAC).

Correlation	Description Appearance	Layer Thickness Interval (µm)	Litres per km^2
1	Sheen (silvery/grey)	0.04 to 0.30	40 – 300
2	Rainbow	0.30 to 5.0	300 – 5000
3	Metallic	5.0 to 50	5000 – 50,000
4	DCTC Discontinuous True Oil Colour	50 to 200	50,000 – 200,000
5	CTC Continuous True Oil Colour	200 to More than 200	200,000 - More than 200,000

Not all BAOAC categories will be seen in every visual image; this depends on the viewing conditions and the way that the oil has spread out. Figure 5-2 is a still taken from the HDTV video of the Norwegian surveillance aircraft just after one of the experimental slick was released. The oil is easily visible as a long, thin, brown-coloured strip on the sea surface. Most of the strip of oil would be categorised as CTC (Continuous True Oil Colour) indicating that it is more than 0.2 mm (200 microns) thick.

The MOB boat in and Figure 5-2 and Figure 5-3 is shown in the red circle.

Figure 5-2 Still from HDTV video of experimental slick just after release (LN-KYV).

Infra-Red (IR) images

The Infra-Red (IR) images produced by the HDIR or FLIR thermal imaging cameras are records of the infrared radiation emitted from the objects in the image. In general, the higher an object's temperature, the more infrared radiation is emitted as black-body (thermal) radiation (e.g. Leifer et. al. 2012). An object that is several degrees warmer than another object will emit more infrared radiation than a cooler object. There is also an additional, more subtle, effect that depends on a particular physical property - the emissivity - of the material being observed in IR. This can lead to objects that are precisely the same temperature in terms of degree Celsius, looking slightly warmer or cooler in the IR image than other objects.

The IR image from HDIR and FLIR systems is most often a black-and-white image that shows the relative apparent temperatures of objects in the image. The usual convention in IR images is that “White is Hot”; objects that are white in the image are apparently warmer than objects that are grey or black. For some uses this convention can be reversed to “Black is Hot”, but all IR images presented in this report use the “White is Hot” convention.

Figure 5-3 is a still from the HDIR video taken from the same position and at the same time as the visual scene in Figure 5-2 . The scene in the image looks very similar. The systems operator has used the “White is Hot” convention and the sea surface is shown as a mid-grey colour. The bright white spot in the slick that is visible in both images is a MOB boat (see red circle in Figure 5-3); it shows up as ‘IR white’ because it - and its occupants - are warmer than the sea surface.

Figure 5-3 *Still from HDIR video of experimental slick just after release (LN-KYV).*

The oil slick shows up as some areas that are darker (more black) than the sea surface and other areas towards the middle of the slick that are lighter (more white) than the seas surface. Close inspection of both images will reveal that the width of the oil slick in the IR image is slightly narrower than width of the oil slick in the visible image. Comparison of the visible image with the IR image can be used to discriminate oil layer thickness as three relative regions:

i. Relatively thick oil is seen as 'IR white' being slightly warmer than the surrounding sea surface. This is because thick oil absorbs solar radiation very effectively and does not lose the heat to the underlying water very well. Areas of thick oil can be several degrees warmer than the surrounding sea surface.

ii. Relatively thin oil is seen in as 'IR black' apparently being cooler than the surrounding sea surface. This is not a genuine temperature effects and is caused by oil having a lower emissivity than water.

iii. Very thin oil, or sheen, that can be seen in the visible image, but is not detected in the IR image.

These oil layer thicknesses are relative and not absolute. The actual temperature of the thick oil regions, and thus the specific IR signature, will depend on the prevailing sunshine and the length of time the thick oil has had to warm up.

The discrimination between 'relatively thick' oil and 'relatively thin' oil can be made on the basis of two thresholds:

i. The threshold where the IR image changes from IR 'white' (warm) to IR 'black' (cool) is at approximately 0.5 to 1 mm oil layer thickness. The thickness of an oil layer detected as IR 'white' (warm) is therefore approximately 1 mm or more.

ii. The threshold where the IR image changes from IR 'black' (cool) to not visible in the IR image is at about 50 to 100 microns (0.05 to 0.1 mm). The thickness of an oil layer detected as IR 'black' (cool) is therefore approximately 0.1 mm.

Images from IR UV line scanners

The Finnish surveillance aircraft was the only aircraft that was equipped with an IR/UV line scanner. The IR thermal imaging system is similar, but not identical, to that of the thermal imaging cameras. Figure 5-4 gives an examples of an image pair from the IR/UV line scanner in the Finnish surveillance aircraft of three vessels conducting operations not associated with the TOF experiments.

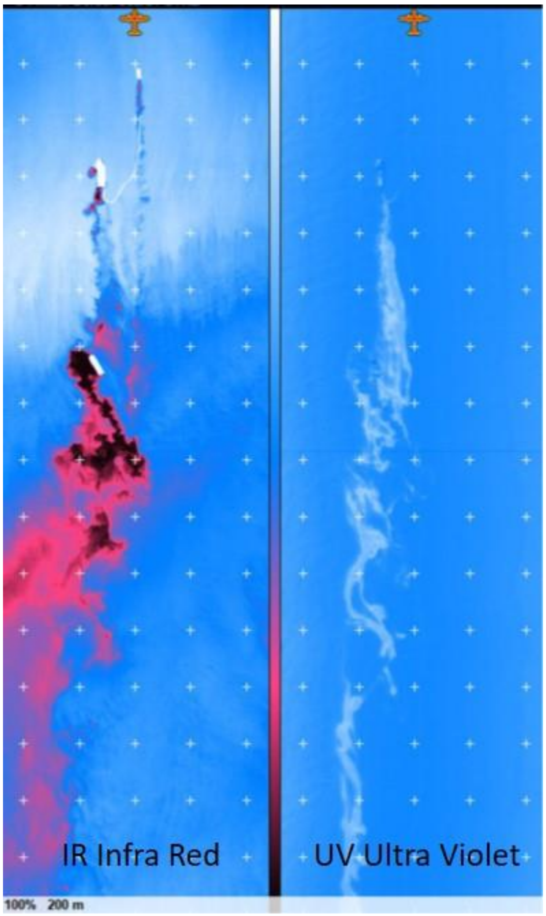

Figure 5-4 Example of IR / UV image pair from the Finnish surveillance aircraft (from another exercise).

Precisely the same vertical view is shown in both images with the IR image presented on the left and the UV image presented on the right. The crosses are superimposed at 200 m intervals. It is a false colour image; the sea surface is blue only because of the system.

i. In the IR image on the left, a "White is Hot" convention has been used.
   - The three vessels show up as IR 'white' because they are warmer than the sea surface.
   - Areas of the image that are IR 'black' are areas of the sea surface that are cooler than the surrounding sea surface.
   - The red /pink colour is used to define areas not apparently as cool as the IR 'black' areas.

ii. In the UV image on the right, the presence of any oil of any oil layer thickness is represented by the lighter colour. UV detects the effect of the aromatic chemical compounds in the oil by a modification of the reflected UV radiation from the sun.

Comparison of the two images allow an unambiguous detection of oil. Oil - of whatever thickness - is only present on the seas surface in the areas indicated as pale colour in the UV image.

By careful comparison, it can be seen that some of the area in the IR image that is IR 'black' (cool) is not due to the presence of thin oil because no oil is detected in the UV image in these areas. The explanation is that under the very calm sea conditions and bright sunlight during the field exercise the very top surface of the sea became warmed to a slight degree. The propulsion units of the vessels brought colder water from below the sea surface and this resulted in cooler areas shown as black and pink / red in the IR image.

Summary of information available from images

Depending on the images available and on the viewing conditions, the thickness of oil in various parts of an oil slick can be categorised according to the relative oil layer thickness as in the Table 5-5, below.

Table 5-5 Categorization of oil slick related to the oil layer thickness

Relative oil layer thickness	Representative oil layer thickness	IR image	UV image	Visual image BAOAC
'Thick' oil	1 mm	IR 'white' (warm)	All oil shows up as lighter coloured area	5. CTC
'Thin' oil	0.1 mm	IR 'black (cool)		4 / 3. DCTC Metallic
Sheen	0.001 mm	Not detected		1 / 2. Sheen
No oil	None	Not detected	Not detected	Not detected

5.1.4 Drones

Four quadcopter drones (RPAS - Remotely piloted aircraft systems) were operated for different monitoring and sampling purposes during the field experiments. Maritime Robotics AS was contracted primary for the HISB experiments with two video drones (DJI Inspire 1) and one drone (MR QUAD) for air-sampling in the smoke-plume. Additionally, Maritime Robotics performed video drone monitoring during the day 2, TOF experiment (June 15th.). The drone operations performed by Maritime Robotics during field test (both camera drones and sampling drone) are summarized in Appendix D.

Additionally, a drone (Indago 2) equipped with both Electro Optical (EO) and IR (Infrared) sensors was tested by Norwegian Coastal Administration (NCA) during some of the releases day 1 (June 14th). The drone was operated by a RPAS-team at "KV Tor" vessel. This drone was not an integrated part of the experimental plans, and is therefore not included. However, the testing of this drone clearly show the great potential in having drones with both EO/IR sensors for documenting the spreading of both thick and thin oil within the slicks.

5.2 Participating vessels

Two response vessels contracted by the Norwegian Coastal Administration (NCA) were allocated for the field experiments; see Figure ***5-5*** (A and B):

i. KV Sortland is a Norwegian coastguard vessel (in operation from 2010) of the "Barents Sea-class". The vessel is 93 m long and 16.6 m wide. KV Sortland was operated as a command vessel during the NOFO OOW 2016. The vessel was responsible for the oil releases of Åsgard Blend. KV Sortland was also the "mother-vessel" for an unmanned surface vessel (USV), with an Aerostat (Ocean Eye with visual and IR video cameras) were stationed and launched from KV Sortland (Figure 5-5 C). Maritime Robotics operated both the USV and Aerostat. Further details are given in website: http://www.maritimerobotics.com/

ii. <u>MS Strilborg</u> is a supply and response vessel, and presently under contract for NCA as an emergency tow-vessel. Strilborg is 74 m long and 18 m wide. The two sampling boats (MOB boats) on MS Strilborg (GTC 700, 7.2 m long, Figure 5-5 D) were both use as sampling boats for ground truth sampling(surface oil and water column) and air monitoring.

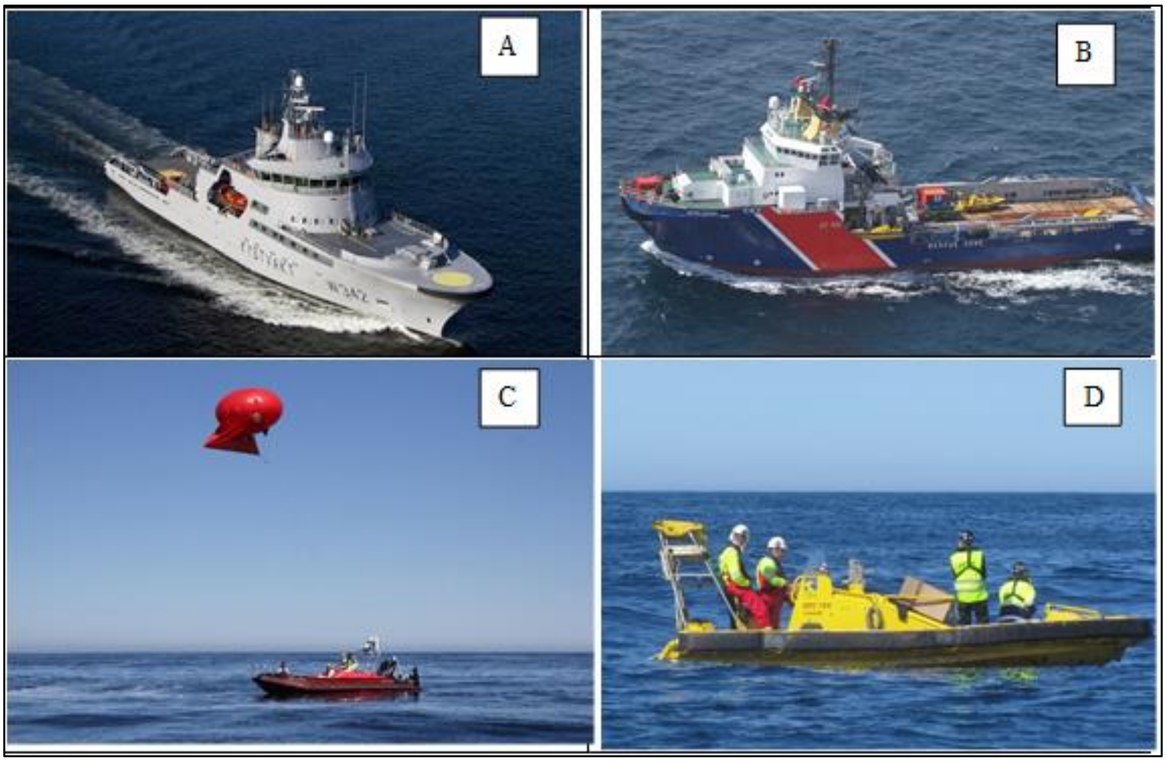

Figure 5-5 Vessels involved in the TOF- experiments: KV Sortland (command vessel), B: MS Strilborg, C: USV with Aerostat, D: Sampling boat (MOB-B boat from MS Strilborg).

5.3 Novel response techniques

The development and construction of prototype response techniques used in the field-testing was not a part of the TOF-project. This took place during the "Oljevern 2015 program *"Mechanical Dispersion of Thin oil films"* funded by NOFO. The purpose was to develop and customize prototype systems to test the potential for mechanical dispersion of thin oil films by using fire-fighting systems Fi-Fi2 according to DNV GL class system (hereafter called Fi-Fi) with monitor capacity of 3600 m^3 seawater/h, and high-capacity water flushing bow-booms connected to existing pump systems available on response vessels. Jason Engineering (http://www.jason.no/) has constructed a flexible container based application system (see Figure 5-6, below) including:

i. High-capacity water flow boom up to 16 m^3 / min
ii. High and low dispersant system with same capabilities as the "standard" dispersant systems on "NOFO vessels" with dispersant equipment with capacity of 30 and 120 L / min

Specification of the Jason prototypes is given in a project memo from Rasmussen et al., (2016).

Figure 5-6 Installation of prototype systems on MS Strilborg at Hammerfest, May 23-25, 2016). Upper left: Deflector on Fi-Fi-monitors. Right: Container based high-capacity water-flow boom and high / low dispersant (manifolds) at the bow. Part of the "Oljevern 2015 program "Mechanical Dispersion of Thin oil films" funded by NOFO.

Figure 5-7 Pre-testing of Fi-Fi-monitors (left) and high-capacity water-flow boom on MS Strilborg at Hammerfest, May 23-25, 2016). Part of the "Oljevern 2015 program "Mechanical Dispersion of Thin oil films" funded by NOFO.

After pre-testing at sea in Hammerfest (May 2016), the following conclusions and recommendations were outlined before the NOFO OOW 2016 field testing (Daling et al. 2016):

i. Use of Fi-Fi monitor system on MS Strilborg (capacity: 3600 m^3/ h):
   a. Spraying pattern <u>without</u> deflector was most powerful.
   b. Deflector: 15-20 m deposition width, not homogenous distribution. Concluded to test Fi-Fi monitors without deflector at 8-10 knots at NOFO OOW 2016
ii. Use of High capacity water flow boom:
   a. Water delivering pump capacity on Strilborg limiting factor (fire pump: ~ 300 m^3/h)
   b. Prior NOFO OOW 2016: Include ballast pump to 550 m^3/h (~3 bar on the nozzles)
iii. Test new dispersant manifolds of high and low dosages (LD): 120 L/min and 30 L/min
   a. Satisfy NOFO standard requirements for offshore dispersant use
   b. Showed very good application pattern (tested from 2 - 15 knots)

c. Bow-wave: Effect on the deposition of dispersant area: > 12 -14 knots
d. Low dosage (30 L/min) application for Åsgard Blend (8-10 knots) used in the TOF-project

5.4 Monitoring and sampling documentation

5.4.1 Air monitoring and human exposure

The instrumentation and methods for air monitoring and human exposure are only briefly described in this report. This will be covered in separate papers (Gjesteland et al, in prep 2017).

Real-time photoionization detectors (PIDs) were placed in the two response vessels and the three MOB boats participating in the releases of Åsgard Blend to measure the concentration of total volatile organic compounds (TVOC) in air. The instruments were calibrated with isobutylene and logged the air concentration of TVOC every 10 seconds throughout the workday. Full-shift personal exposure to benzene, toluene, ethylbenzene, xylenes (BTEX), naphthalene and n-hexane was measured with passive thermal desorption tubes (ATD) attached in the participants breathing zone. The equipment was delivered and analyzed by SINTEF Molab Oslo.

Urine samples from the participants were collected before and after the work shift to measure biological uptake of benzene after exposure. The equipment was delivered and analyzed by the Health and Safety Laboratory in England.

5.4.2 Ground truth oil sampling documentation

One of the two MOB-boats on MS Strilborg designated MOB-B was primarily allocated for surface sampling and water column monitoring with the following instrumentation:

- Surface oil slick thickness measurements (synchronized to aerial survey; see Figure 5-8)
    - > 3 mm: Use of a Plexiglas oil/water sampler. Visual measurements on site
    - < 3 mm: PP-pad. Gravimetric quantification
    - < 3 µm: Teflon net (post-analysis by gas chromatography or spectrophotometric quantification)
- Surface sampling for physicochemical characterization of oil properties
    - On site: Viscosity, water content, emulsion stability, dispersibility field test
    - Post laboratory analyses: Viscosity, evaporative loss, density etc.
- Water column: Oil concentration (UVF / chemistry) of water samples and in-situ particles (oil droplet) size measurements by using LISST-100 places at 1 m depth (see Figure 5-9).

See also Appendix B an overview of the analysis from the ground-truth sampling.

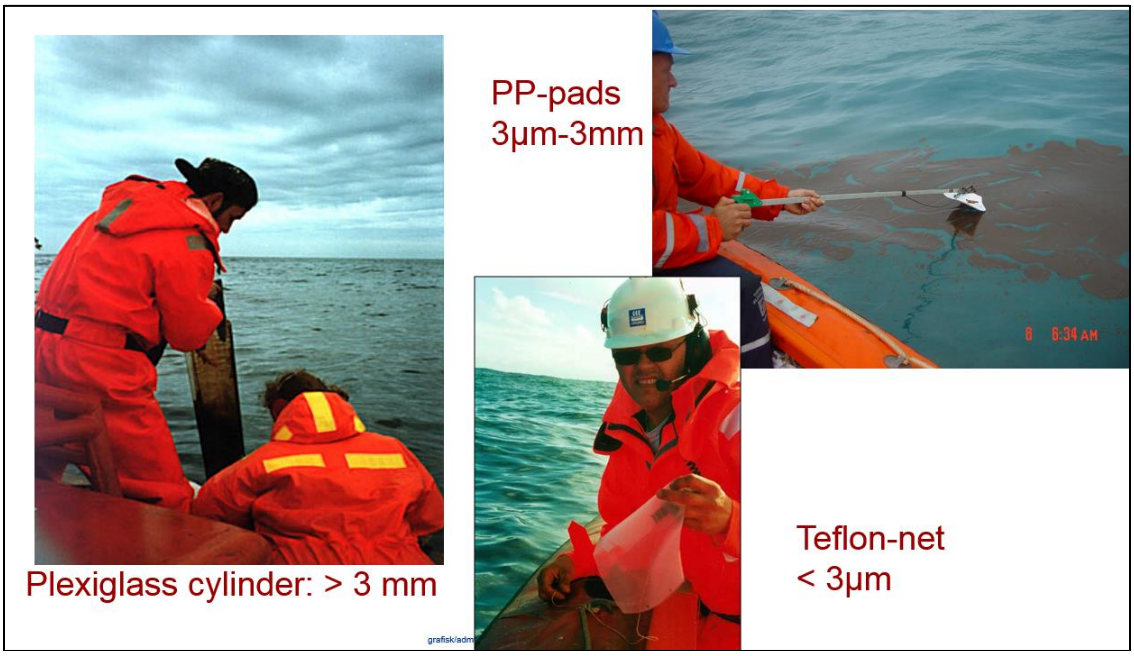

Figure 5-8 Different methodologies for measuring oil slick thicknesses.

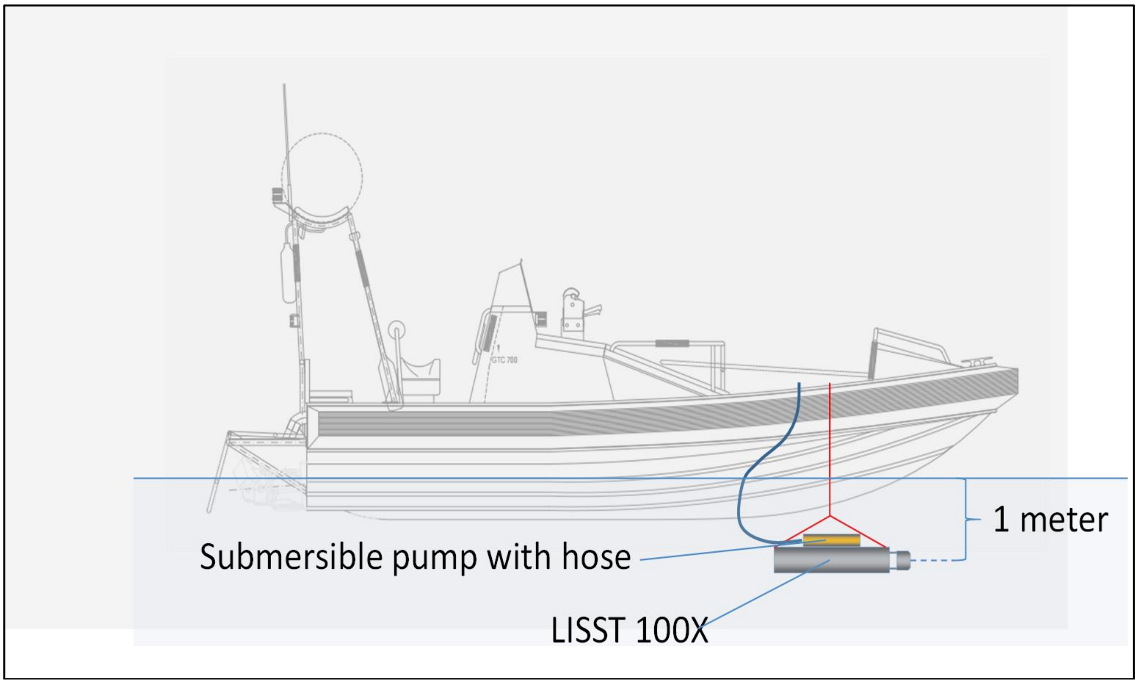

Figure 5-9 Schematic of the sampling boat MOB-B instrumented for in-situ monitoring of oil concentration and oil droplet size measurements using LISST 100X mounted at 1 min depth and submersible pump for water sampling.

6 Experimental releases – planning and strategies

6.1 Planning and overview of experimental releases

During the preparation prior the field trial, SINTEF (Daling and Sørheim, 2016) and Alun Lewis Consult worked out a detailed experimental plan in close cooperation with NOFO. The plan included specification and weather criteria for the different releases. Due to the complex integration between the planned TOF and HISB experiments, a detailed logistic timeline of the experiments for day 1 and day 2 was also developed prior the field trial. The aim of such plan was to allow needed changes e.g. timing, order of releases due to weather forecasts or technical incidents by minimizing as much as possible the risk for loosing important logistic elements during the experiments

The final release order of experiment 3 and 4 (TOF and HISB experiments) was decided on site by the On Scene Coordinator (OSC) at NOFO due to the prevailing calm weather conditions during day 1 (< 5 m/s wind) and with a weather forecast of up to 15 m/s wind speed during the night for day 2. Figure 6-1 shows the final order of the three releases (Exp. 3.1, 3.2 and 3.3) with the Åsgard Blend.

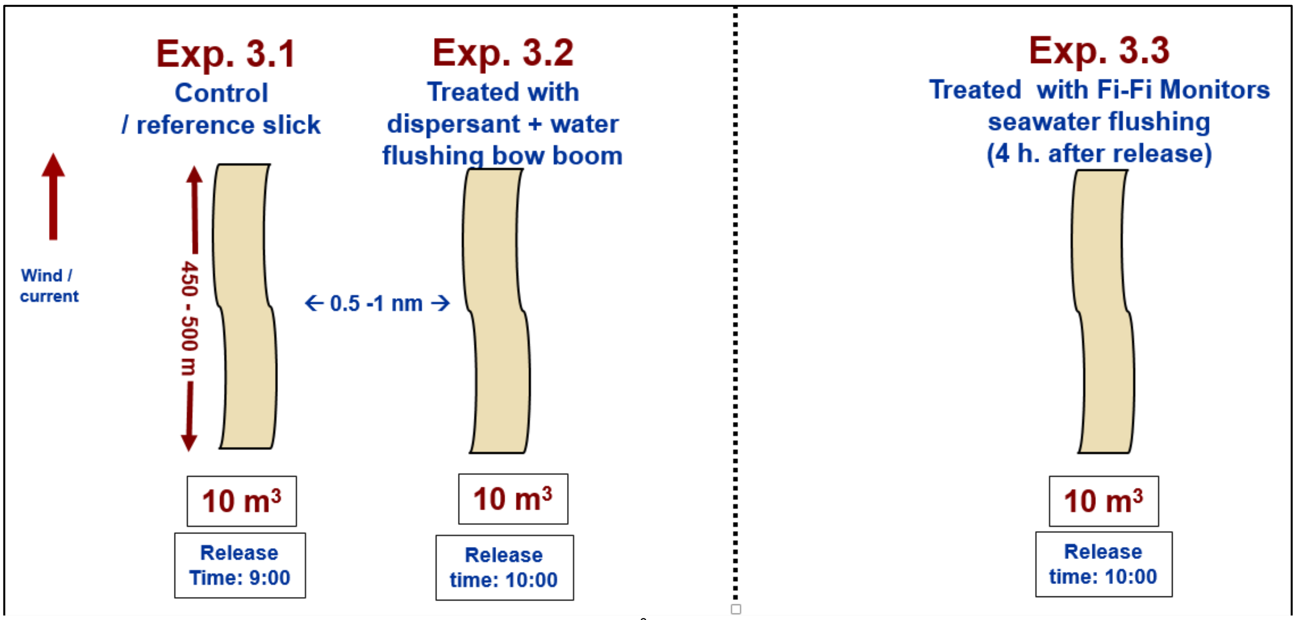

Figure 6-1 Schematics of the three releases with Åsgard Blend. Exp. 3.1 and 3.2 releases performed June 14$^{t.h.}$ (day 1) under non-breaking wave conditions and Exp. 3.3 released June -15th (day 2) under breaking wave conditions.

6.2 Release arrangement and release strategy

The aim was to allow the oil to spread out to form an average film thickness in the region of 0.2-0.5mm. A numerical model was used to simulate spreading of oil according to Fay's formulas under different release conditions, and specific input properties of Åsgard Blend were used (Johansen, 2016 A). Figure 6-2 gives an example of the simulated initial spreading through a weir system with initial width of the overflow system (Yo) =: 1 m) over a distance of 600 m over 5 min (against the wind). The simulations gave an average oil thickness of about 0.2 mm (see red thin line) and a slick width (black thin line) of 25-30 m after about 1 hour (3600 sec) after release of 10 m^3 of Åsgard Blend. The thin lines in the figure are compensated for evaporative loss.

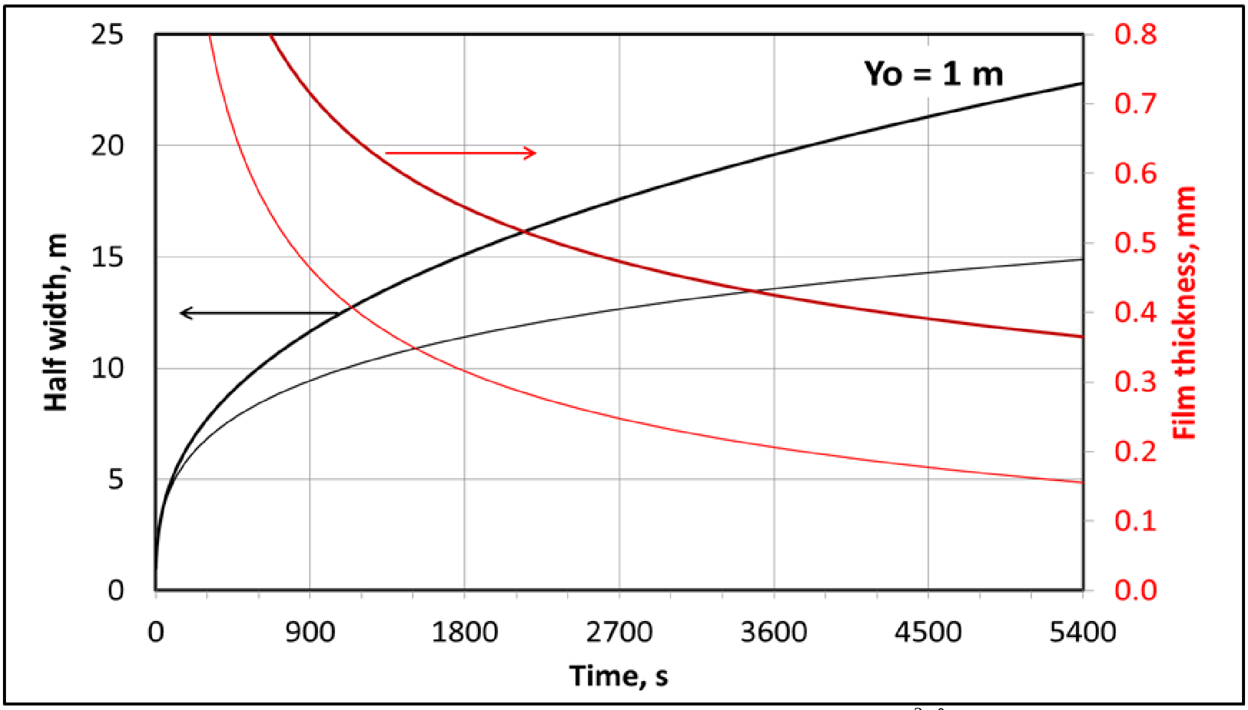

Figure 6-2 Example of spreading simulation (Johansen, 2016 A) of 10 m³ Åsgard Blend released through a weir system (initial width of the overflow system (Yo = 1 m) over a distance of 600 m over 5 min. (against wind). Thin red line shows the average film thickness (compensated for evaporative loss) as function of time after release.

Based on the spreading simulations, NOFO constructed a "floating weir system" suspended from a crane and about 10 m from the side of KV Sortland, so the released oil would not come in contact with the hull (see photos in Figure 6-3).

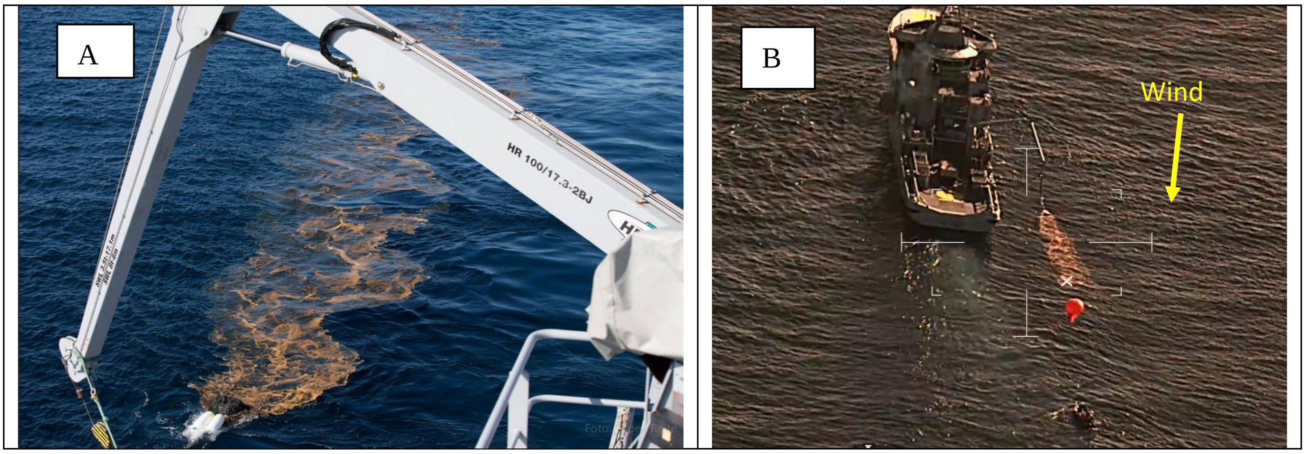

Figure 6-3 A):Release arrangement for the TOF experiments. Åsgard Blend released from KV Sortland. B): Monitoring of VOC concentration in the air down-wind to the slick during and after release by the USV with Aerostat.

Prior each release, 10 m³ of the Åsgard Blend was transferred from the transport tanks to a calibrated "day-tank". The accuracy of the released volume of oil in each experiment were assumed to be within +/- 100 L (ref. NOFO). The oil was pumped (using a TK-6 centrifugal pump) out from the day-tank through a 20 + 10 m long (5 inch) hose at a pump rate of 2 m^3 / min. out to the floating weir.

Figure ***6-4*** is a schematic illustration of the release strategy showing the positions of the different platforms (vessels and sampling boats) during each release:

1. The oil was released directly into the wind at a vessel (KV Sortland) speed of 3 knots over a distance of 400-600 m. At the end of release, the vessel would move upwind before leaving the slick area for positioning for the next release (0.5 nm to the side of the released slick).
2. An oil-drifting buoy with AIS positioning system was released in to the slick during the release.
3. The USV with Aerostat was in a "stand-by" positioned downwind at a safety distance (approx. 50 m up-front) to the slick for measuring concentration of VOC in the air prior, during and after the release.
4. Sampling boat (MOB-B), acted as a "marker" for the release vessel for "end position" of the oil release, and using smoke signals marking the wind drift prior/during the release. About 30 min. after the release MOB-B went into the slick for surface oil sampling at different positions tracking down-wind through the slick
5. During and after (up to 30 min) the release, MOB-C performed air monitoring of VOC concentrations by tracking around in different down-wind positions to the slick.
6. During release, MS Strilborg was in a down-wind position about 150-200 m up-front to the drifting slick and therefore potentially exposed to air-borne VOC from the slick. Continuous measurements of TVOC concentration were carried out by PID sensor placed at different heights (working deck and bridge).

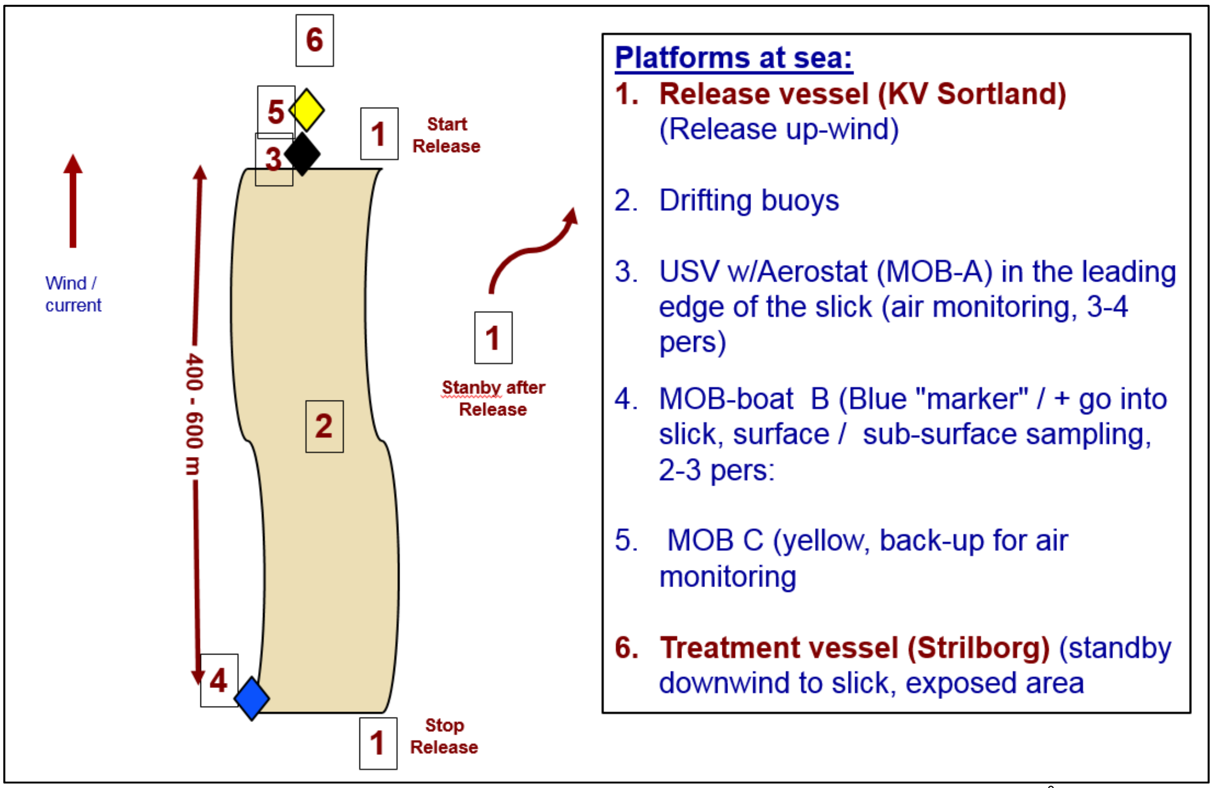

Figure 6-4 Release strategy and positioning of platforms / boats during releases of Åsgard Blend.

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7 Field experiments – Results and discussion

7.1 Experiment TOF 3.1 – Reference slick

The main goal with experiment 3.1 was to study and document the behaviour and fate of Åsgard Blend when spilled in calm sea conditions with non-breaking wave (< 5 m/s wind speed) without any response treatment. This was to compare the slick behaviour with that of subsequent releases treated with different response options. In order to generate a relevant initial thin oil film as possible, 10 m^3 of Åsgard Blend was released over a distance of 400 - 500 m to obtain a calculated average thickness of < 0.5 mm within 0.5 hour after release.

7.1.1 Overall Timeline for TOF 3.1 experiment

The sea on June 14th was very calm with no breaking waves (significant wave height ~0.5 m). In the morning, at the start of the experiment, the wind was around 3 m/s from NNE, and remained so until the evening when the wind increased to about 5 m/s at 19:00 LT (Local Time). During the night, the wind speed further increased to 14-15 m/s. Table 7-1 summarizes the timeline (based on the log) during release of experiment 3.1.

Table 7-1 Timeline (log) of the release of experiment TOF 3.1- Reference slick.

Local Time (LT)	Activity
08:40	MOB B/C and USV in position, start air monitoring
09:42	Smoke signal
08:43 – 08:50	Releasing oil (10m^3 of Åsgard Blend). Position: Start: N60°0.0799' E2°23.429', Stop at N0°0.0960' E2°23.910'
08:42	Release AIS buoy (MMSI 992572022)
08:50	Reports of air monitoring from sampling boats (USV and MOB C): LEL < 1 %, measured PID-TVOC: 250 – 500 ppm
08:55	Drones in the air)
09:20 – 09:45	Surface monitoring (MOB B) - Good ground-truth samples gathered (pads and oil samples)

7.1.2 Oil behaviour during release

Figure 7-1 is a still from the aerial video recording from the Norwegian surveillance aircraft during the release from KV Sortland at 08:47 LT. The red ellipse indicates the position of the released oil. The yellow circle shows the positions of the two sampling boats MOB-C and USV with Aerostat performing air monitoring downwind to the slick. MS Strilborg, behind the sampling boats, was about 200 m further downwind from the slick. MOB-B released a smoke signal (grey ellipse), indicating that the oil had been released at an angle about 20° from the wind direction.

Figure 7-2 to the left shows Visual (A-1) and FLIR (A-2) images taken during release (08:48 LT). The IR 'black' (cool) area in A-2 indicates that the surface of the oil was cooler than the surrounding seawater immediately after release. This was likely due to the high degree of evaporation of light volatiles taking place. Pictures to the right shows Visual (B-1) and FLIR (B-2) about 15min after release (09:02 LT). The FLIR (B-2) is switching from IR 'black' (cool) over to IR 'white' (warm), most likely because the sun was heating the thick oil.

Figure 7-2 (A-1 and A-2) shows that during the release the oil rapidly spread out to a width of about 10 m. After 15 min (right-B-1 and B-2), the width had increased to 15-20 m. This is in a good agreement to the model simulations of the initial spreading (Figure 6-2).

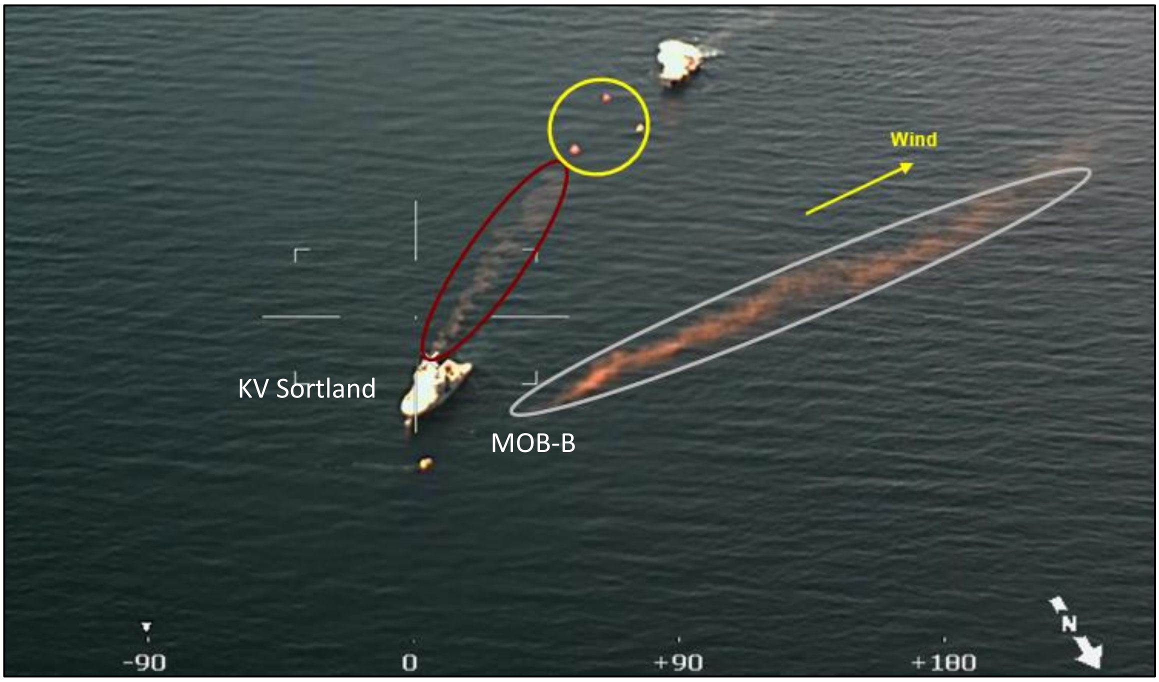


Figure 7-1 During release of experiment 3.1. (08:47 LT). Photo: LN-KYV

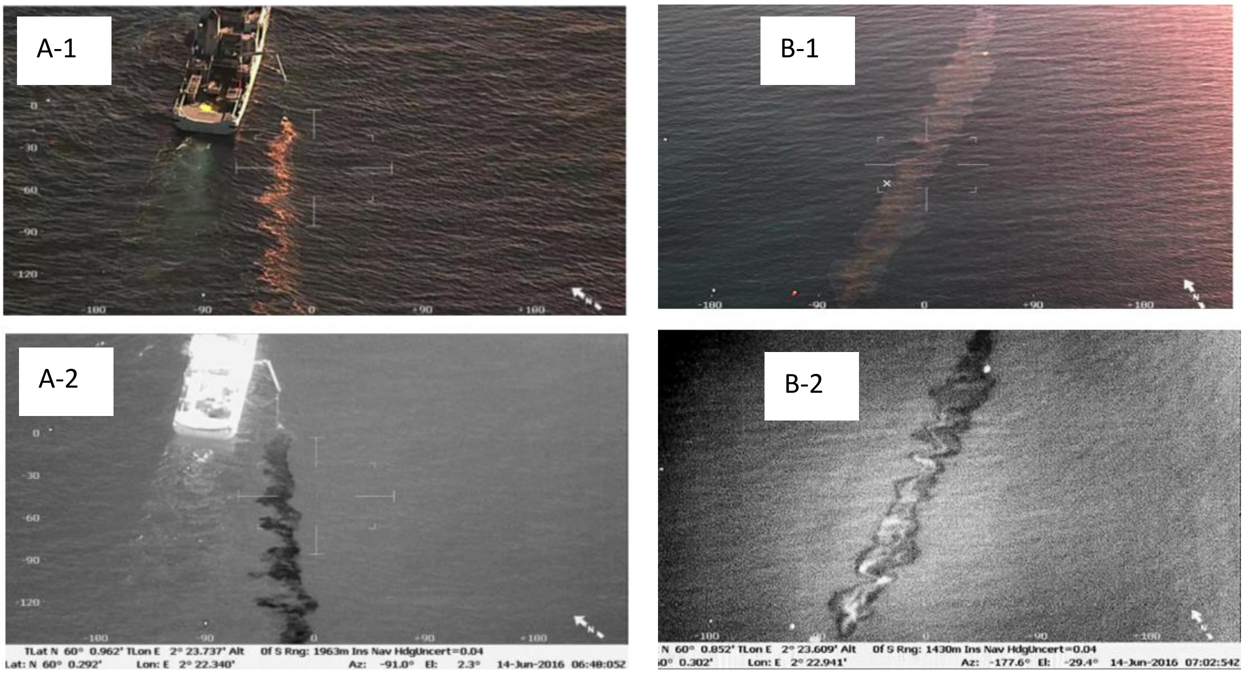


Figure 7-2 Left: Visual (A-1) and FLIR (A-2) images during release (08:48 LT). IR 'black' indicates oil cooler that seawater. Right: Visual (B-1) and FLIR (B-2) about 15min after release (09:02 LT). IR is switching from IR 'black' (cool) over to IR 'white' (warm) as the oil heated up by the sun. Photo: LN-KYV

7.1.3 Oil behaviour after release

The FLIR images taken about 40 min. after release (Figure 7-3 B) shows that the thick oil in the slick, detected as IR 'white' (warm) is about 30 - 40 m wide. This is in a good agreement with model prediction of the spreading and average thickness as illustrated in

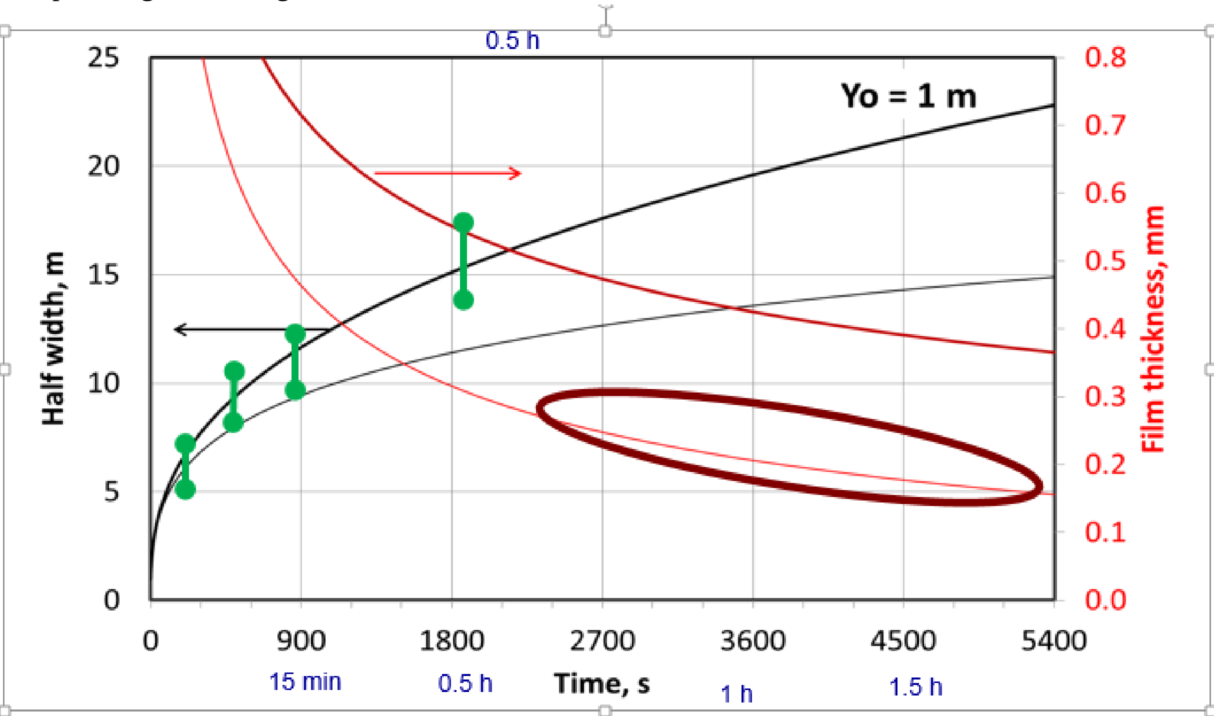


Figure *7-4* (see green dots in the figure). However, the visual photo in Figure 7-3 A shows that the slick is surrounded by a thin sheen (not detectable by FLIR) giving a total slick width of about 100 m (including sheen).

In Figure 7-3, the sampling boat (MOB-B) can be seen in the middle of the slick (yellow circle), taking surface samples of the oil within the IR 'white' (warm) area of the slick. The properties of the surface oil (samples taken between 30 - 60 min after release) showed:

- Oil thicknesses: 0.5 - 1 mm (taken in area with thick oil)
- Water content in oil: < 10 %
- Viscosity of oil: < 20 mPa.s
- Evaporative loss: approximately 35 wt.% (based on GC-FID (post-analysis))

The ground-truth documentation are in good correlation to the OWM-model prediction of the weathering properties of the Åsgard Blend (see Appendix A).

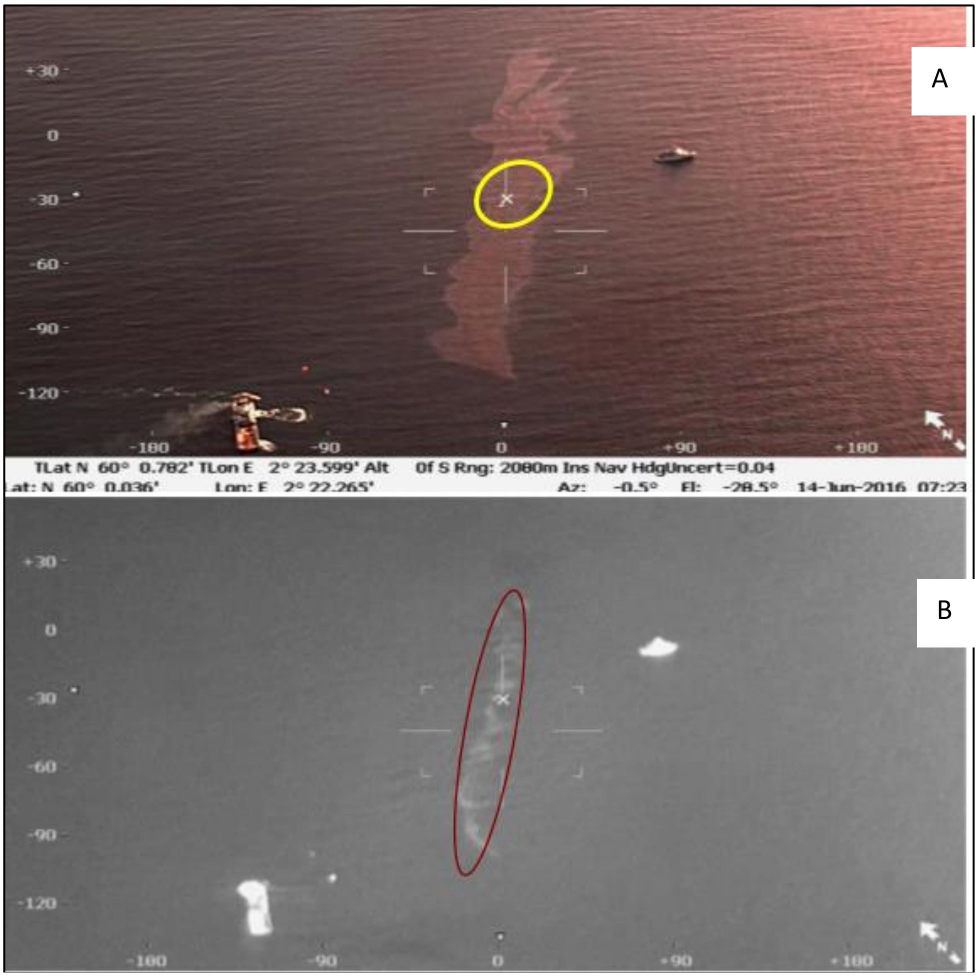


Figure 7-3 The FLIR images taken about 40 min. after release of TOF 3.1 shows that the thick oil in the slick detected as IR 'white' (warm) is about 30 - 40 m wide. Photo: LN-KYV

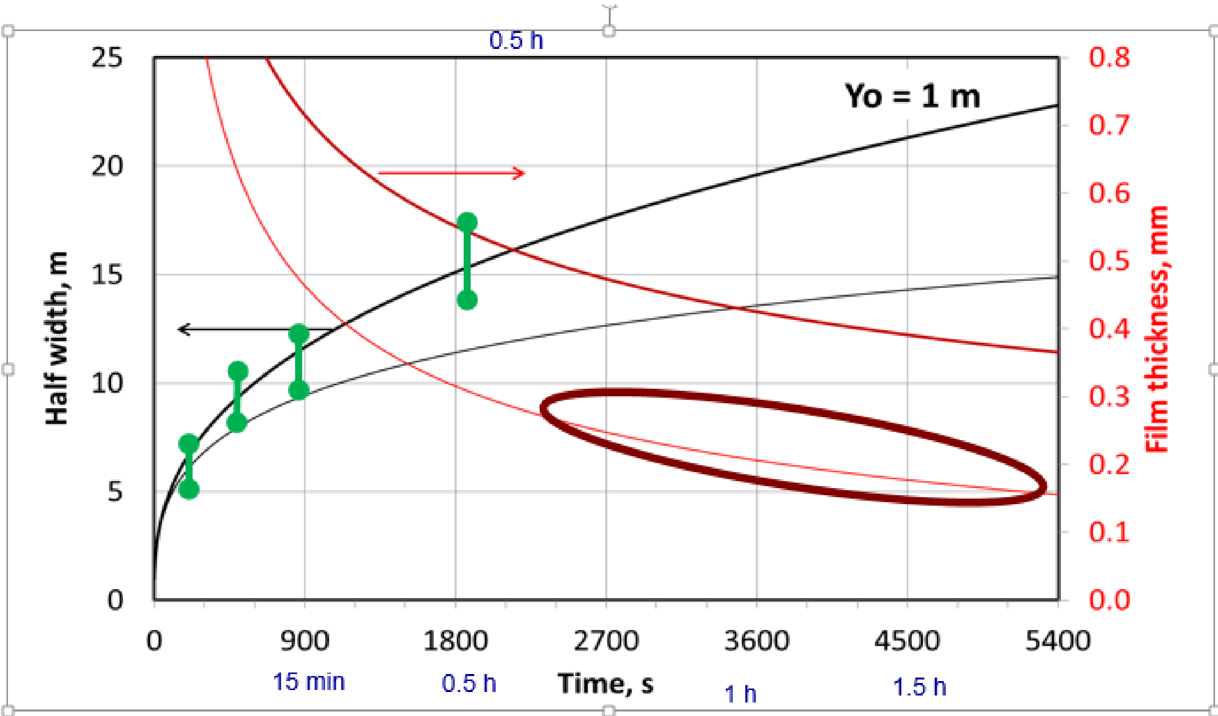


Figure 7-4 Observed initial spreading of the slick (green dots) of the IR detectable area of TOF 3.1 versus modelling. The observed slick is about 30 - 40 m wide. The red circle indicates the average film thickness in the range of 0.2-0.3 mm after 0.5-1 h after release.

The next available image of TOF 3.1 is an IR/UV line scan taken from the Finnish surveillance aircraft about 1.5 hours after release at 10:19 LT, Figure 7-5. Figure 7-6 shows the IR line scan images made 20 and 40 minutes later at 10:40 and 11:00 LT.

In the image taken at 10:40 LT (Figure 7-6), the total slick area (UV+ IR 'black' (cool) and IR 'white' (warm)) is approximately 157,500 m^2. The calculated distribution of the oil (see Table 7-2, below) shows that the majority of the oil volume (76%) is within the IR 'white' (warm) area, (assuming average thicknesses 1-2 mm) representing only 3.5 % of the total slick area. The thin sheen (UV only) represents 86% of the slick area, but contains only 2 % of the oil volume. The IR 'black' (cool), assumed an average thickness 0.1 mm, represent an area of 11%, and an oil volume 22 % of the slick. If we only consider the IR-detectable area (IR black and IR-white, total 22,500 m^2), and assume an evaporation of 50%, this correspond to an average thickness of 0.22 mm. This is in good agreement to the spreading model at 1.5 hours after release (see Figure 7-4).

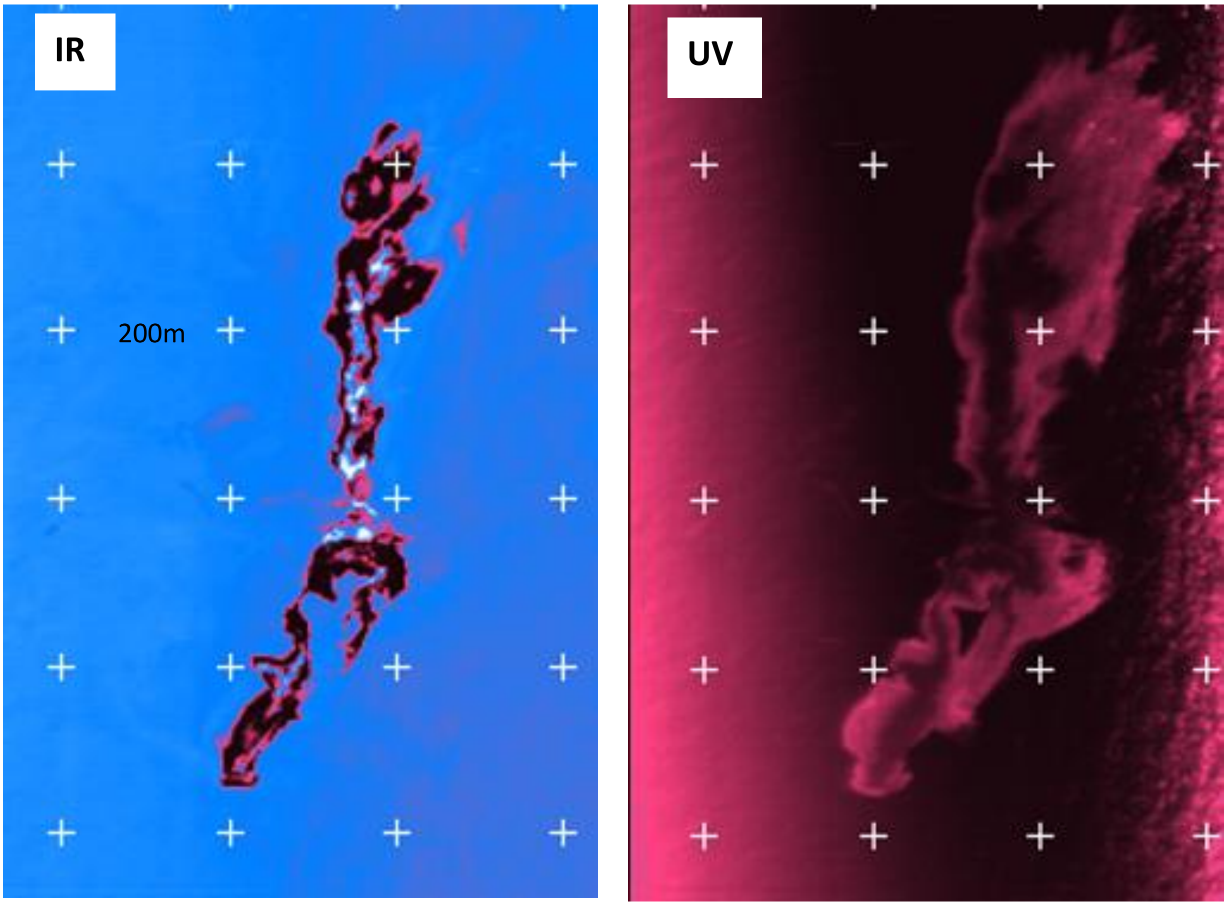


Figure 7-5 IR / UV line scanning images of TOF 3.1 slick 1.5 h after release (10:19 LT), ©Finnish Border Guard / SYKE.

Table 7-2 Distribution of the oil within the reference 3.1 slick 10:40 LT (about2 hours after release, Figure 7-6)

	Area (%)	**Thickness (mm)**	**Amount Oil m^3**	**Volume (%)**
UV only	86	< 0.05	0.4	2
IR black	11	0.1	1.7	22
IR white	3.5	1 – 2 mm	5.5	76

The IR images shown in Figure 7-5 and Figure 7-6 indicate no further spreading of the thick oil area. Instead, the area of thick oil contracted to form very distinct, narrow "bent bands" of IR ‘white’ (warm), thick oil that were < 10-20 m wide. The surrounding sheen seemed to have limited the spreading of the thick slick under these very calm sea conditions. Such characteristic "bent bands" of thick oil surrounded by sheen were also documented during calm sea conditions in the Macondo incident (Overton, 2011). Unfortunately, no ground-truth samples of the surface oil at this stage was performed. However, according to the OWM predictions, the water content was assumed to be low (< 20 vol. %) with an evaporative loss of 50-55 % (representing a 150-160°C+ residue) and low viscosity (< 200-300 mPa.s). The oil was therefore assumed not having any significant solidifying properties due to low pour point and/or yield-stress at that stage.

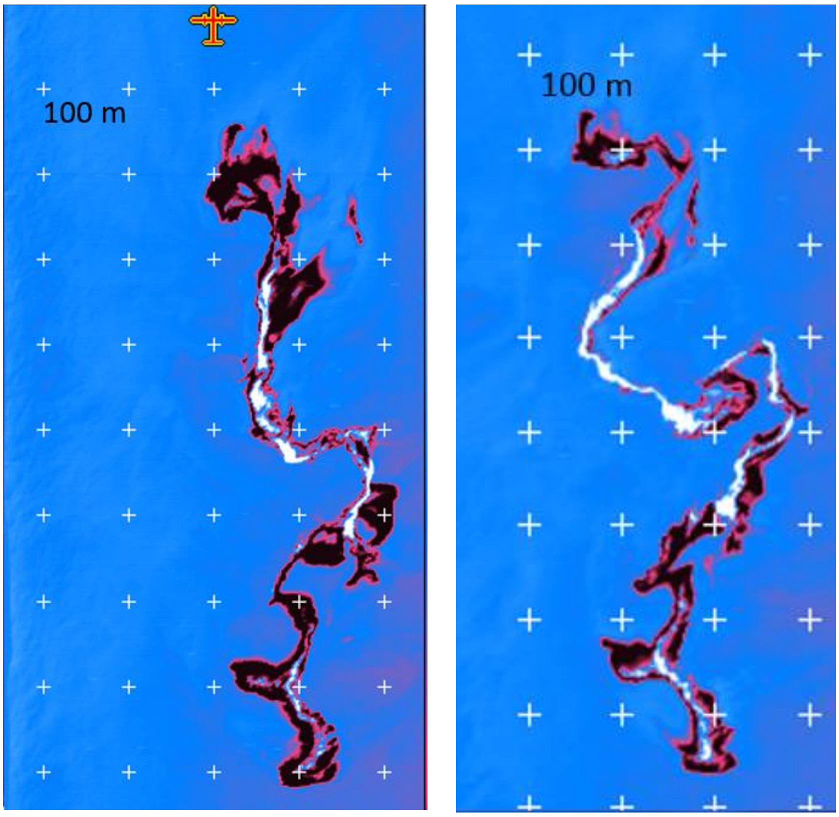


Figure 7-6 IR line scanning images of 3.1 slick ca. 2 h after release (10:40 and 10:59 LT), ©Finnish Border Guard / SYKE.

Figure 7-7 shows an overview FLIR image taken 11:00 LT of both the non-treated TOF 3.1 reference slick with the characteristic “bent bands" of thick oil (IR ‘white’ (warm)) and the TOF 3.2 slick (see chapter 7.2).

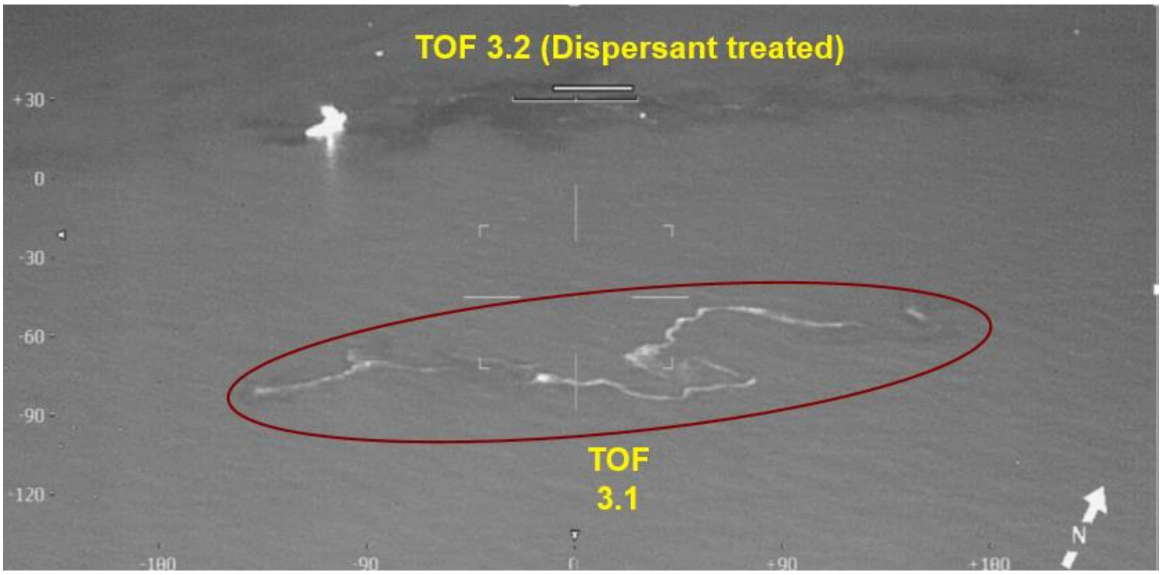


Figure 7-7 Overview FLIR image taken 11:00 LT of both the non-treated 3.1 (red circle) slick with the characteristic "bending bands" and the dispersant treated 3.2 slick in the background ©Finnish Border Guard / SYKE.

7.1.4 Further fate and behaviour of the TOF 3.1 slick residue

Due to the change in the release order (see chapter 6.1 for planning and strategies) during the first day (June 14th), it was not logistically possible to carry out further ground-truth sampling of the surface oil for slick TOF 3.1 during the afternoon. However, the results from the laboratory characterization (see chapter 4) of the Åsgard Blend and other paraffinic and waxy light crude oils and condensates indicates that the Åsgard Blend residue remaining on the sea surface would have started to become semi-solid within a few hours in calm weather conditions. The predictions in Appendix A show that the pour point of the Åsgard Blend residue will be higher than the sea temperature within 3-4 hours after release. It is therefore most likely that when the wind conditions start to increase in the evening after the TOF 3.1.slick had been at sea for 10-12 hours, the remaining thick oil residue (bands) would be semi-solid. The laboratory studies with similar residues (e.g. Vale and Skarv) showed that such weathered residual oil on the sea will lose its potential for being dispersed into small oil droplets in breaking wave conditions (Ramstad et al., 2016).

The residue of the Åsgard Blend was therefore able to remain on the sea surface during the next night in breaking wave conditions. The next morning (June 15th), the Norwegian surveillance aircraft detected "non-combatable" patches of the slick that "started to break up". During the afternoon (wind speed 6-8 m/s) these patches were gradually broken up. In the evening at 18:35 (LT), the Finish aircraft estimated the remaining patches to be (BAOAC minimum-maximum) only 120-1130 litres. Next day, there were no traces of oil (ref. NOFO.) These observations are consistent with our general understanding that the fate of semi-solid oil residue under breaking waves conditions is to be gradually broken up into individual lumps or flakes with sizes depending on sea and release conditions. Such individual lumps will therefore be challenging both for detection and

monitoring and for effective oil spill response mitigation. In addition, previously studies have also shown that emulsified lumps have not the same potential for biodegradation compared to dispersed oil with oil droplets less than 50-70 micron. The rate and degree of biodegradation of oil in the water column are highly dependant on the oil droplets size (Brakstad et al., 2014 and 2015).

7.2 Experiment TOF 3.2 - Low dispersant application and high-capacity water flushing bow-boom

The TOF 3.2 slick was released under same conditions as the TOF 3.1 reference slick. The main purpose of the TOF 3.2 experiment was to document the effect of low-dosage (LD) (30 L/min) dispersant treatment about 1 hour after release in calm, non-breaking wave sea conditions. The plan included to study the effect of introducing an artificial turbulence 0.5-1 hour after the dispersant operation by passing through the slick using the high-capacity water flushing bow-boom system installed on MS Strilborg.

7.2.1 Overall Timeline for experiment TOF 3.2

The timeline log for the 3.2 experiment is given in Table 7-3.

Table 7-3 Timeline (log) of the release of experiment 3.2- treated with LD dispersant followed by high-capacity water flushing bow-boom.

Local Time (LT)	Activity
10:00	MOB B/C and USV in position, start air monitoring
10:02	Smoke signal
10:03 – 10:09	Releasing oil (10 m^3 of Åsgard Blend). (Position: Start: N60°01.0' E002°22.9', Stop at N60°01.2' E002°23.3' (450 m long slick)
10:08	Release AIS buoy (MMSI 992572049)
10:17 – 10:26	Surface oil sampling (in the thickest areas within the slick)
10:28: **10:28 – 10:31:** **10:39 – 10:42:** **10:44 – 10:45:** **10:48 – 10:51:** **10:51**	Start Dispersant application: 1. Dispersant spray pass (LD), with wind (6-8 knots; 3-4 m/s) 2. Dispersant spray pass (LD), with wind (6-8 knots; 3-4 m/s) 3. Dispersant spray pass (LD), against wind (approx. 4 – knots; 2 m/s) 4. Dispersant spray pass (LD), with wind (6-8 knots; 3-4 m/s) Stop dispersant application, Total of 600 L Dasic NS was applied
11:05 – 12:00:	Flushing with water high capacity- boom: good visual effect. Water-boom (PS) touching the surface during the 2nd turning of MS Strilborg. The boom was raised to 1.5 m above the sea surface Working fine in that position.
10:10 – 12:00:	Finnish aircraft performed surveillance during and after the release of 3.2. Extensive aircraft surveillance documentation by the Finish aircraft also during the dispersant spraying operation and during the high capacity water flushing. No MR drones were in activity during experiment 3.2.

7.2.2 Oil behaviour and VOC concentrations in air during and after release of TOF 3.2

The release of TOF 3.2 was done in a similar way as was done for the TOF 3.1 reference release. The TOF 3.2 slick was released about 1- 1.5 hour after the release of the TOF 3.1 slick, at a distance of about 0.5 nm to the NW, i.e. to the side of the 3.1 slick (see tracking of drifting buoys Figure 7-8). The sea state on June 14th during the release of the TOF 3.2 slick was very calm with no breaking waves and a significant wave height of ~ 0.5 m. The drift direction of the TOF 3.2 slick, and other slicks, was initially to the SW under the influence of the prevailing low speed NE wind.

However, as seen in Figure 7-8, the slick drift direction of the slicks changed to the NW from around 13:00 to 15:00 LT, due to the change in the tidal current direction, before the SW drift continued under the strengthening NE wind.

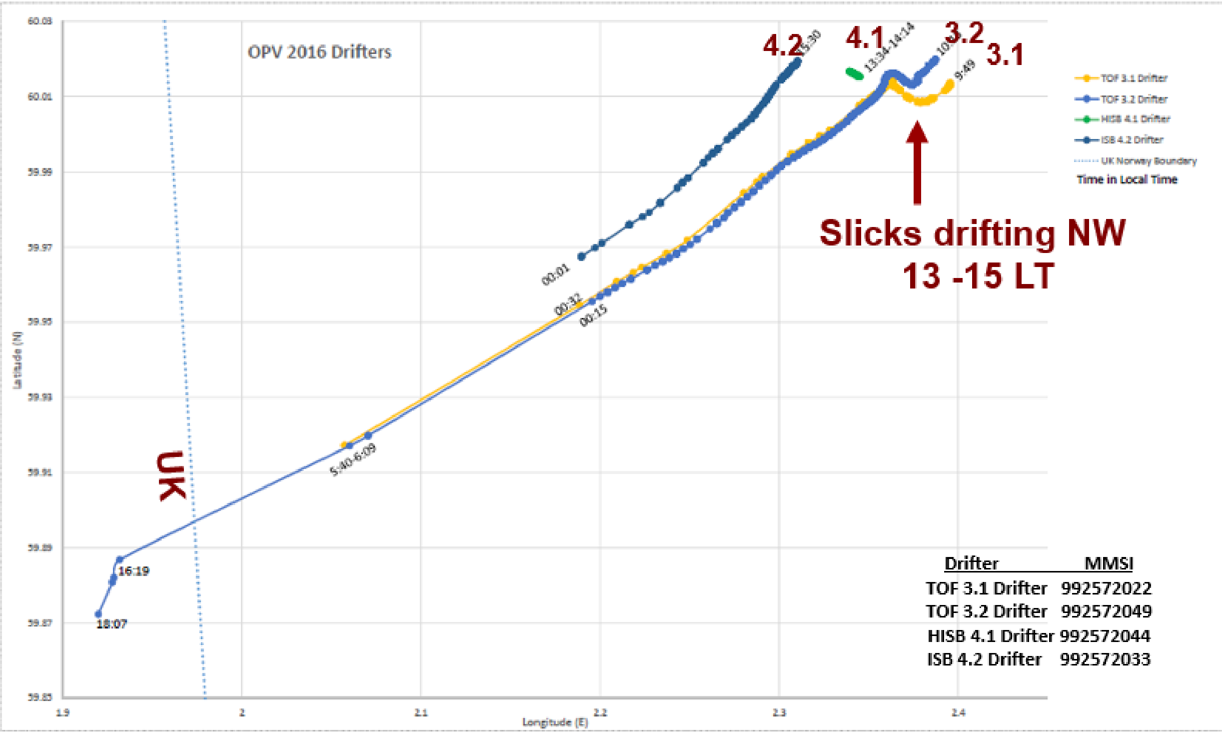


Figure 7-8 Overview of the tracking of drifting buoys released in the different slicks.

Figure ***7-9*** is a still from the Finish surveillance aircraft HDTV recording taken 5-10 min after the release from KV Sortland at 10:13 LT. The oil was released with a 40 - 45º deviation from the upwind direction. The red ellipse indicates the position of the released oil. The USV sampling boat with Ocean Eye (Aerostat) was performing air monitoring downwind to the slick, while MS Strilborg was moving from its position about 200 m downwind to the slick to an upwind position for preparation for the dispersant application.

Figure ***7-10*** is taken by the HDIR camera (FLIR) on the Finish remote sensing aircraft at 10:14 LT, one minute after the picture taken in Figure ***7-9***. The released oil behind KV Sortland is within the red ellipse. The image reveals that the high-resolution HDIR camera is able to detect the plume of VOCs that is evaporating from the slick and into the air, as indicated by the grey ellipse. The graph in Figure ***7-10*** shows the response of the photoionization (PID) detectors placed on the main deck on MS Strilborg, indicating a concentration of 50-100 ppm TVOC when the vessel travelled through the VOC plume at 10:14 LT. The green circle show the position of the USV- sampling boat with the Aerostat (hanging at 60-80 meter height).

The Figure ***7-11*** is a still image from the uncooled IR-video camera at the Aerostat, taken at the same time as the in Figure 7-10 (10:14 LT). This reveals that the uncooled IR camera is also easily able to detect the plume of 50-100 ppm VOC concentrations in the air. Such detection of VOC plume by IR has not previously been reported for releases of fresh crude oils from field trials.

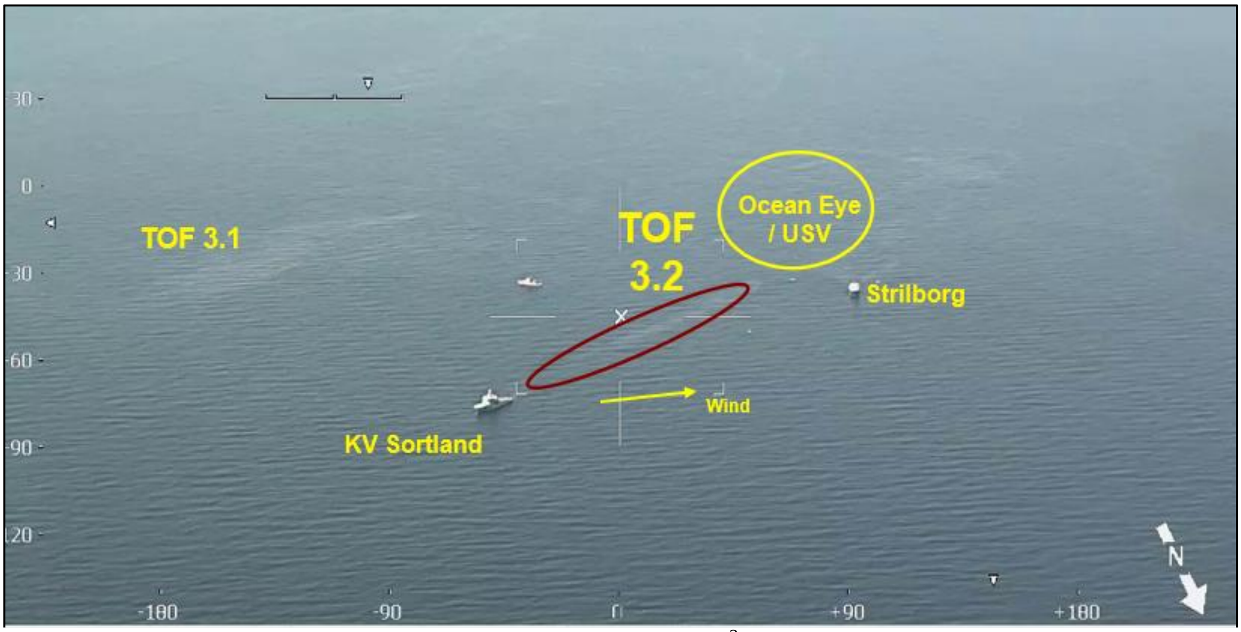


Figure 7-9 Overview picture taken 5-10 min after the 10 m^3 release of 3.2 (red circle) from KV Sortland (10:13, LT) (©Finnish Border Guard / SYKE).

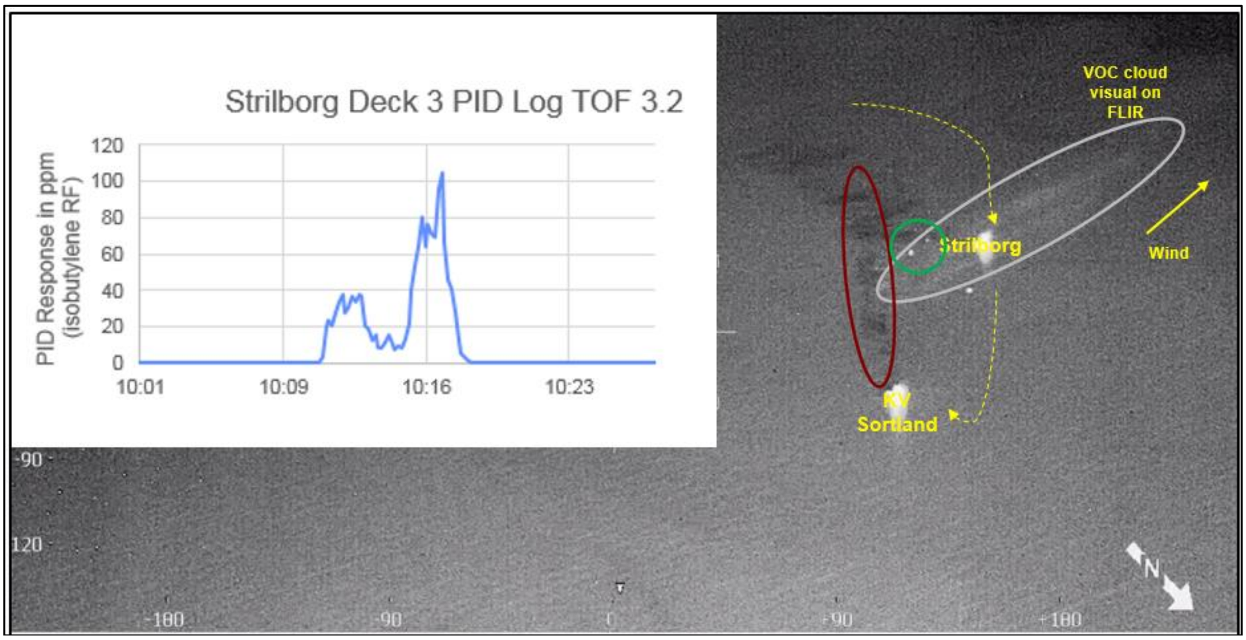


Figure 7-10 FLIR image 10:14 LT 5-10 min after release. The grey circle show the plume of volatiles that is evaporating to the air, 50-100 ppm TVOC measured by photoionization (PID) detectors placed on the main deck on MS Strilborg when the vessel travelling through the VOC plume at 10:14 LT. Green circle shows the position of USV wit Aerostat (Photo: ©Finnish Border Guard / SYKE).

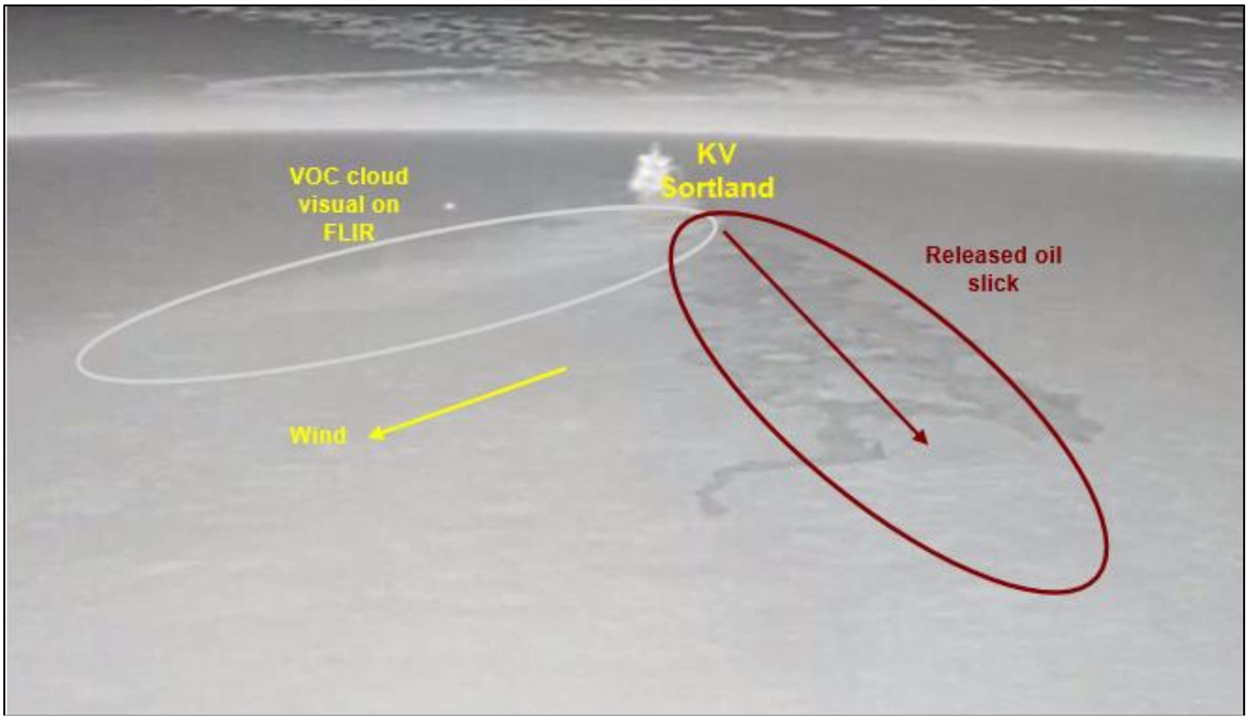


Figure 7-11 Image from IR camera on Aerostat (10:14 LT) (©Maritime Robotics, Ocean Eye).

7.2.3 Effect of dispersant treatment

Prior the dispersant application, MOB-B sampling boat conducted some surface sampling at 10:16 to 10:26 LT in the thickest patches (see also Appendix B):

Oil thickness:	1 - 3 mm (in the thickest area)
Evaporation:	approx. 25 %
Water uptake:	0 vol. %
Viscosity:	< 15 mPa.s

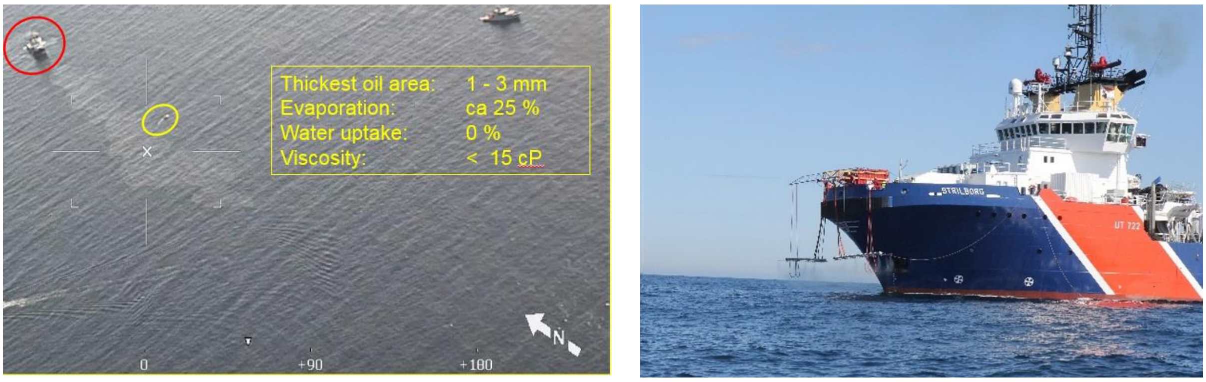


Figure 7-12 Left: Just prior MS Strilborg (red circle) initiated the dispersant application (10:26): Yellow circle: Sampling boat finished surface sampling (Photo: ©Finnish Border Guard / SYKE). Right: 10 28-10:51 (LT) low dosage application from MS Strilborg (Photo: SINTEF).

During the period 10:28 until 0:51 LT, 30 to 50 min after release, the TOF 3.2 slick was sprayed with dispersant using the container-based dispersant application system installed on MS Strilborg. The "low" dosage boom was used with an application rate of 30 L / min. The dispersant deposition swath width from MS Strilborg was 26 m. The vessel applied the dispersant at 6-8 knots.

Figure 7-13 is an operational table showing of effective dosage as a function of application speed. This table is a general table for crude oils based on general experience. The green/yellow colours the general optimal dosages for crude oils in general (DOR of 1:20 to 1:100). Orange colour indicate is the under- or over dosages based on experiences on general crude oils.

In the TOF 3.2 slick we assume an average thickness of 0.1 - 0.2 mm for the IR ‘black’ (cool) area within the slick, which gives a typical DOR of 1:20 - 1:50 (see green circle). For the thickest area of oil (IR ‘white’ (warm)) we assume an average thicknesses of 1-2 mm that corresponded to an effective dispersant-to-oil ratio (DOR) dosage in the range of 1:170 - 1:400, as indicated by the red circle in the application table in Figure 7-13.

	Oil thickness (mm)						
Application speed (knots)	0,1	0,2	0,5	1	2	3	4
1	1 : 3	1 : 6	1 : 14	1 : 28	1 : 55	1 : 83	1 : 110
2	1 : 6	1 : 11	1 : 28	1 : 55	1 : 110	1 : 165	1 : 220
3	1 : 8	1 : 17	1 : 41	1 : 83	1 : 165	1 : 248	1 : 330
4	1 : 11	1 : 22	1 : 55	1 : 110	1 : 220	1 : 330	1 : 440
5	1 : 14	1 : 28	1 : 69	1 : 138	1 : 275	1 : 413	1 : 550
6	1 : 17	1 : 33	1 : 83	1 : 165	1 : 330	1 : 495	1 : 660
7	1 : 19	1 : 39	1 : 96	1 : 193	1 : 385	1 : 578	1 : 770
8	1 : 22	1 : 44	1 : 110	1 : 220	1 : 440	1 : 660	1 : 880
9	1 : 25	1 : 50	1 : 124	1 : 248	1 : 495	1 : 743	1 : 990
10	1 : 28	1 : 55	1 : 138	1 : 275	1 : 550	1 : 825	1 : 1100

Figure 7-13 Application table showing the effective DOR as function of oil thickness and application speed. The table is for the low dosage dispersant system (30 L/min) and assuming an effective swath width of 26 m (which is the effective swath width for the dispersant application system when installed on MS Strilborg.

A total of 600 litres Dasic Slickgone NS (dispersant) was applied during four spray passes to cover the thickest (IR-detectable) part of the TOF 3.2 slick. Aircraft guided the application. At the start of the dispersant operation, the IR-detectable part (IR ‘white’ (warm) and IR ‘black’ (cool)) of the slick was about 700 m long by 60-80 m wide. Allowing for approximately 25% volume loss by evaporation, there would have been 7.5 m^3 oil in this area of 49,000 m^2 with an average oil layer thickness approximately 0.2 mm. This is within the intended oil layer thickness for the experiments. However, the oil was composed of two distinct areas of relatively thick oil (IR ‘white’ (warm)) and relatively thin oil (IR ‘black’ (cool)).

Figure 7-14 shows the IR-line scanner images during the first and second spray passes. Both sprays were applied with the wind direction. The first spray pass focused on the port side of the 50-80 m wide IR detectable thick oil. A significant area of thick oil (IR-white) was therefore not covered through this first pass. This can be seen both in Figure 7-14 A/B and Figure 7-15. During the next three passes with dispersant application at 10:39 to 10:51 (LT), the total area of thick oil was treated. By that time the slick had been spread out to a much thinner slick (only UV and IR 'black' (cool) with no IR 'white' (warm) remaining) to an total area of 800 m x 300 m slick, see Figure 7-19).

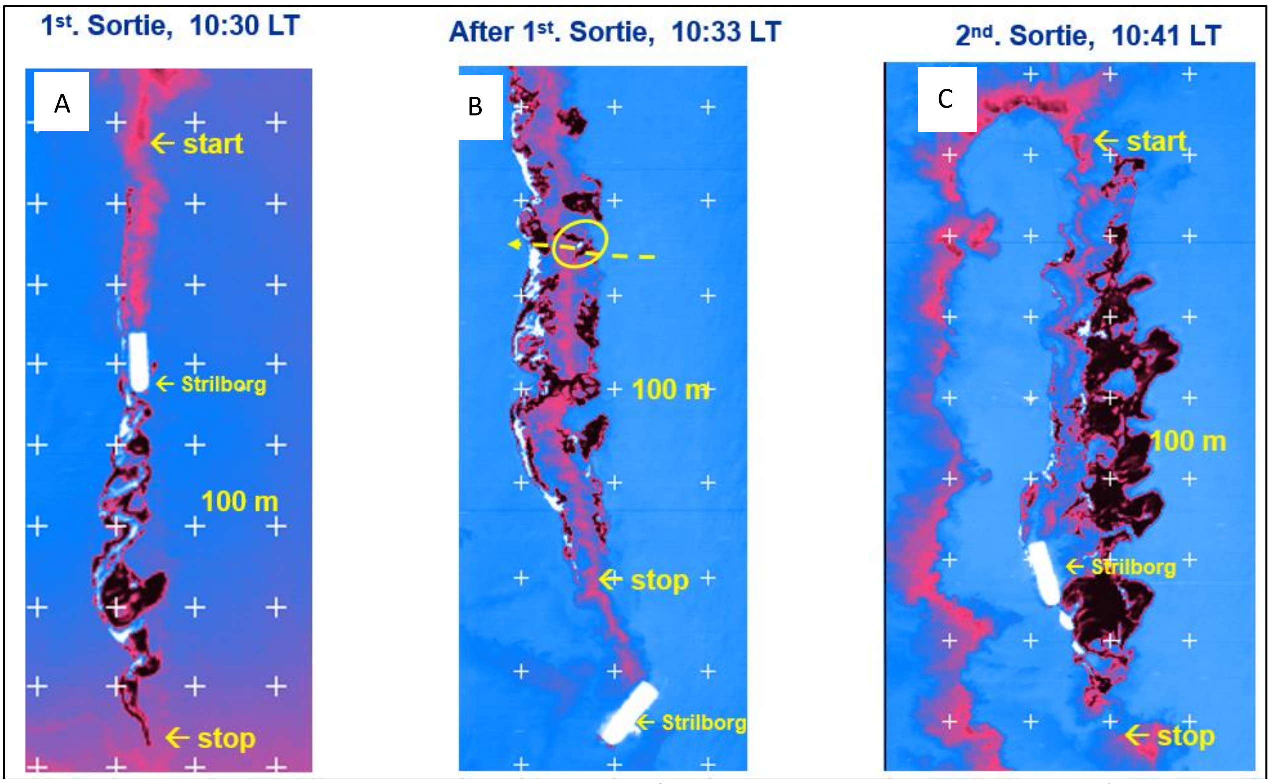


Figure 7-14 IR- line scanner images. A: During 1st sorties (10:30, LT), B: Just after 1st sortie. Yellow line/ circle shows the transect of sampling boat performing water column monitoring of dispersed oil concentrations and oil droplet size distribution. C: End of 2nd sorties (10:41 LT) (©Finnish Border Guard / SYKE).

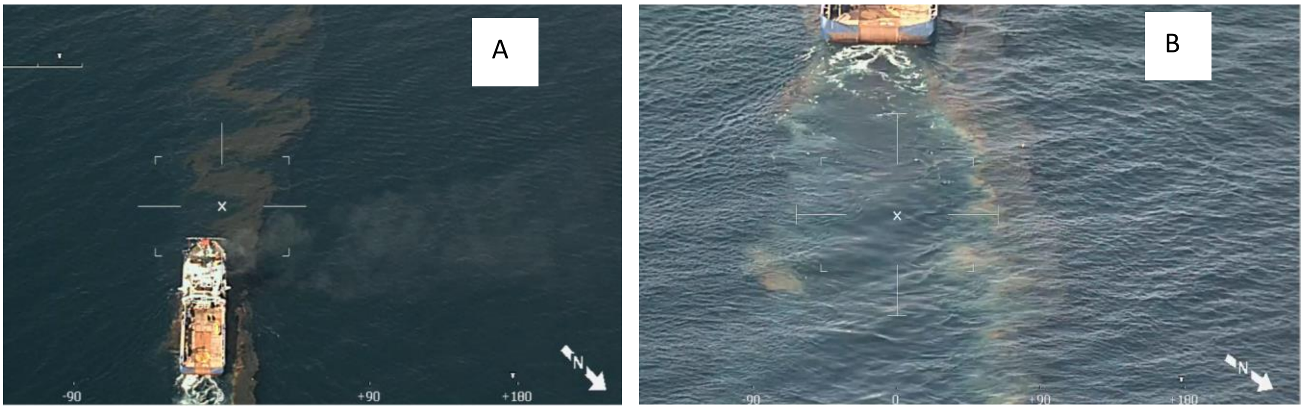


Figure 7-15 During 1st sortie of dispersant application by MS Strilborg (taken 10:30, LT) ©Finnish Border Guard / SYKE.

Figure 7-15 A shows the Continuous True Colour (CTC) area of thick untreated oil ahead of the vessel. Figure 7-15 B shows the significant effect of the dispersant treatment. The 26 m wide swath of thick oil treated with dispersant was rapidly dispersed as a light brown plume in the water column behind MS Strilborg. The immediate dispersion that take place is likely due to the dispersant being very easily mixed into the low viscosity oil (still below < 50 mPa.s), followed by the turbulence from the vessel passing through the slick at 6-8 knots.

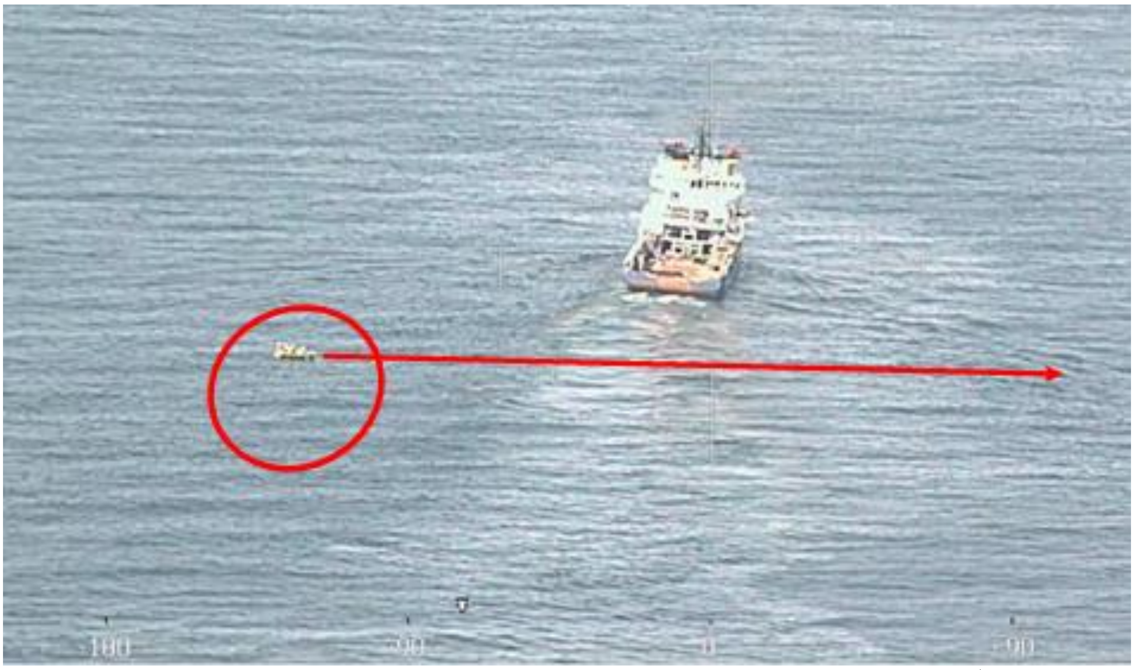


Figure 7-16 Transect 1 of water column monitoring across the slick after the 1st. pass of dispersant application by MS Strilborg (taken 10:31, LT) (©Finnish Border Guard / SYKE).

After the first spray pass through the slick, the MOB-B sampling boat with UVF / LISST conducted the first transect across the slick (illustrated in Figure 7-16). A total of three transects were conducted during and after the dispersant application. Figure 7.17 illustrates the response of oil concentrations measured by the LISST during these transects. The red line shows the total response (including both dispersed oil and air bubbles). The blue line represents the oil concentrations only by subtracting the air bubbles, mainly representing the particles > 200 µm. The response of dispersed oil by LISST has been calibrated to chemical analysis of water samples. The calibrated LISST data showed a typical concentration of 5-10 ppm (max. peak of 20 ppm) of dispersed oil (measured at 1 m. depth) in the dispersant treated area. This is in good agreement to previous experimental field trials with dispersant application of crude oil slicks with 2-4 mm emulsion thicknesses (e.g. Lichtenthaler and Daling, 1985, Lewis et al., 1995, Daling et al., 2002, Jensen et al., 2008).

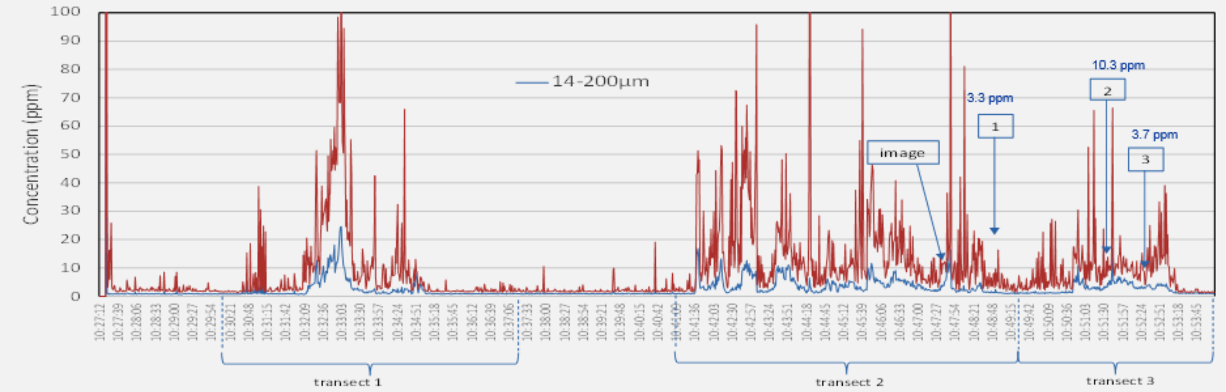


Figure 7-17 Summarizes the LISST documentation during the water column monitoring after dispersant treatment of slick 3.2 (10:30- 10:55, LT).

Figure 7-18 shows an overview of the dispersant treated area during the last spray pass, showing a significant effect of the overall dispersant treatment. A major part of the surface oil was dispersed into a light brown plume in the water column. The graph in Figure 7-18 shows examples of droplet size distribution by LISST measurements when transecting the area. The droplet size are mainly in the range 10-150 microns (vmd. 70-100 microns). This indicate that even a very low dispersant to oil ratio (likely in the range of DOR 1:50 - 1:300) for the thick area of IR-white oil is sufficient to effectively disperse the low-viscosity oil into very small oil droplets.

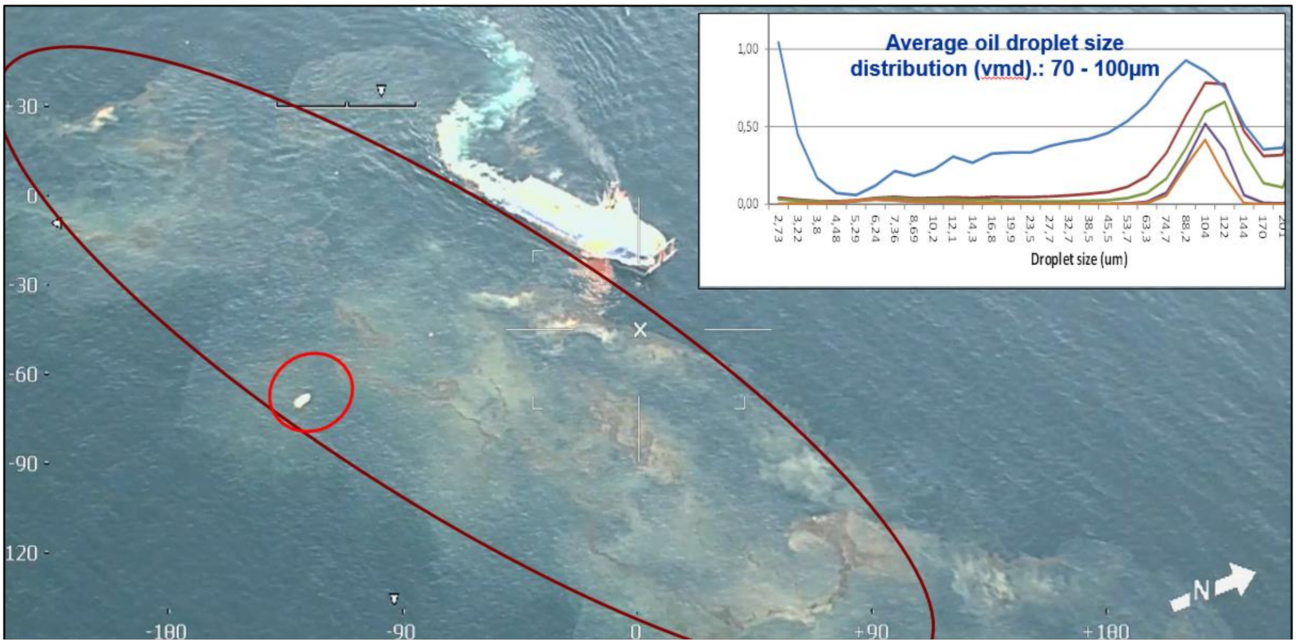


Figure 7-18 Overview picture of the dispersed area during the last (4th) application sortie (picture taken 10:45 LT). Significant effect of the dispersant treatment: Oil dispersed into light brown plumes in the water column (5 – 10 ppm dispersed oil at 1 m depth by sampling boat transects (red circle). The graph: Examples of oil droplet size distribution done by the LISST (©Finnish Border Guard / SYKE).

Still some IR-black oil are present after the dispersant treatment, see IR line scanner in Figure 7-19 and the FLIR images in Figure 7-7. However, no IR-white of thick oil remain in contrast to the situation for the TOF 3.1 experiment where the reference slick had characteristic bent bands of thick oil (IR-white) in the mm-range. The red circles very close to the vessel in Figure 7-19, show that the wake of temporary cold water from the vessel movement, may give a "false picture" of IR-black image. However, the UV image (Figure 7-19 B) reveals that there is no oil close to the vessel. This is important to take into account when treating the IR images. The IR-black area further away from ship is however oil.

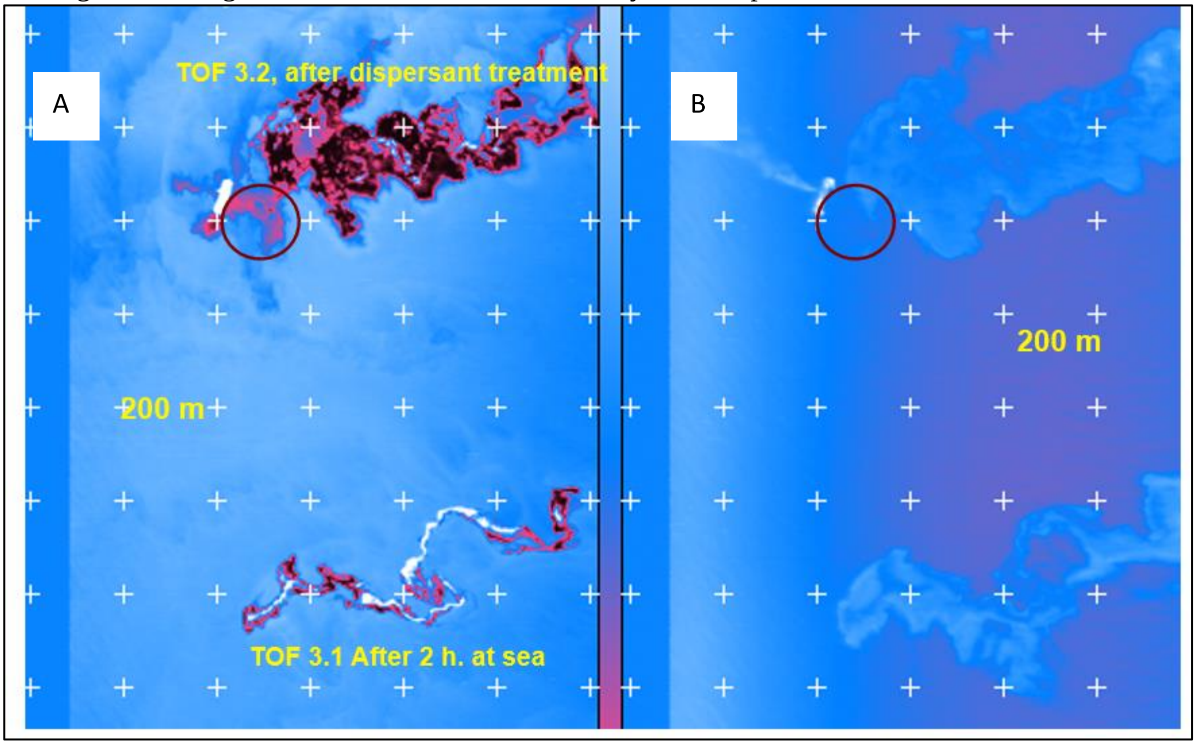


Figure 7-19 IR (A)/ UV (B) line scanning taken 11:02 (LT) document the significant effect after dispersant treatment (but prior the water flushing). Compared to non-treated TOF 3.1 reference slick with the characteristic "bending bands" of thick oil (©Finnish Border Guard / SYKE).

Conclusion

Comparison with the non-treated reference slick, the aerial and water-columns documentation of the low-dosage dispersant treatment show that the majority of the surface oil (IR-white area) was broken up and rapidly dispersed as small droplets into the water column. This show that a very low Dispersant-to-Oil ratio (DOR 1:300 - 1:400 for the thickest oil) was a sufficient dosage for this low-viscosity oil (< 50 mPa.s). Only a thin oil film (IR black and UV visible) remained after dispersant treatment.

7.2.4 Effect of high-capacity bow-boom water flushing

Due to the very calm sea state with no breaking waves, it was as planned decided to introduce artificial turbulence to the remaining thin oil film about 0.5-1 hour after the dispersant application. During the period from 11:05-12:00 (LT), MS Strilborg made several passes through the slick with high speed (10 knots). The high-capacity water flushing boom sprayed 9 m^3/ min. of seawater ahead of the bow-wave of the vessel (see Figure 7-20 A). Picture B in Figure 7-20 was taken from the starboard side of MS Strilborg during the water flushing, and shows the visual effect of the water flushing by generating of a light brown plume of dispersed oil into the water column. Unfortunately, there was no monitoring from sampling boats of oil concentrations and oil droplet size in the water column during this water flushing operation.

One operational experience with the water flushing bow-boom hanging 1 m above the sea surface was that on one occasion the boom dipped into the water during one of the turns with MS Strilborg in 10 knots speed. This bent one of the stays on the lifting boom. To avoid this from happening again, the water flushing booms were lifted up 1 m to 1.5 m height above the surface at the outer end on each boom. Subsequent studies / experiments in the SINTEF tower basin under similar water flushing conditions (using the same nozzles, water flow etc. as in the field trial) have shown that the change in boom height from 1 to 1.5 m was not critical for the dispersion effectiveness /oil droplet size (Leirvik, 2017).

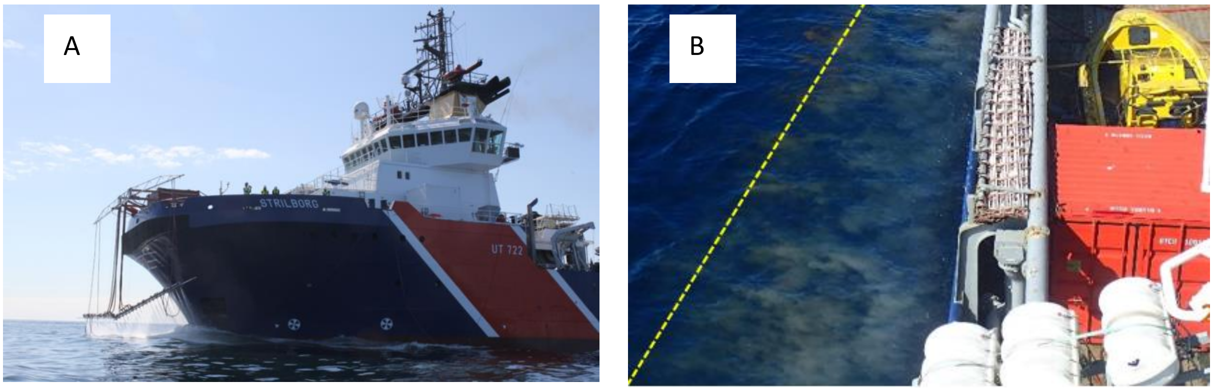


Figure 7-20 A: MS Strilborg using high volume water flushing, 0.5 - 1 h after dispersant treatment. B: Visual effect of the artificial turbulence water flushing; generating a "light brown plume" of dispersed oil along the side and behind the vessel (photo: SINTEF).

An IR / UV line scan image taken during the water flushing (Figure 7-21 taken 11:38, LT) shows that the TOF 3.2 slick was spread out into a thin oil film (no IR-white remaining) by the water flushing. The total slick area is about 1000 x 500 m wide. The TOF 3.1 reference slick (including band of IR-white) is approaching the 3.2 slick.

During the afternoon / evening surveillance aircraft and satellite SAR-images (e.g. RiaSat-1 19:15, LT, Figure 7-22) show that the reference slick TOF 3.1 had drifted into the remaining sheen of the TOF 3.2 slick because of change in slick drift direction due to tidal current. Total area of slick 3.1 and 3.2: approx. 0.5-1 x 4 km. The area with narrow bands with thick oil from slick TOF 3.1 is indicated by the red circles in Figure 7-22.

It is likely that the very thin sheen of slick TOF 3.2 left after the dispersant application and water flushing became totally dispersed during the night under breaking wave conditions. The patches of oil detected by the aircraft the next day most probably originated the bands /windrows with thick semi-solidified oil (IR white) left over from the TOF 3.1 reference slick.

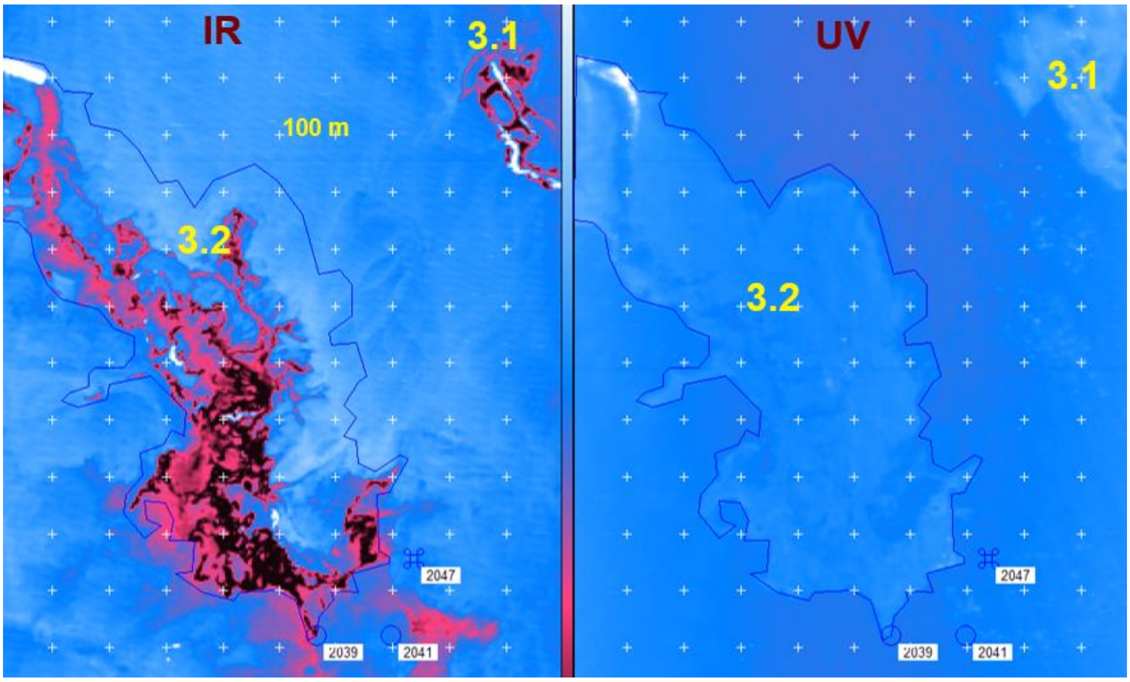


Figure 7-21 IR / UV line scanner image of slick 3.2 taken during water flushing (taken 11:38, LT) (©Finnish Border Guard / SYKE).

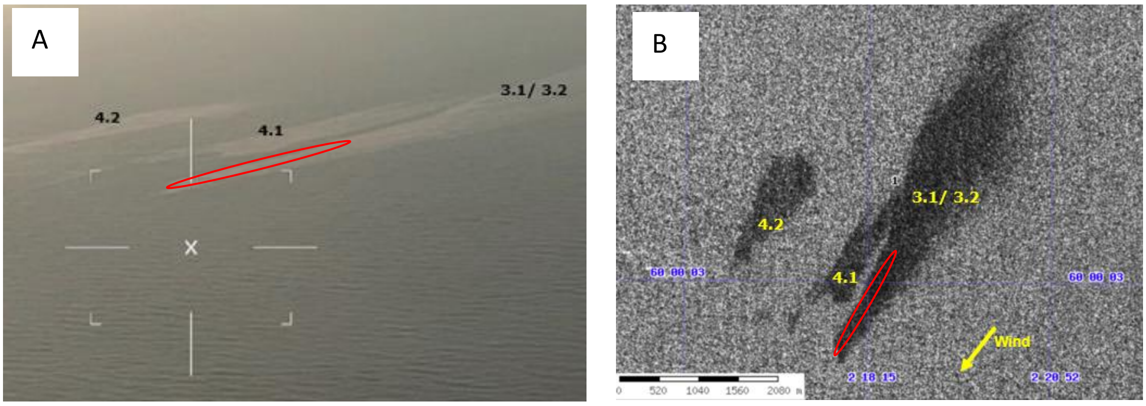


Figure 7-22 A: Overview photo of the test-site area taken 18:55 LT (©Finnish Border Guard / SYKE), and B: A similar satellite SAR image taken 19:15, LT (RiaSat-1). Slick 3.1 has drifted into the remaining sheen of the 3.2. Total area: 0.5-1 x 4 km.

Conclusion:
An overall positive experience was gained by combining low-dosage dispersant treatment followed by introducing artificial turbulence using the bow boom water flushing on Strilborg at high treatment rates (8 – 12 knots). This shows the potential for such an operative response strategy with high encounter rate to reduce the oil film lifetime from light crude oils /condensates under calm weather conditions, which again will reduce the potential risk for environmental damage like seabird fouling.

7.3 Experiment 3.3 – Reference slick in breaking waves treated with water flushing Fi Fi-monitors

The weather conditions on day 2 (June 15th) were very different from that on day 1. During the night, there had been windy conditions with breaking waves. At 06:00 (LT), the wind speed was 13 m/s, declining to 6-7 m/s at 10:00 (LT). NOFO therefore decided to follow "Plan B" ("Release criteria for breaking wave test conditions"), as described in the field plans (Daling and Sørheim, 2016) with the following two experiments:

i. Release 3.3: A "reference" slick of 10 m^3 Åsgard Blend with no initial treatment, focusing on the monitoring of VOC concentrations in the air and the spreading, distribution and behaviour of the surface oil by aerial surveillance and ground truth monitoring.
ii. Release 3.4: A follow-up release (2 hours after) of 10 m^3, Åsgard Blend, with treatment options (Fi-Fi monitors or dispersant treatment).

The first slick was released at 10:00 LT in accordance with the plan. However, spill trajectory modelling conducted during the morning indicated a slick drift in the SSW direction with risk for drifting into UK waters. The NOFO OSC decided at noon to cancel the second release, instead responding to the already released oil by using water flushing with the Fi-Fi monitor installed on MS Strilborg.

7.3.1 Overall Timeline for TOF 3.3 experiment

The conditions on June 15th during the release of slick TOF 3.3 were a 6-7 m/s wind from NNE, with breaking waves (significant wave height 1-1.5 m). The wind stayed constant during the day. At 16:00 LT, the wind was reported to be 8 m/s and still from NNE. Table 7-4 summarizes the timeline (based on the log) during release of experiment TOF 3.3.

Table 7-4 Timeline (log) of the release of experiment 3.3- Åsgard Blend reference with Fi-Fi treatment.

Time (LT)	**Activity**
09:58	MOB B/C and MOB- KV ("Sjøbjørn") in position, start air monitoring
09:58	Smoke signal
10:00 – 10:05	Releasing oil (10 m^3 of Åsgard Crude Blend).' Position: N60°00.30'E E002°23 (470 m long slick)
10:03	Release AIS buoy (MMSI 992572049)
10:05 – 10:50	Air monitoring in leading edge of the slick.
10:05	Air monitoring boat reporting: LEL signal (10% LEL) : Sampling boat is backing to about 80 m downwind to the front edge of the slick
10:23 – 11:00	Surface oil sampling (in the thickest areas within the slick)
11:30 – 12:30	New drifting trajectories performed. OSC decided not to release the last 3.4 slick, due to risk for drifting into UK sector. OSC decided to treat slick with Fi-Fi- monitors)
12:30 – 12:54:	Sampling surface oil / emulsion (in the thickest area of windrows with emulsion
12:55:	Start Fi-Fi monitor treatment. 1st. sorties with wind (8 -10 knots). Good treatment
13:05 – 14:00	2. Sortie – 4. Sortie with Fi-Fi: Slick spread over a larger area.
15:00 – 15:02	Dutch aircraft: reports 0.5 X 3 km.: 80% sheen, 15% metallic, 5 % DCTC : BAOAC: Min: 0.4 m^3 max: 5.2 m^3 emulsion (light brown colour)
18:00 – 18:02	Finnish aircraft: reports: still observation of small patches of DCTC. Decide to go for a final treatment with Fi-Fi on the remaining small patches of emulsion.
18:40 – 18:50	Fi-Fi monitor treatment. Difficult to find DCTC within the slick. Guided to area by Finnish aircraft. Good treatment. Finish: 18:50. No remaining visual oil

7.3.2 Oil behaviour after release

Figure 7-23 A is a still from the aerial video recording just after the release of TOF 3.3 from KV Sortland at 10:05 LT. Compared to day 1 (June 14th with a very low wind conditions), it was much easier to release the 10 m^3 of Åsgard Blend directly into the wind. The position of the air-sampling boat (red circle) was initially 50 m downwind to the front edge of the slick, calculated to be the location for maximum exposure to the VOCs evaporating from the oil (Johansen, 2016 B). A short time after starting the release, the explosimeters indicated 10% LEL. The photoionization detectors (PID) measured a concentration of TVOC in the range of 500 ppm at that time. The air monitoring sampling boat (MOB-KV) was therefore according to the HSE-plans moved to a position 80-100 m downwind to the front edge of the slick (see Figure 7-23B). The PID concentrations were in the range 300-500 ppm TVOC throughout the 30 min. of air monitoring after the release (paper by Gjesteland et al., 2017, in preparation).

About 15-30 min. after release surface sampling boat (green circle in Figure 7-23 B took oil samples and several PAD oil thickness measurements within the slick (10:15-10:30, LT, Appendix B), giving the following properties:

- Thickness: approx. 0.5 mm (span 0.4 - 1.2 mm)
- Water content: 20 - 25 % water entrained in the oil (unstable)
- Viscosity: < 100 mPa.s (measured at shear 10s^{-1})
- Evaporative loss: approx. 33 wt.% (based on GC-FID (post-analysis))

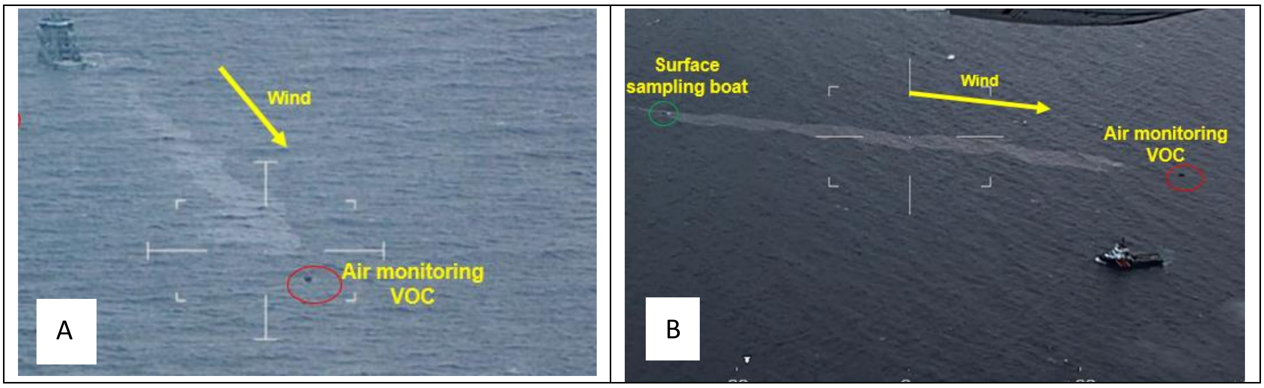


Figure 7-23 A: 10:05 (LT) Just after release stopped. Air monitoring ca 50 m down-wind to slick front (red circle) B: 10:10 (LT): Photo: LN-KYV

After about 3 hours after release of TOF 3.3, just prior the Fi-Fi water flushing operations, surface sampling was carried out at 12:45 to 12:55 (LT), primarily in the narrow windrows/band of emulsified oil (see Figure 7-24). The following properties were measured:

- Thickness: approx. 1.5 mm
- Water content: 60 - 80 % water / "loose" emulsion with a light brown colour
- Viscosity: 330 mPa.s (measured at shear 10s^{-1})
- Evaporative loss: approx. 50 wt.% (based on GC-FID (post-analysis))

Figure 7-24 shows the bands of loose emulsion surrounded by area of primarily "Sheen and Metallic", i.e. oil film thickness < 50 micron (BAOAC).

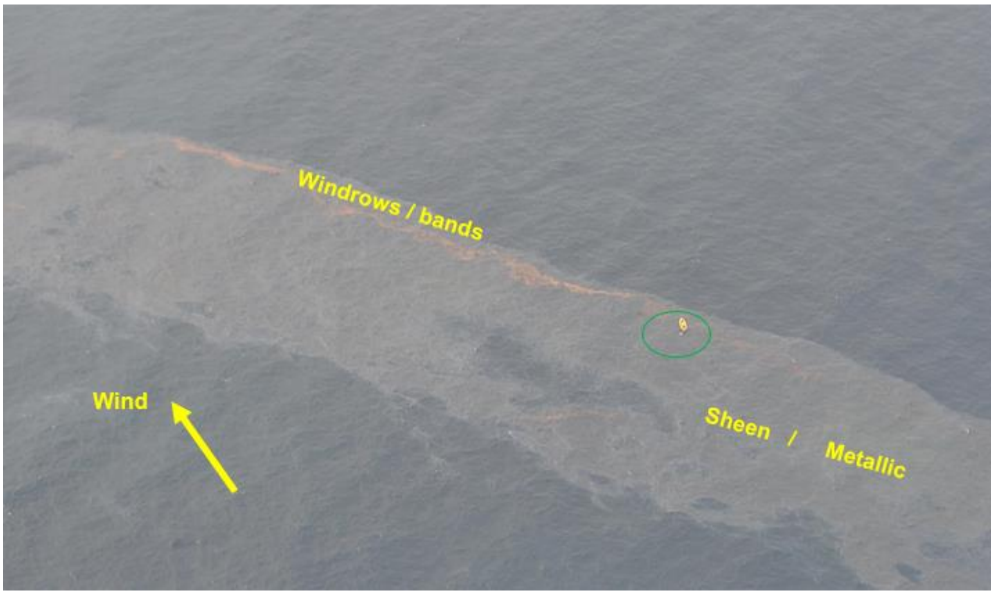


Figure 7-24 Bands of loose emulsion (1-2 mm thick) surrounded by a thin oil film of primarily "Sheen" and "Metallic" (i.e. < 50 micron, BAOAC) in experiment TOF 3.3 (13:14 LT), (©Finnish Border Guard / SYKE).

7.3.3 Effect of water flushing using Fi-Fi monitors

In the period between 12:55 and 14:00 LT (i.e. 3-4 h after the release), four sorties of water flushing were performed using the starboard Fi-Fi monitor on Strilborg (see Figure 7-25). The water delivery capacity of the Fi-Fi monitor was 3600 m^3/ h (1 m^3 seawater / second). The vessel speed during the treatment was 8-12 knots. The deposition area from the monitor was 30-60 m from the side of the vessel. The effective deposition area of the water jet on the sea surface was a diameter of about 10 m. The deflector ("knife") installed on the monitor for splitting the water jet, was also tested. This gave a much wider distribution of the water, but at the same time a far less turbulence/energy. The main water flushing was therefore performed without the deflector.

Figure 7-25 Water flushing using SB Fi-Fi monitor on MS Strilborg. Drone video by Maritime Robotics (A) and ©Finnish Border Guard / SYKE (B).

Figure 7-26 illustrates the effect of Fi-Fi water flushing on the surface of the thin oil film. Both the still photo (A) and the IR/UV-line scanner image (B/C) are taken at 13:20 LT, during the second sortie. Figure 7-26 A shows how the thin oil film (primarily metallic, i.e. < 50 µm in the BAOAC categorisation) was broken up by the impact of Fi-Fi water flushing in combination with the turbulence generated by the vessel itself at 8-

12 knots. The IR/ UV line scan images show clearly that the thin oil film was totally broken up within the treated area (see yellow circle).

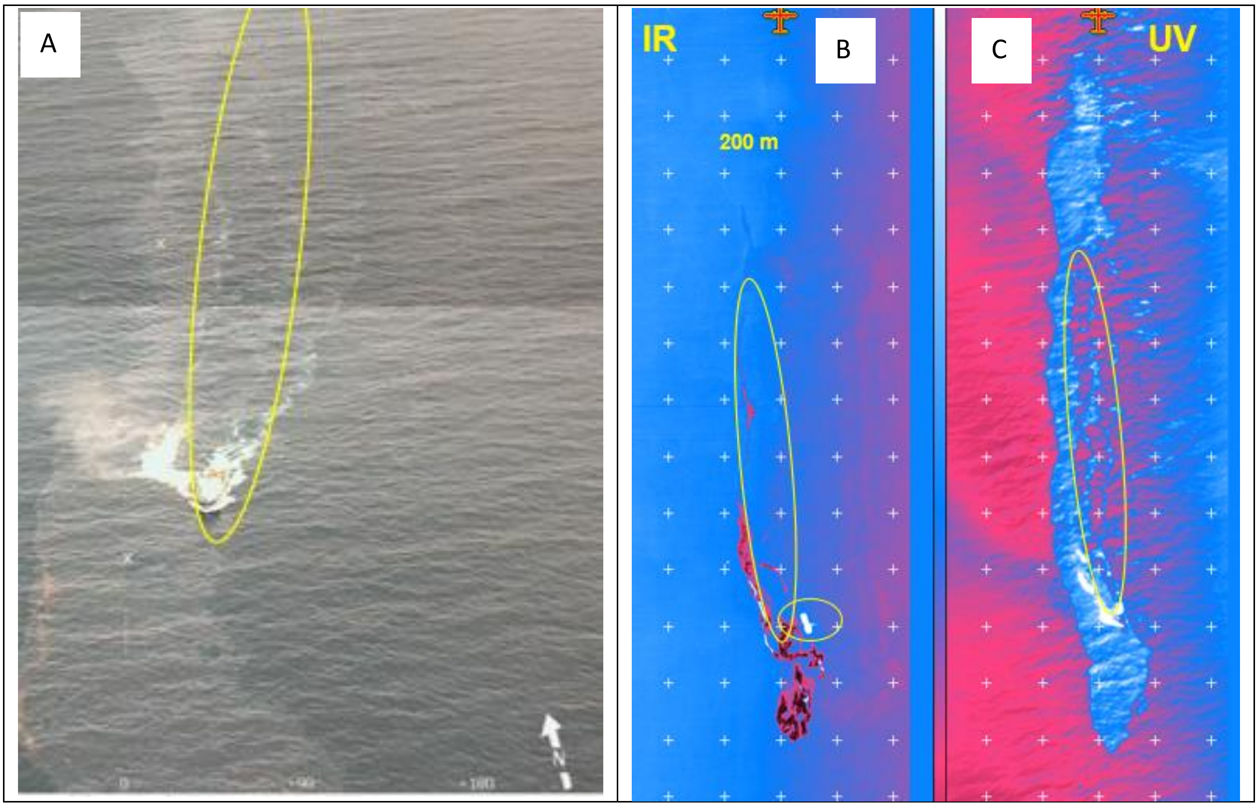


Figure 7-26 *Effect of Fi-Fi monitor treatment on area with thin oil film (Metallic-BAOAC / IR-Black) during the 2nd sortie (taken 13:20, LT). A: Still photo from aircraft video. B/C: IR/UV-line scanner image (also at 13:20, LT). (©Finnish Border Guard / SYKE).*

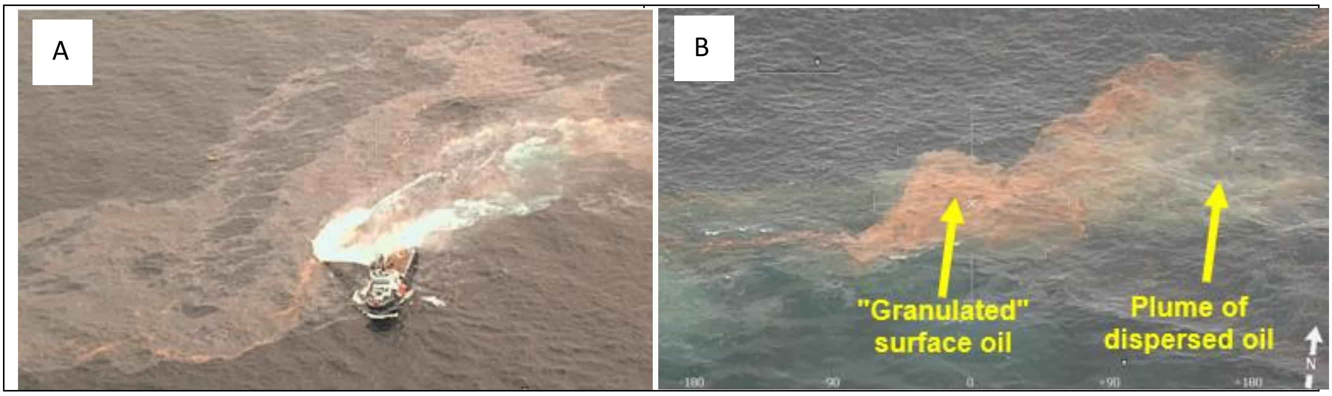


Figure 7-27 A: *Example from the Fi-Fi water flushing on windrows / band of "loose" emulsified, thick oil. B: After water flushing: The windrows / bands become more "granulated" on the surface, and creation of a light brown plume of dispersed oil in the water (13:13 – 13:38 LT). (©Finnish Border Guard / SYKE).*

Figure 7-27 shows the effect of the Fi-Fi water flushing on the band/windrows of "loose" emulsified oil with film thicknesses around 1.5 mm and viscosity of approx. 330 mPa.s (at shear $10s^{-1}$). The narrow bands of this relatively thick and semi-solid oil residue where broken up by the impact of water flushing from the Fi-Fi monitors into small pieces, or granules. Additionally, light brown plumes of dispersed oil was also generated as shown in Figure 7-27 B.

The two IR line scan images in Figure 7-28 illustrate the overall effect of the Fi-Fi water flushing. Figure 7-28 A shows the situation in an early phase in the water flushing at 13:20 LT, with the presence of windrows of thick oil. Figure 7-28 B shows the same slick 23 min. later at 13:43 (LT) after the Fi-Fi treatment with no significant areas of thick oil (IR ‘white’ (warm)) remaining. Only a few small patches of thick oil were reported (see log in Table 7-4). The TOF 3.3 slick was converted to only a thin oil film that was detectable only in UV and as IR ‘black’ (cool). Such thin oil films are much more easily broken up and naturally dispersed from the surface by the prevailing wave action compared to bands/windrows of much thicker oil.

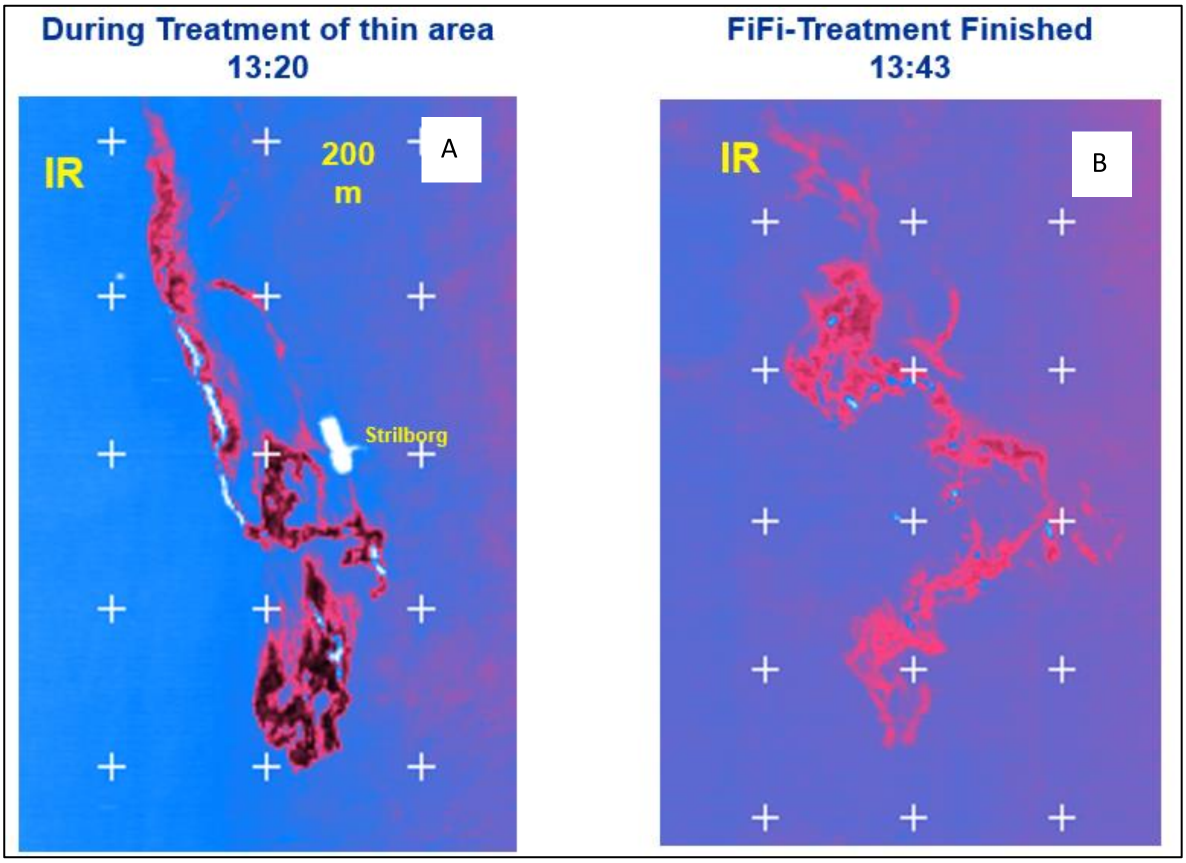


Figure 7-28 IR-line scanning images demonstrate the effect of Fi-Fi water flushing of the TOF 3.3 slick. A: In an early phase of the water flushing (13:29 LT). B: Slick 25 min. later (13:43, LT).

After each sortie with Fi-Fi water flushing, the MOB-B boat with the LISST instrumentation performed transects across the slick. Figure 7-29 A summarizes the oil concentrations measured by the LISST during these transects.

In the same way as for the dispersant treatment in slick TOF 3.2, the red line in Figure 7-29 A shows the total response (including both mechanically dispersed oil and air bubbles) produced by the Fi-Fi treatment on the TOF 3.3 slick. The blue line in the same figure represents the oil concentrations by subtracting the air bubbles, mainly representing the particles > 200 µm. The response of dispersed oil by LISST has been calibrated to chemical analysis of water samples (Figure 7-30). Calibrated LISST data shows typical concentrations of 10 to 30 ppm of dispersed oil in the area treated with Fi-Fi water flushing.

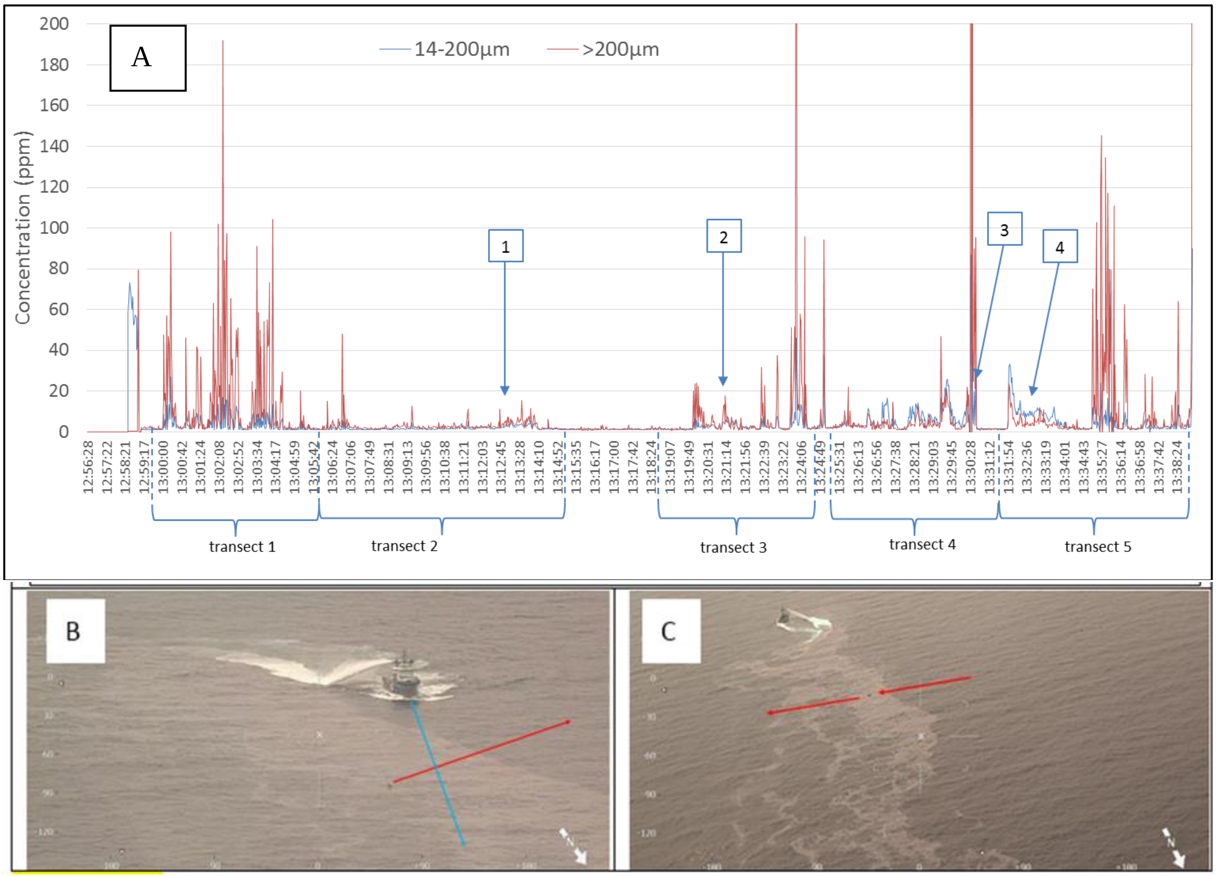


Figure 7-29 A: Summarizes the response of oil concentrations by the LISST from transects. B: Photo showing from the transect 4 by the MOB-B, and C: from transect 5 after the 3rd. sortie with Fi-Fi treatment (©Finnish Border Guard / SYKE).

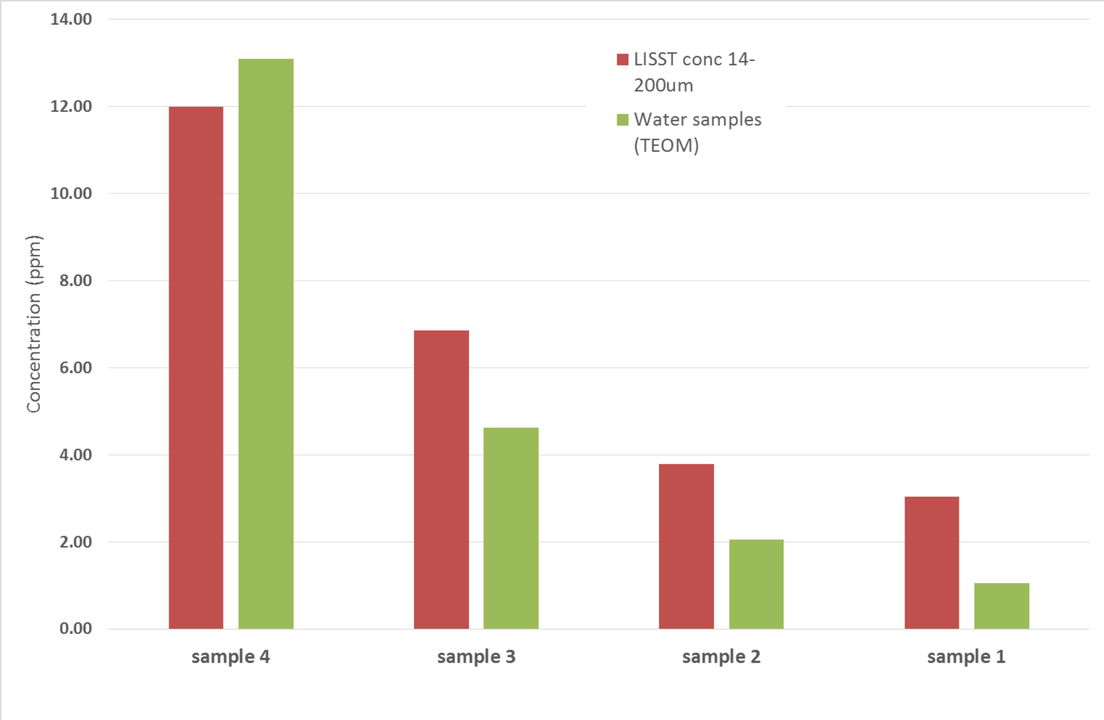


Figure 7-30 Correlations between oil concentrations (TEOM) quantified in water samples with corresponding concentrations of particles < 200 µm measured by the LISST.

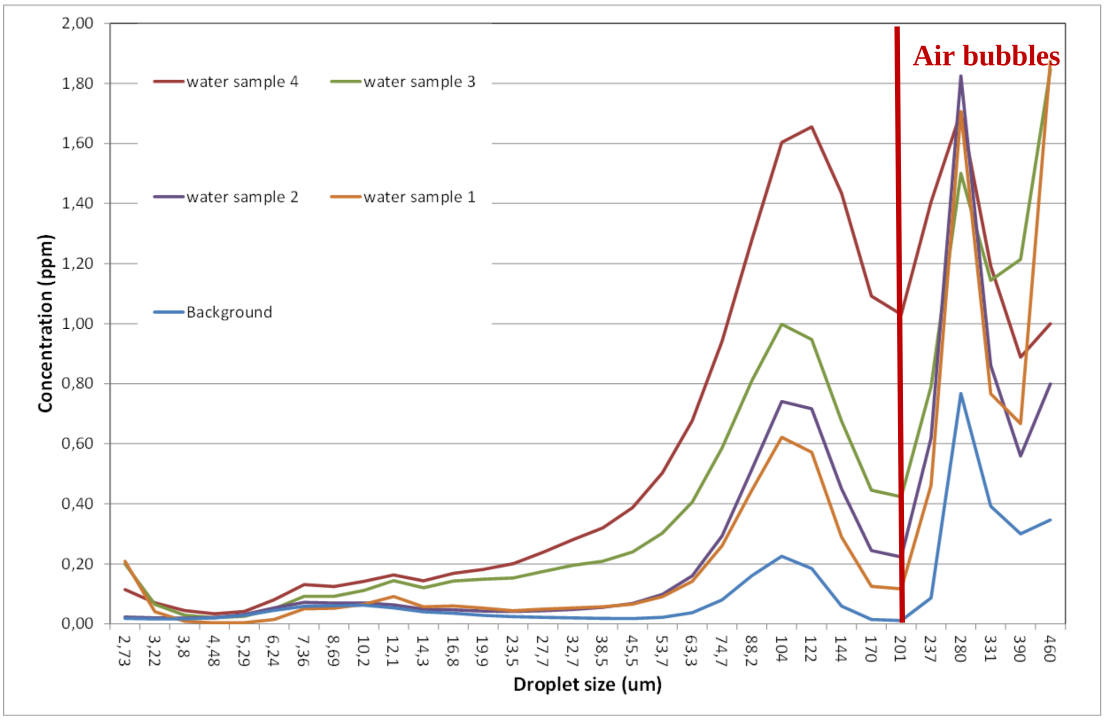


Figure 7-31 Examples of droplet size distribution of mechanically dispersed oil droplets after Fi-Fi-flushing.

The droplet size distribution (Figure 7-31) is in the region from 30 to 200 µm, with a volume median diameter (vmd) of 100 to 120 µm. The vmd of the droplet size distributions generated by the Fi-Fi water flushing is slightly larger than the vmd generated by low dosage dispersant treatment of the TOF 3.2 slick.

Experimental water flushing nozzle testing in the SINTEF tower basin and model predictions of oil droplets size distribution of mechanically dispersed oil generated by water flushing (part of the Oljevern 2015 project, Leirvik, 2017), have shown that the generated oil droplet size depends on the viscosity of the oil. Calculations based on the "modified Weber-approach" (Johansen et al., 2013) indicate that in order to get a vmd of less than 70-100 µm then the viscosity of the oil should preferably be less than 50-100 mPa.s (at shear rate 1000 s^{-1}). This corresponds approximately to a viscosity of less than 150-300 mPa.s when measured at shear rate 10 s^{-1}. The viscosity of the "loose" emulsion from slick TOF 3.3 just prior the Fi-Fi water flushing was 330 mPa.s at shear 10 s^{-1}. The viscosity was therefore slightly higher than the estimated upper viscosity limit to produce a vmd less than 100 µm for optimal water flushing.

Conclusion:
The overall experience with the Fi-Fi water flushing in experiment TOF 3.3 was promising, but the concept was not tested under the most optimal conditions for such response strategy. The original plan for testing the Fi-Fi concept was to perform the treatment within 1-1.5 hour after release i.e. before the oil residue had become too weathered / emulsified and reached too high viscosity. The decision to treat the slick 3-4 hours after the release was therefore not an optimal timing. However, the Fi-Fi treatment clearly demonstrated the potential for reducing the lifetime on the sea surface with release of Åsgard Blend. This was evident both on the granular appearance of the weathered and emulsified residue with viscosity of around 330 mPa.s (shear $10s^{-1}$) that remained in the bands of relatively thick oil, and by the documented plumes of mechanically dispersed oil droplets into the water column. This testing indicated that the operative "time window" after release for effective water flushing using Fi-Fi monitors is relatively short to ensure low viscosities of the weathered oil / condensate residue.

Recent laboratory experimental studies using the Åsgard Blend in combination with theoretical considerations (Leirvik et al., 2017, Johansen et al., 2013) have shown that water flushing can effectively break up low viscous oils (less than 150 to 250 mPa.s) or before the oil has started to form non-Newtonian (semi-solid) behaviour. If the water flushing of the TOF 3.3 slick had been carried out within the original planned timeline of 1-1.5 hours after the release, the oil (emulsion) viscosity, according to the oil weathering prediction (OWM), would have been in the viscosity area of 150 to 200 mPa.s. Model predictions (Leirvik, 2017) show that such viscosities would give oil droplet size in the range of 70-100 µm (vmd.) when using mechanical dispersion with Fi-Fi water flushing.

7.4 Human Exposure

Real-time air measurements. The concentration of TVOC was high immediately after release of oil, but rapidly decreased to zero within the first hour. The concentration was highest in the MOB boats working close to the oil slick. Compared to the heavy Grane crude oil (released in connection to the herder/ in-situ burning experiments), the Åsgard Blend slicks yielded five times higher concentration of TVOC in the air in the sampling boats when operating close downwind to the slick after release. However, the concentrations rapidly declined to within 30 min after release of oil, and close to zero within the first hour

Personal air measurements. Personal exposure to benzene was highest for participants in the MOB boats working close to the oil slick where the exposure level for some participants was close to the Norwegian limit value. Thus, this exposure was high enough to require protective measures. The exposure on the two response vessels was equivalent to background levels of benzene.

Biological measurements. The urine samples confirmed that the protective equipment (3M half-mask 4255 and nitrile gloves) used during the releases works well to prevent uptake of benzene. In the MOB boats, the few participants (5) who did not use masks had some uptake of benzene in their body.

Based on these findings, a recommendation for oil spill personnel responding to instant surface releases of light crude oils / condensates is therefore not to initiate respond the first 0.5 -1 hour after release to allow for evaporation. For continuously releases, the response area should take height for a drifting time of > 0.5 -1 hour, i.e. typically 0.5 - 1 km downwind to the release source. Personal protective equipment (gloves and mask) is strongly recommended for oil spill personnel operating close to the slick. For more detailed results see paper by Gjesteland et al., 2017.

8 Conclusion and Recommendations

The following conclusions were made from the field experiments

Three experimental releases of 10 m^3 of Åsgard Blend were placed onto the sea surface in the planned way to produce long, narrow slicks with an average oil layer thickness in the range of approximately 0.2 mm to 0.5 mm. The initial spreading behaviour of the oil was in accordance with the modelled spreading behaviour. The experiments of Åsgard Blend were released as followed:

- TOF 3.1: Reference slick without any response treatment (day 1, non-breaking waves)
- TOF 3.2:Release and slick treatment with low dosage dispersant followed by high-capacity bow boom water flushing (day 1, non-breaking waves)
- TOF 3.3:Reference slick (day 2, breaking waves) – treatment with water flushing from Fi-Fi monitors 3-4 hours after release

In the conditions of very low wind speed and no breaking waves that prevailed during the oil releases of the TOF 3.1 and TOF 3.2 slicks, the oil remained as long narrow slicks. A small area of sheen spread out from the periphery of the released oil, but this had a minimal effect on the overall average oil layer thickness. The average oil layer thickness then decreased by approximately 25 to 35% in the 30 minutes to 1 hour after release as the more volatile components evaporated into the air. The evaporative loss of the volatile components caused the oil remaining on the sea surface to increase in viscosity. The pour point of the oil residue increased to approach and eventually exceed the prevailing sea temperature. The flow behaviour of the oil on the sea became increasingly non-Newtonian and the oil gradually became semi-solid.

<u>Air monitoring and human exposure</u>

The content of volatile components in Åsgard Blend is representative for many of the light crude oils and condensates produced and transported on the Norwegian Continental Shelf. The plumes of volatile organic components (VOCs) evaporating from the oil slicks and into the air were visible to the IR cameras in the surveillance aircraft and on the Aerostat at TVOC (total VOC) concentrations in the air were measured to be 50-100 ppm using a PID-instruments.

The measurements show that there is a real exposure to benzene close to a bulk spill of light crude oil at sea. Personal protective equipment (gloves and mask) is therefore recommended for cleanup work close to the oil slick. The mask must be stored in an airtight place before and after exposure.

Based on these findings, a recommendation for oil spill personnel responding to instant surface releases of light crude oils / condensates is therefore not to initiate response the fist 0.5 -1 hour after release to allow for evaporation. For continuously releases, the response area should take height for a drifting time of > 0.5 -1 hour, i.e. typically 0.5 - 1 km downwind to the release source. For continuous spill, the exposure time may be longer. The recommendation does not apply for the shoreline response operations

<u>TOF 3.1 Slick without any response treatment</u>: The oil remaining in the TOF 3.1 reference slick was not a thin oil layer of even thickness. The oil was distributed over the first hour after release into two distinct areas:

- Narrow bands of thick oil approximately 1-2 mm was observable in the IR images as IR 'white' (warm). This was formed from the original narrow strip of oil that was laid down from KV Sortland. This narrow band of oil contained approximately 80% of the total oil volume that remained on the sea.

- A larger surrounding area of relatively thin oil approximately 0.1 mm thick or less that was observable in the IR images as IR 'black' (cool). This area was formed by a limited amount of spreading of the oil. The area of relatively thin oil contained approximately 20% of the total oil volume.

The narrow band of relatively thick oil area in the TOF 3.1 slick did not spread further, instead remaining of broadly constant area, the shape of which was distorted by the effects of the low speed winds and the currents in the hours after release. Over time, the remaining residue of oil became semi-solid. The relatively thin oil area spread out somewhat further with time and appeared to produce an increasing area of sheen with time. Under the calms sea conditions, the areas of thick and thin oil in the TOF 3.1 slick persisted into the late afternoon. During the evening, the wind speed increased to 5 m/s and became 14 - 15 m/s overnight. The patches of oil detected by the aircraft the next day most probably originated from bands /windrows with thick semi-solidified oil (IR white) left over from the TOF 3.1 reference slick. These remnants were judged to be non-combatable.

TOF 3.2 Slick treatment with low dosage dispersant and high-capacity bow-boom water flushing: The initial behaviour of the TOF 3.2 slick was very similar to that of the TOF 3.1 reference slick until it was sprayed with dispersant, starting 20 minutes after the release had ended. Dispersant spraying with four spray passes took 23 minutes. The span in slick thickness resulted in estimated DORs (Dispersant to Oil Ratio) between of 1:20- 1:400 that showed to be effective. Dispersed oil concentrations at one metre depth were 10 to 20 ppm and the dispersed oil droplets size diameters were around 70 to 100 µm. Because of the very calm conditions, the dispersant-treated oil remaining on the sea surface was then subjected to 9 m^3/min of water sprayed from the high-capacity boom from MS Strilborg moving through the TOF 3.2 slick at 10 knots. This added turbulence spread the remaining oil out into a larger area of relatively thin oil and contributed to further dispersion of the oil into the water column.

The high-capacity water flushing bow-boom system was not tested on the TOF 3.2 slick as a stand-alone / independent treatment. However, after the field testing more fundamental follow-up laboratory basin experiments have been carried out as a part of the Oljevern 2015 project using low-weathered Åsgard Blend oil and similar nozzles and test conditions as in the field. These high-capacity water flushing experiments in combination with theoretical considerations have shown a clear potential to disperse the oil into small oil droplets (< 70 -100 µm) for being an effective response method for low viscous oils (< 150 – 250 mPa.s).

TOF 3.3 Slick treatment with water flushing from Fi-Fi monitors: The TOF 3.3 slick was released in slightly rougher sea conditions with a wind speed of 6-7 m/s. The Åsgard Blend was weathered on the sea surface for 3-4 hours longer, than originally planned before the treatment. The oil had started to emulsify in the areas of relatively thick oil and the viscosity had risen to about 330 mPa.s, which is higher than optimal for the maximum effectiveness of water flushing. The narrow bands of relatively thick 'loose' emulsion where broken up by the impact of 3600 m^3/ hour (1 m^3 / minute) of water from the Fi-Fi into small pieces, or granules. The intensive water flushing caused the oil to be spread out as a larger area of relatively thin oil. Light-brown plumes of dispersed oil in the water column were visible and the concentration of dispersed oil in the water column in transects made 10-15 min. after the water flushing was measured to be 10-30 ppm with dispersed oil droplets diameters of 100-120 microns. The experiment indicated that the operational time-window for water flushing using Fi-Fi monitors might be relatively short with this type of oil. This technique will become less effective if the viscosity of the oil has become too high (> 150 to 250 mPa.s) or if the oil has started to solidify.

Recommendations and suggested further documentation

Findings from such field trials may be valuable input in optimizing response strategies during real spill incidents from such oil spill, and showing the importance for combining different monitor platforms and sensor to get an overview of a spill situation. Extensive experimental data were gained through this field trial using the Åsgard Blend light crude / condensate. However, the planned test program was not entirely accomplished for various reasons. There is still the potential for extending the documentation of the fate and behaviour of different condensates, light crude oils or light refined products. Further documentation could be obtained by:

- Laboratory experiments
    - Extend the test matrix for water-flushing with the test method designed during the Oljevern 2015. Testing a larger range of oils and weathering degrees with a wider variation in viscosity would establish more robust and fundamental documentation as a basis for estimating the precise time-window for water-flushing
- Field-testing
    - Field-testing (in 2017): Use existing offshore oil production sites where, during periods with calm weather, areas of thin oil on the sea surface are formed due to produced water discharge. These areas could be used to systematically test the operative aspects of Fi-Fi and the high-capacity water flow boom use. Such tests would need to be planned and accomplished in close cooperation with remote sensing aircraft.
    - Field testing (in 2018): The promising demonstration of the of these response concepts during the 2016 NOFO OOW field trial should be extended at the future NOFO OOW trials planned for 2018. It is recommended that similar experiments be conducted, but using less persistent condensates or a surrogate such as a marine gas oil.

9 References

Brakstad O.G., P.S Daling, L-G Faksness, I.K Almås, S-H Vang, L. Syslak, F. Leirvik, "Depletion and biodegradation of hydrocarbons in dispersions and emulsions of the Macondo 252 oil generated in an oil-on-seawater mesocosm flume basin", *Marine Pollution Bulletin*, 84, pp. 125-134, 2014

Brakstad O.G, T. Nordtug and M. Throne-Holst, Biodegradation of dispersed Macondo oil in seawater at low temperature and different oil droplet sizes", *Marine Pollution Bulletin,* 93, pp. 144-152, 2015.

Daling, P. S., P.J Brandvik, D. Mackay and Ø. Johansen, "Characterisation of crude oils for environmental purposes", *Oil & Chemical Pollution* 7, pp. 199-224, 1990.

Daling, P.S., Mackay, D., Mackay, V., Brandvik, P.J, "Droplet size distribution in chemical dispersion of oil spills: Towards a mathematical model", *Oil and Chemical Pollution* 7, pp.173-198, 1990/91.

Daling, P.S. and T. Strøm, "Weathering of Oils at Sea: Model/Field Data Comparisons", *Spill Science and Technology Bulletin,* Vol. 5, no. 1, pp. 63-74, 1999.

Daling, P.S., I. Singsaas, M. Reed and O. Hansen, "Experiences in Dispersant Treatment of Experimental Oil Spills", *Spill Science and Technology Bulletin,* Vol. 7, Nos. 5-6, pp. 201-213, 2002.

Daling, P.S and K.R.Sørheim, "Field plan for testing and monitoring of Thin Oil Films (TOF) experiment during NOFO OPV-2016" . Petromaks 2 TOF Project memo. June 2016.

Overton, Ed., *Presentation of the behaviour of the Macondo spill,* Personal communication, 2011.

French, D., M. Reed, S. Feng, K. Jayko, S. Pavignano, H. Rines, T. Isaji, S. Puckett, A. Keller, F. French, III, D. Gifford, E. Howlett, J. McCue, G. Brown, E. MacDonald, J. Quirk, S. Natzke, B. Ingram, R. Bishop, and M. Welsh, *The CERCLA Type A Natural Resource Damage Assessment Model for Coastal and Marine Environments (NRDAM/CME),* Vol. I. Report to Office of Environmental Affairs, Washington, D.C., 1997.

Gjesteland, I, B.E., Hollund, J. Kirkeleit, P. S. Daling and M. Bråtveit, "Oil spill field trial at sea: Measurement of Benzene exposure", *Annals of Work Exposures and Health*. Accepted, 2017.

Johansen, Ø, Brandvik, P.J, Farooq, U, "Droplet Breakup in subsea oil releases- Part 2 Predications of droplet size distributions with and without injection of chemical dispersants", *Marine Pollution bulletin* 73 pp. 327-335, 2013.

Johansen, Ø 2016 A. Surface spreading of thin oil slicks: Technical memo (19.01.2016) Petromaks 2 TOF

Johansen 2016 B: Concentration of volatiles downwind on thin condensate slicks. Technical memo (19.01.2016) "Petromaks 2 TOF-project".

Lewis, A., P.S. Daling, T. Strøm-Kristiansen, A. Nordvik and R.J. Fiocco, "Weathering and Chemical Dispersion of Oil at Sea", *Proceedings of the 1995 International Oil Spill Conference,* API, Washington D.C., pp. 157-164, 1995.

Lewis, A. "Current status of the BAOAC (Bonn Agreement Oil Appearance Code)", http://www.bonnagreement.org/site/assets/files/3952/current-status-report-final-19jan07.pdf. Report to Bonn Agreement, and the Netherlands North Sea Agency Directie Noordzee, 2007.

Leifer, Ira; Lehr, William J.; Simecek-Beatty, Debra; Bradley, Eliza; Clark, Roger; Dennison, Philip; Hu, Yongxiang; Matheson, Scott; Jones, Cathleen E.; Holt, Benjamin; Reif, Molly; Roberts, Dar A.; Svejkovsky, Jan; Swayze, Gregg; and Wozencraft, Jennifer, 2012 "State of the art satellite and airborne marine oil spill remote sensing: Application to the BP *Deepwater Horizon* oil spill" (2012). *Publications, Agencies and Staff of the U.S. Department of Commerce*. 345. http://digitalcommons.unl.edu/usdeptcommercepub/345http://digitalcommons.unl.edu/usdeptcommercepub/345?utm_source=digitalcommons.unl.edu%2Fusdeptcommercepub%2F345&utm_medium=PDF&utm_campaign=PDFCoverPages

Leirvik, F., "High volume nozzle treatment of thin oil films" Project memo 2017, NOFO Oljevern 2015 program.

Lichtenthaler, R.G. and P.S. Daling, "Aerial application of dispersants - comparison of slick behaviour of chemically treated versus non-treated slicks". *Proceedings of the 1985 Oil Spill Conference*, API, Washington D.C., pp. 471-478, 1985.

Jensen, H., J.H. Andersen and P.S. Daling, "Recent Experience from Multiple Remote Sensing and Monitoring to Improve Oil Spill Response Operations", *Proceedings from the 2008 International Oil Spill Conference*, pp. 407-4412, May 4-8 Savannah, Georgia, USA, 2008.

NOFO: *Oil on Water (OPV) 2016*, Report to Norwegian Authorities, 34 p. (In Norwegian), 2016.

NOFO: *Oil on Water (OPV) 2016*, Operasjonsordre-NOFO Olje på vann 2016 EDOCS-15148 (In Norwegian), 2016.

Ramstad, S., K.R, Sørheim and P.S. Daling, *Thin Oil Films – Properties and behaviour at sea. Laboratory studies and oil weathering predictions*. SINTEF report, 27892 (Petromaks 2 TOF), 107 p., 2016.

Rasmussen, C., P.S. Daling, K.R Sørheim, "Konstruksjon av prototyper" (In Norwegian). Project memo; October, 2016, NOFO Oljevern 2015 program.

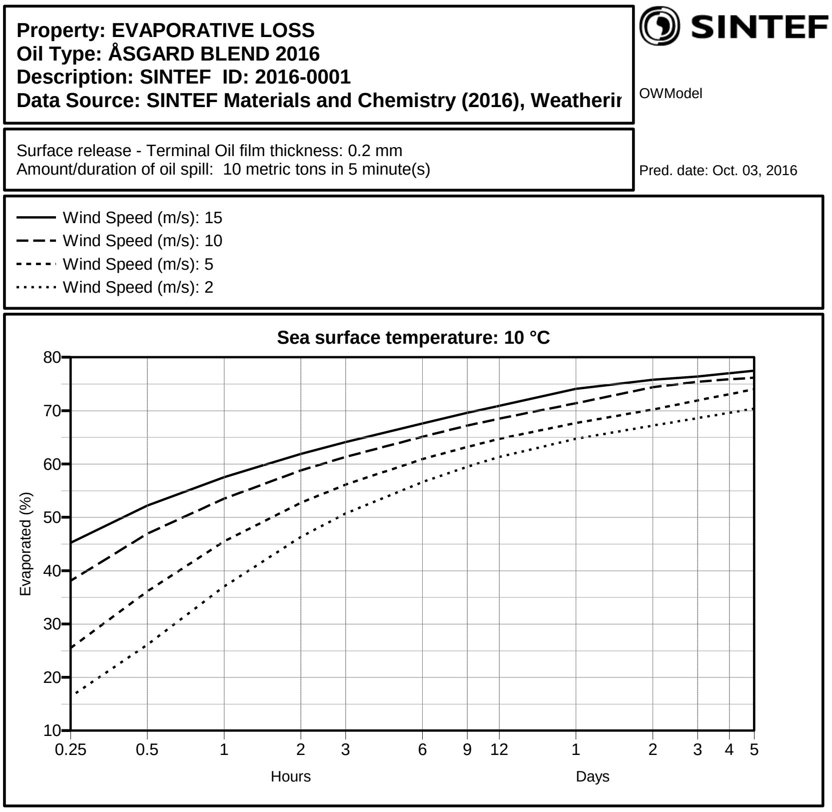
Appendix A Oil Weathering Model (OWM) predictions

Relevant oil properties from a limited laboratory weathering characterization of the Åsgard Blend 2016 prior the field trial have been used as input to the to SINTEF Oil Weathering Model (OWM). Two sets of predictions at two different conditions were conducted:

- Weathering predictions made of Åsgard Blend prior the field trial using sea temperature at 10 ºC, and an average terminal thickness of 0.2 mm

- Updated weathering prediction after the field trial based on prevailing sea temperature (12.5-13°C) and oil film thickness measured in the thickest area of the slicks (1 mm)

The OWM-predictions of the Åsgard Blend are given in Figure A1 to Figure A9.



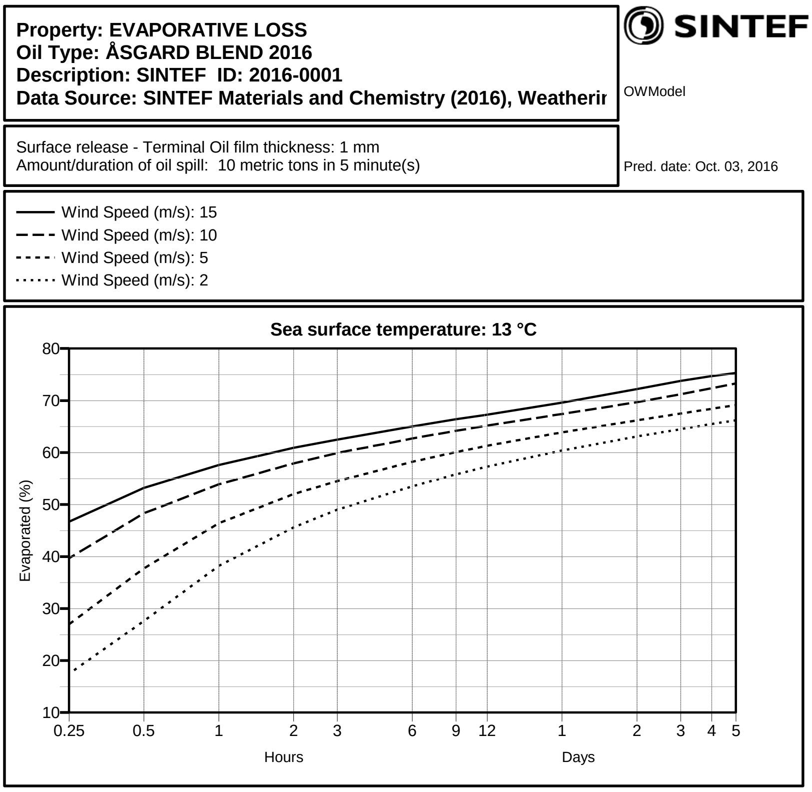
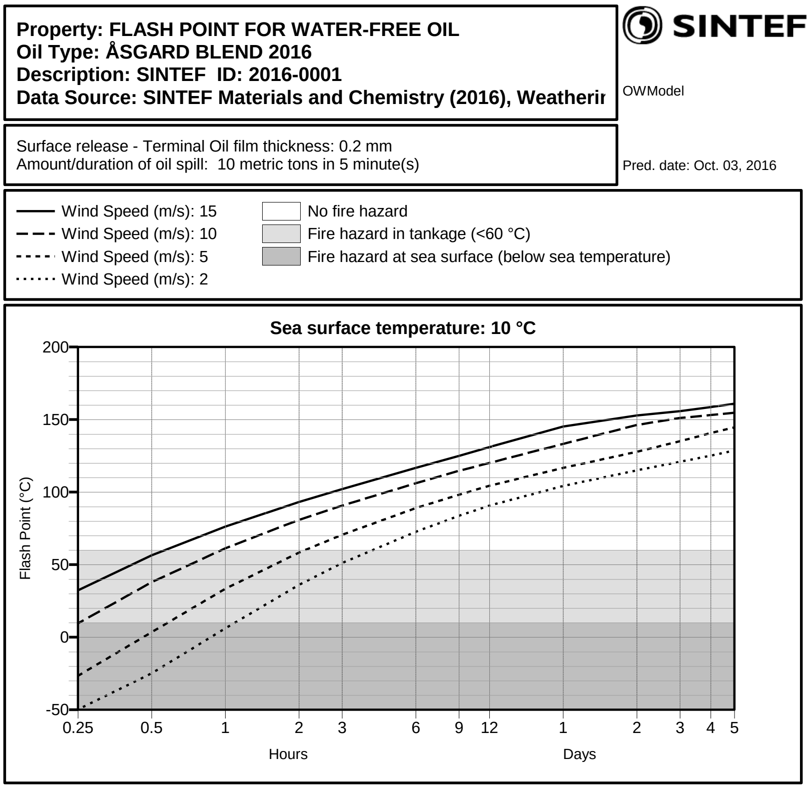


Figure A 1 Evaporation of Åsgard Blend at 10 °C (0.2mm) and 13 °C (1mm)



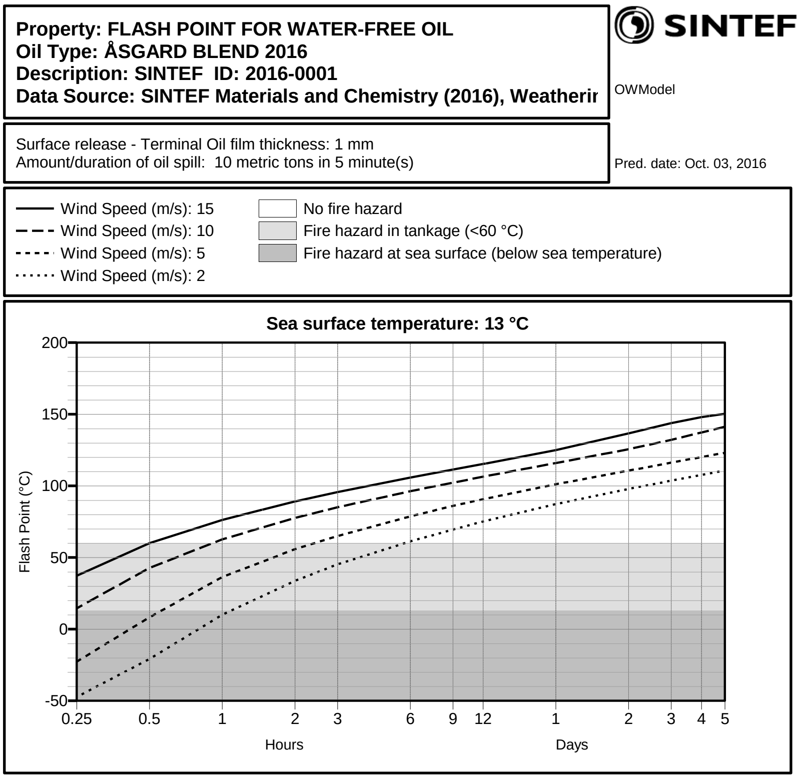
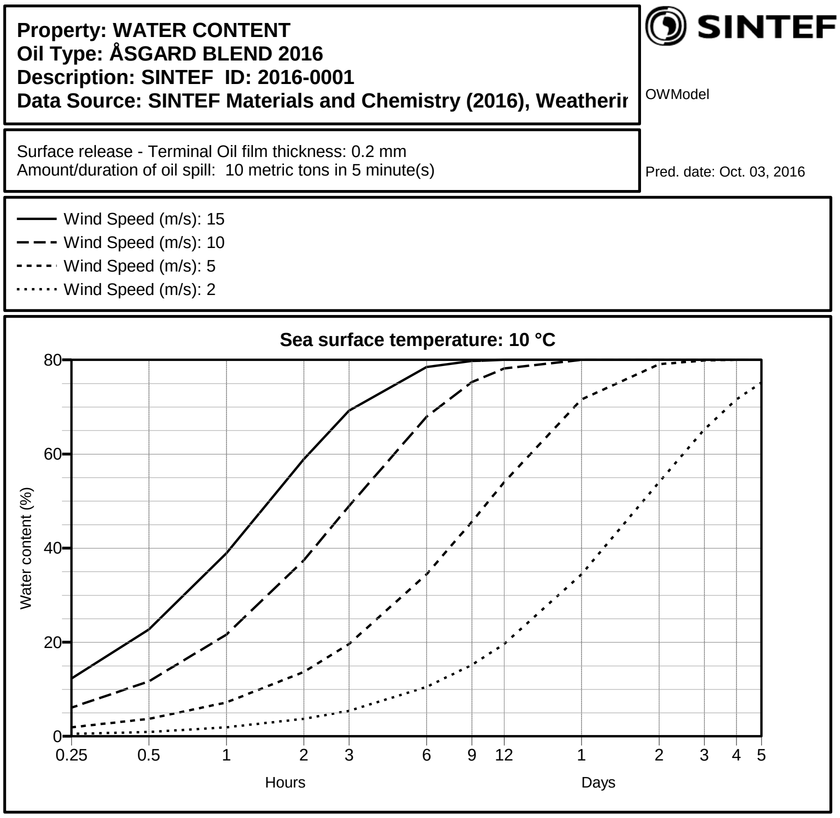


Figure A 2 Flash point of Åsgard Blend at 10 °C (0.2mm) and 13 °C (1mm).



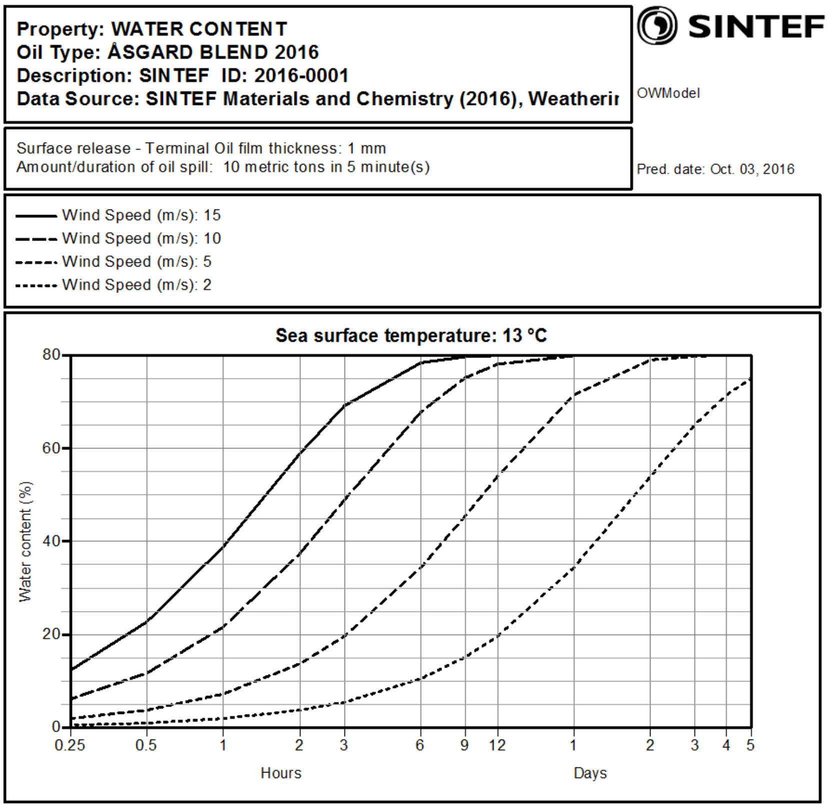


Figure A 3 Water content of Åsgard Blend at 10 °C (0.2mm) and 13 °C (1mm).

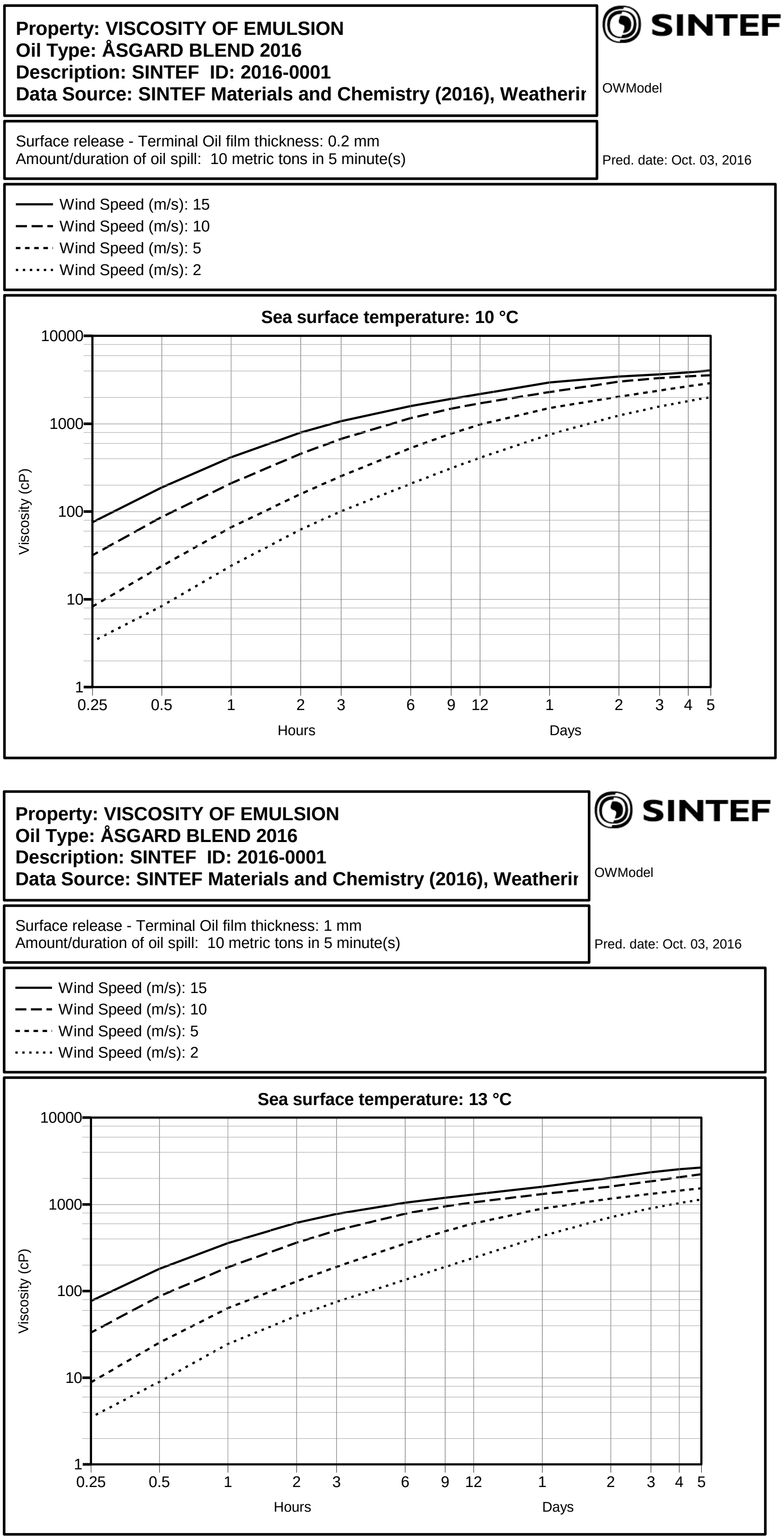
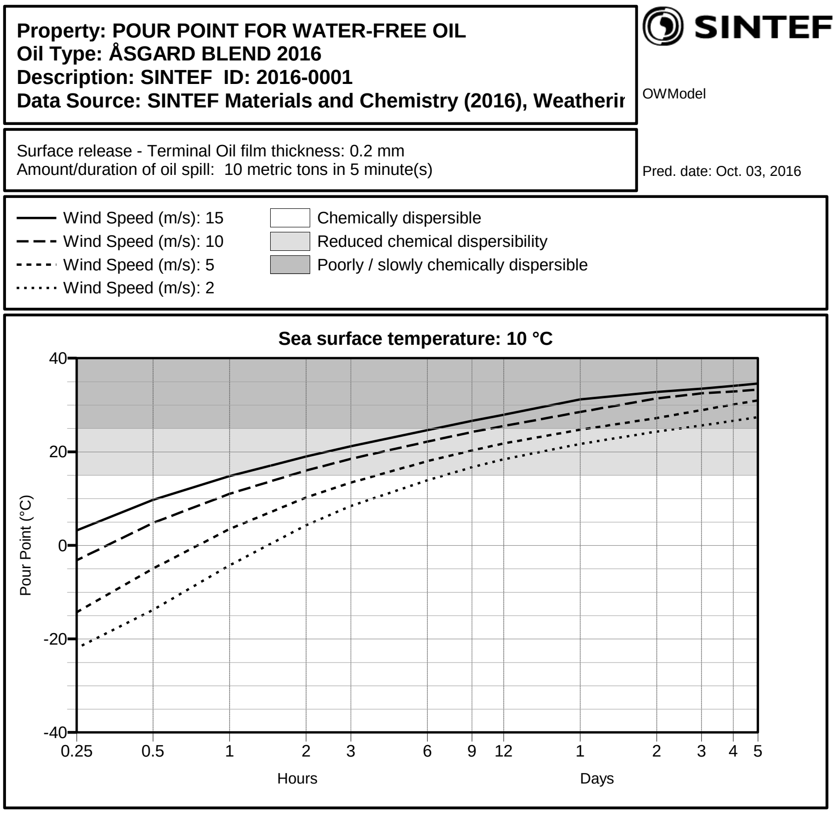


Figure A 4 Emulsion viscosity of Åsgard Blend at 10 °C (0.2mm) and 13 °C (1mm).



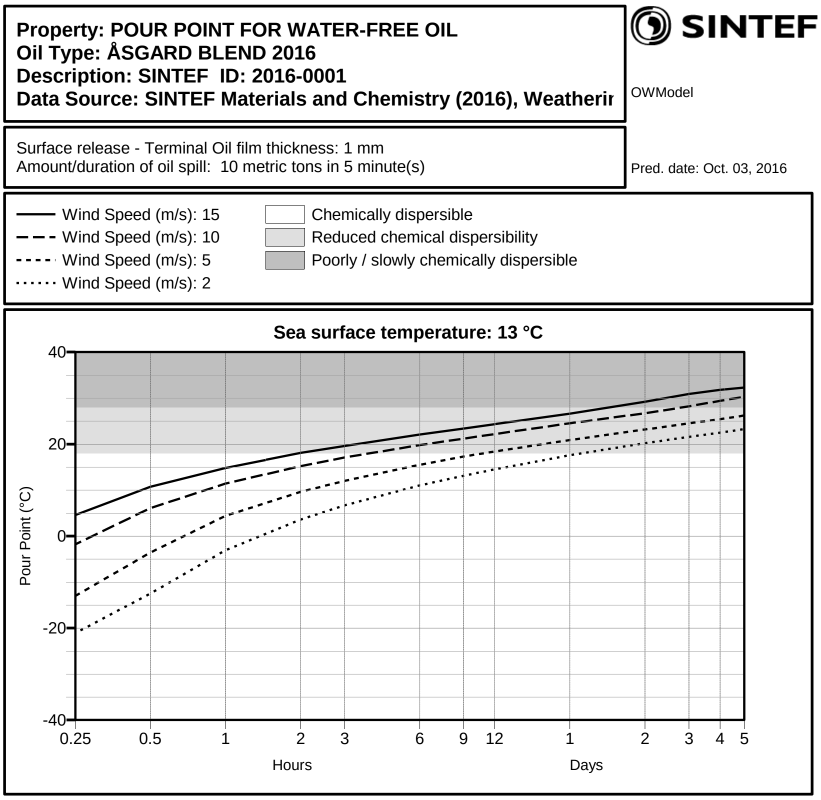


Figure A 5 Pour point of Åsgard Blend at 10 °C (0.2mm) and 13 °C (1mm).

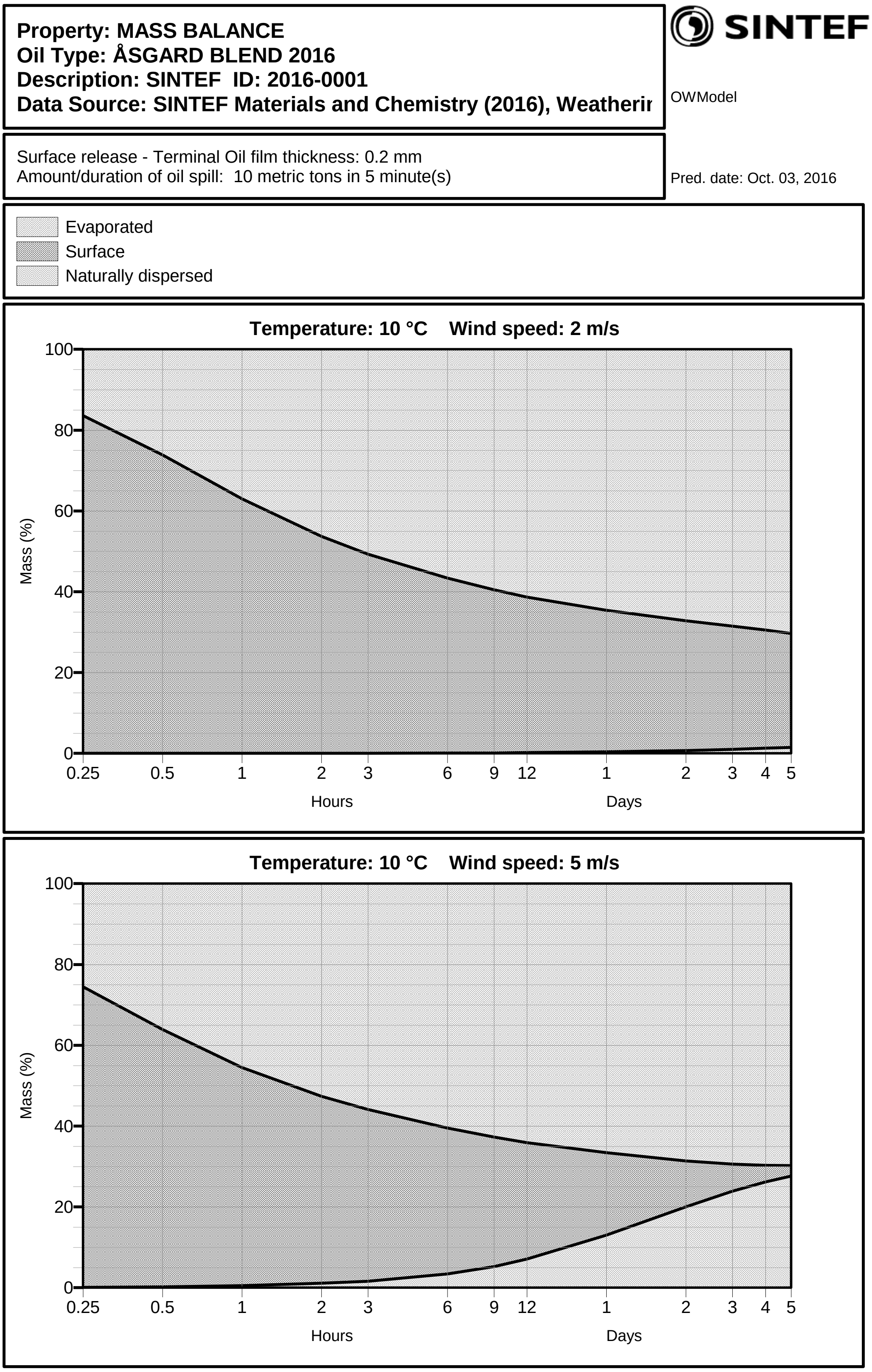


Figure A 6 Mass balance of Åsgard Blend at 10 °C (0.2mm) 2 and 5 m/s

Property: MASS BALANCE
Oil Type: ÅSGARD BLEND 2016
Description: SINTEF ID: 2016-0001
Data Source: SINTEF Materials and Chemistry (2016), Weatherir

SINTEF

OWModel

Surface release - Terminal Oil film thickness: 0.2 mm
Amount/duration of oil spill: 10 metric tons in 5 minute(s)

Pred. date: Oct. 03, 2016

Evaporated
Surface
Naturally dispersed

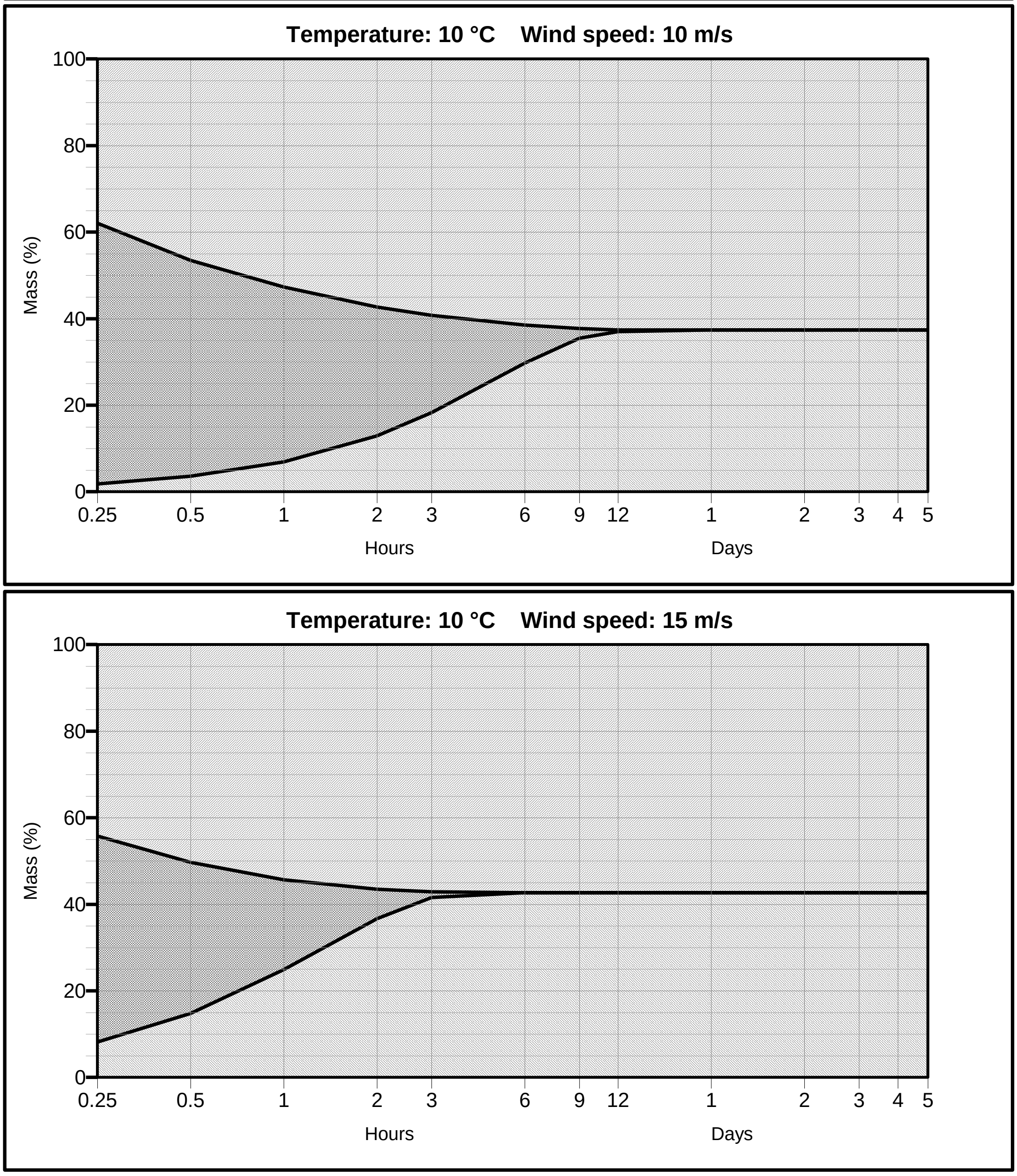


Figure A 7 Mass balance of Åsgard Blend at 10 °C (0.2mm) 10 and 15 m/s

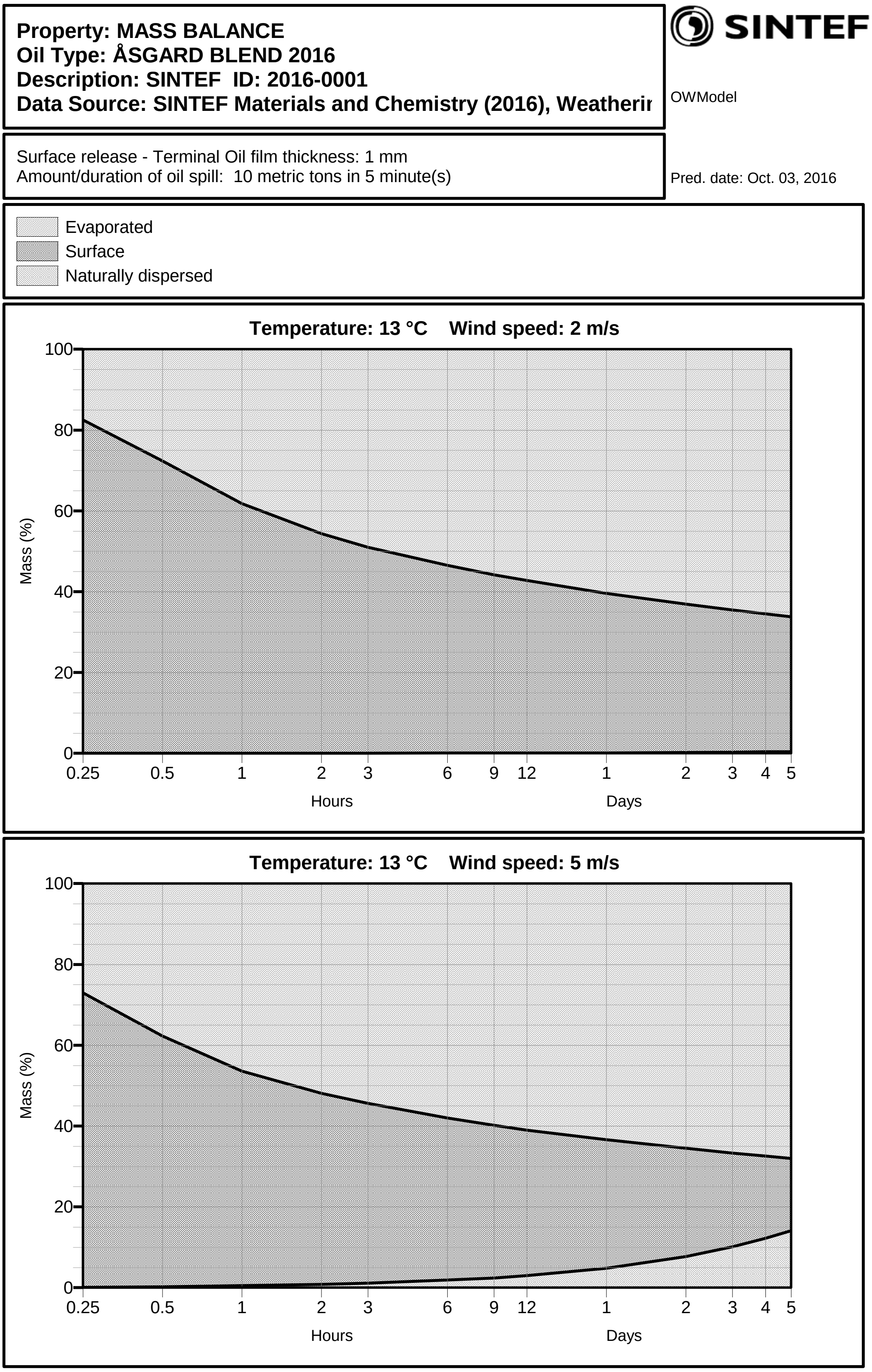


Figure A 8 Mass balance of Åsgard Blend at 13 °C (0.2mm) 2 and 5 m/s

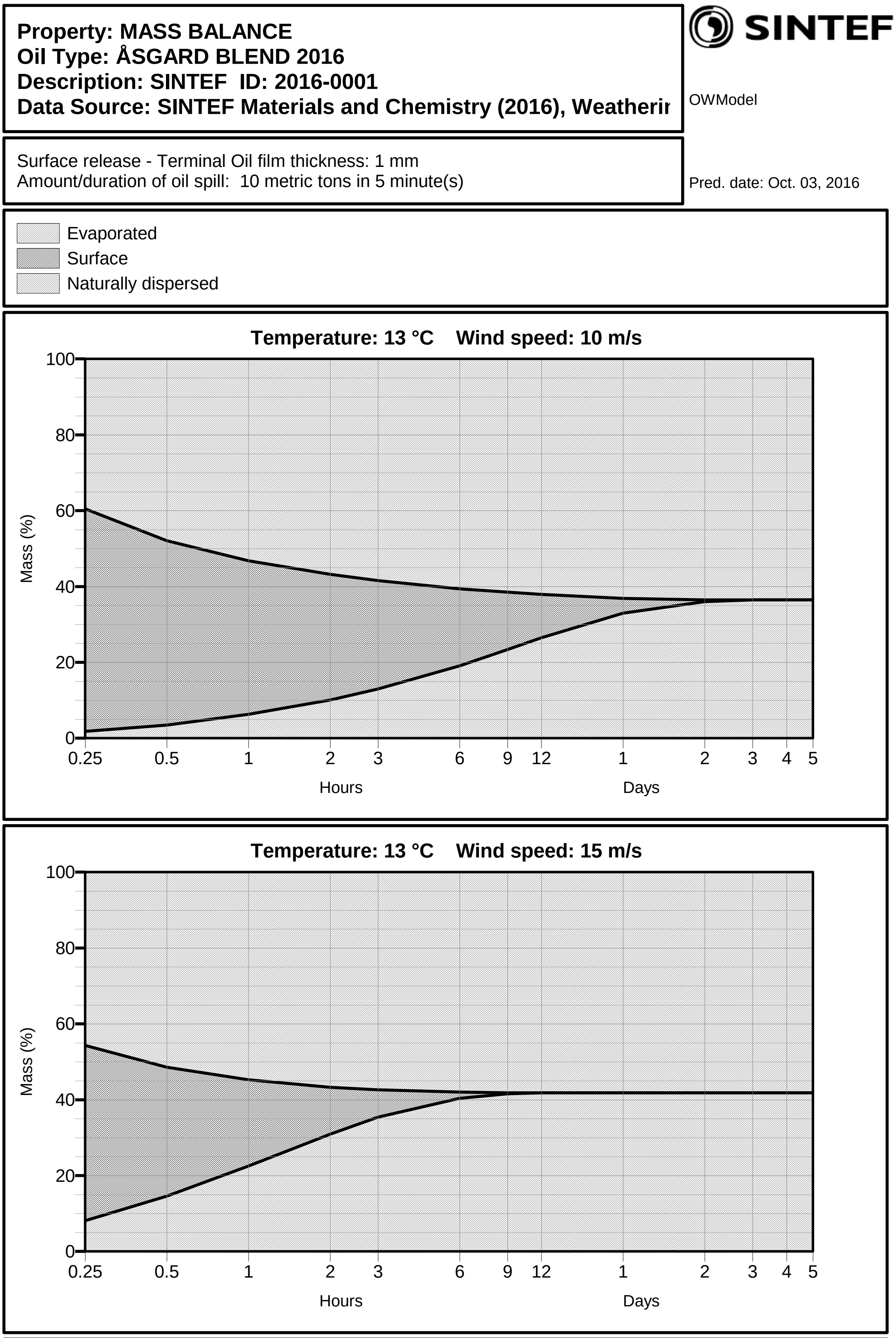


Figure A 9 Mass balance of Åsgard Blend at 13 °C (0.2mm) 2 and 5 m/s

Appendix B Ground-truth surface sampling of Åsgard Blend

Table B 1 shows an overview of analysis of the ground-truth surface sampling of Åsgard Blend for experiment 3.1 (reference no treatment), 3.2 (Low dosage dispersant) and 3.3 (Fi-Fi monitor treatment). Figure B 1 shows the predicted evaporative loss of Åsgard Blend compared with the ground-truth evaporative loss measured in the field.

Table B 1 Analysis from ground-truth surface sampling (oil thickness and physical properties of oil /emulsion in the thick areas for Åsgard Blend.

Oil slick thickness (PAD samples) in thick oil areas:

Sample	Time UTC	weight w. oil + bag (g)	weight w. oil (g)	Density (g/ml)	Emulsion oil thickness (mm)		waterfree oil thickness	Comment
TOF 3.1 - 14.06 - 09:02	07:02	54,81	42,12	0,83558	**0,95**	10	0,86	
TOF 3.1 - 14.06 - 09:03	07:03	37,95	25,26	0,83558	**0,57**	10	0,52	
TOF 3.1 - 14.06 - 09:04	07:04	64,82	52,13	0,83558	**1,18**	10	1,06	
TOF 3.1 - 14.06 - 09:17	07:17	65,25	52,56	0,83558	**1,19**	10	1,07	not full coverage on pad
	08:15							Pad discarded?
TOF2 før disp 14.06 - 10:17	08:17	167,49	154,80	0,81595	**3,59**	0	3,59	
TOF2 før disp 14.06 - 10:19	08:19	133,87	121,18	0,81595	**2,81**	0	2,81	
	08:21							Pad discarded?
TOF2 etter disp 14.06 - 10:52	08:50	39,99	27,30	0,8	**0,65**	6	0,61	
TOF2 etter disp 14.06 - 10:53	08:51	103,81	91,12	0,8	**2,16**	6	2,03	
TOF2 etter disp 14.06 - 10:55	08:55	79,16	66,47	0,8	**1,57**	6	1,48	
TOF2 etter disp 14.06 - 10:57	08:57	193,28	180,59	0,8	**4,27**	6	4,02	Oil on both sides of pad
TOF 3 15.06 - 10:14	08:16	65,8	53,11	0,8	**1,26**	25	0,94	
TOF 3 15.06 - 10:18	08:20	37,24	24,55	0,8	**0,58**	25	0,44	
TOF 3 15.06 - 10:21	08:23	81,35	68,66	0,8	**1,63**	25	1,22	
TOF 3 15.06 - 10:23	08:25	68,97	56,28	0,8	**1,33**	25	1,00	
TOF 3 15.06 - 12:47	10:50	81,79	69,10	0,8	**1,64**	80	0,33	

Physical properties of oil / emulsion in thick oil areas:

Forsøk	Dato	tid etter release	Time LT	Time UTC	Komment	Total volum	Vannvolu	KF	Vanninnhold (v%)	Viskositet 13°C 10s-1	Tetthet (g/ml)	Korrigert for	Fordampet (\	Ca toppegrad
TOF 3.1	14.06.2016	ca, 30 min	09:15	07:15		290	30	0,2	**10**		0,83558	0,8352024	35 %	115 C+
TOF 3.2	14.06.2016	ca 20 min	10:25	08:25	før disp	7,5	0	0,1	**0**	anta < 50 cP	0,81595	0,8157417	25 %	95 C+
TOF 3.2	14.06.2016	ca 1 time	11:04	09:04	etter disp	7,7	0,5	0,1	**6**	anta < 100	0,84306	0,8428789	42 %	145 C+
TOF 3.3	15.06.2016	ca 15 min	10:20			7,5	1,9	0,1	**25**	anta < 100	0,83767	0,8374835	ca 37 %	125 C+
TOF 3.3	15.06.2016	ca. 2.5 time	12:42		før FiFi				**80**	327	0,86423		ca 50 %	160 C+
TOF 3.3	15.06.2016	ca. 4 timer	13:57		etter Fifi				**80**	210	0,86123		ca 50 %	160 C+
HISB 4.2	14.06.2016	ca30 min	15:55			7,7	0	1,1	**0**		0,91485	0,913636	< 5%	

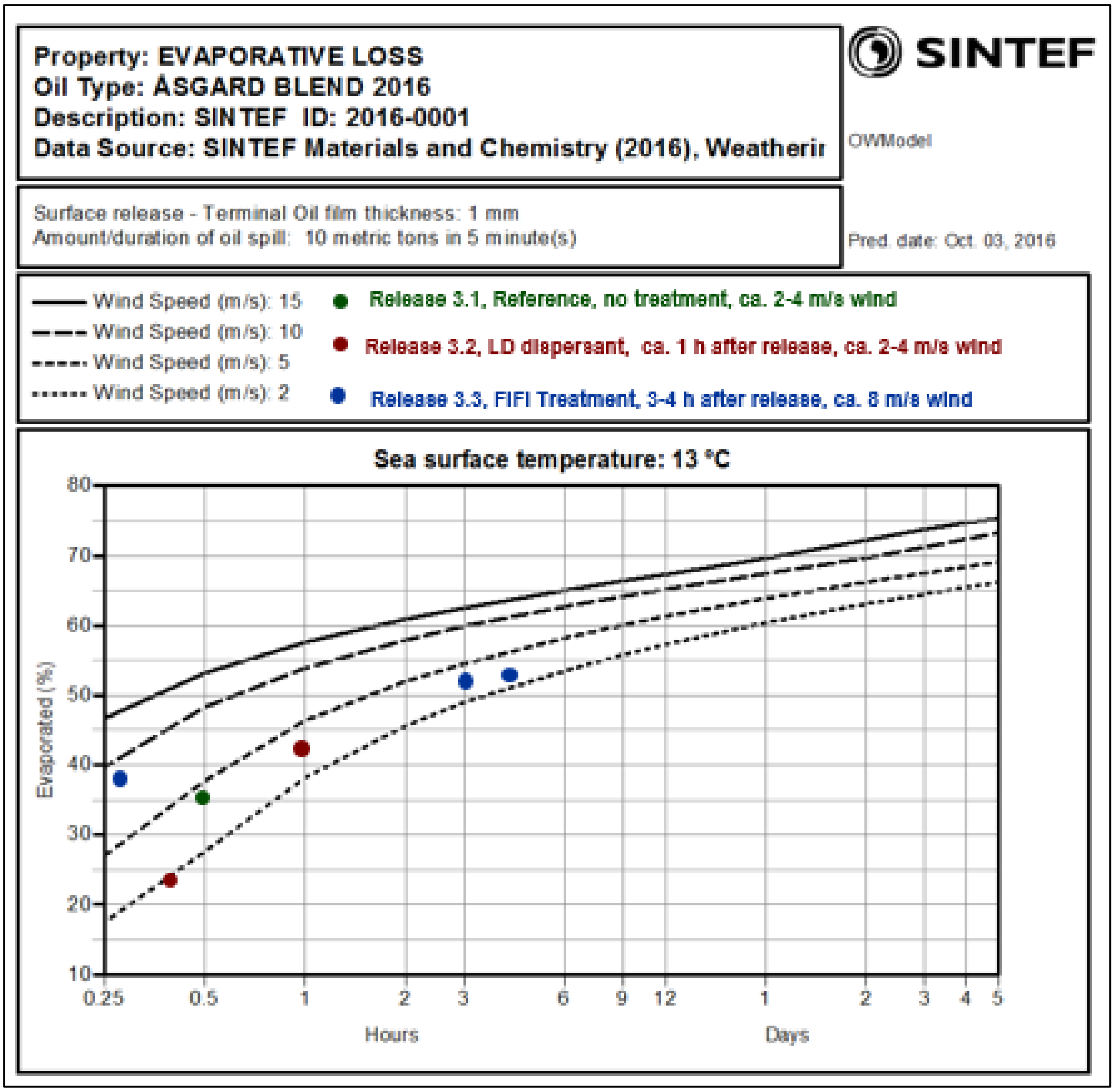


Figure B 1 Predicted evaporative loss with the measured ground truth data from the field-testing for experiment 3.1 (reference no treatment), 3.2 (Low dosage dispersant) and 3.3 (Fi-Fi monitor treatment).

Appendix C Aircraft surveillance

By Alun Lewis

Notes

- A total of 10 missions, five on each day, were flown by the three available aircraft.
- The aircraft were not tasked solely on the experimental slicks. They also gathered information for NOFO on the other activities on the exercise.
- The Norwegian aircraft is chartered by Norwegian Coastal Administration and NOFO and the data is theirs.
- The Finnish and the Netherlands aircraft were there on a no-cost to NOFO basis; it is part of the Bonn Agreement and HELCOM arrangements to invite then so that they could 'see' real oil on the water in controlled conditions. The cost for the aircraft and crews attending was borne by the Netherlands and Finnish Governments and the data gathered is theirs. They must be given proper credit in any reports etc.

Aerial Monitoring Day 1. Tuesday 14th June, morning

Local Time	08:00	08:10	08:20	08:30	08:40	08:50	09:00	09:10	09:20	09:30	09:40	09:50	10:00
UTC	06:00	06:10	06:20	06:30	06:40	06:50	07:00	07:10	07:20	07:30	07:40	07:50	08:00
Activity	Planned		→	→	3.1 release				pad sampling				
Aircraft	NORWAY OOW14.01												
Local Time	10:00	10:10	10:20	10:30	10:40	10:50	11:00	11:10	11:20	11:30	11:40	11:50	12:00
UTC	08:00	08:10	08:20	08:30	08:40	08:50	09:00	09:10	09:20	09:30	09:40	09:50	10:00
Activity	3.2 release			Spray 1	Spray 2, 3	Spray 4		water flushing through spray boom					
Aircraft		FINLAND OOW14.02											
Local Time	12:00	12:10	12:20	12:30	12:40	12:50	13:00	13:10	13:20	13:30	13:40	13:50	14:00
UTC	10:00	10:10	10:20	10:30	10:40	10:50	11:00	11:10	11:20	11:30	11:40	11:50	12:00
Activity									4.1 release				
Aircraft	NO AIRCRAFT ON SITE BECAUSE OF AIR TRAFFIC CONTROL FAILURE											NETHERLANDS	

SINTEF

Aerial Monitoring Day 1, Tuesday 14th June, afternoon

Local Time	**14:00**	**14:10**	**14:20**	**14:30**	**14:40**	**14:50**	**15:00**	**15:10**	**15:20**	**15:30**	**15:40**	**15:50**	**16:00**
UTC	12:00	12:10	12:20	12:30	12:40	12:50	13:00	13:10	13:20	13:30	13:40	13:50	14:00
Activity		**1st ignition**			**2nd burn**		booming of burn residue				4.2 release	flushing	
Aircraft	NETHERLANDS OOW 14.03												
Local Time	**16:00**	**16:10**	**16:20**	**16:30**	**16:40**	**16:50**	**17:00**	**17:10**	**17:20**	**17:30**	**17:40**	**17:50**	**18:00**
UTC	14:00	14:10	14:20	14:30	14:40	14:50	15:00	15:10	15:20	15:30	15:40	15:50	16:00
Activity	sampling		sampling	sampling	**Main burn**		**New ignition**		disperant on unburned area				
Aircraft	NORWAY OOW 14.04											FINLAND	
Local Time	**18:00**	**18:10**	**18:20**	**18:30**	**18:40**	**18:50**	**19:00**	**19:10**	**19:20**	**19:30**	**19:40**	**19:50**	**20:00**
UTC	16:00	16:10	16:20	16:30	16:40	16:50	17:00	17:10	17:20	17:30	17:40	17:50	18:00
Activity								4.3 release			Herding		
Aircraft	FINLAND OOW 14.05												
Local Time	**20:00**	**20:10**	**20:20**	**20:30**	**20:40**	**20:50**	**21:00**						
UTC	18:00	18:10	18:20	18:30	18:40	18:50	19:00						
Activity	main burn	sampling		dispersant									
Aircraft													

Aerial monitoring – day 2- Wednesday 15th June, morning

Local Time	**08:00**	**08:10**	**08:20**	**08:30**	**08:40**	**08:50**	**09:00**	**09:10**	**09:20**	**09:30**	**09:40**	**09:50**	**10:00**
UTC	06:00	06:10	06:20	06:30	06:40	06:50	07:00	07:10	07:20	07:30	07:40	07:50	08:00
Activity				UK slicks				Current Buster			Current Buster		
Aircraft				NORWAY OOW 15.01									
Local Time	**10:00**	**10:10**	**10:20**	**10:30**	**10:40**	**10:50**	**11:00**	**11:10**	**11:20**	**11:30**	**11:40**	**11:50**	**12:00**
UTC	08:00	08:10	08:20	08:30	08:40	08:50	09:00	09:10	09:20	09:30	09:40	09:50	10:00
Activity	3.3 release		sampling				sampling						
Aircraft	NORWAY OOW 15.02												
Local Time	**12:00**	**12:10**	**12:20**	**12:30**	**12:40**	**12:50**	**13:00**	**13:10**	**13:20**	**13:30**	**13:40**	**13:50**	**14:00**
UTC	10:00	10:10	10:20	10:30	10:40	10:50	11:00	11:10	11:20	11:30	11:40	11:50	12:00
Activity				sampling		sampling	FiFi	FiFi	FiFi	FiFi	FiFi	FiFi	FiFi
				aircraft tasked to UK waters									
Aircraft				FINLAND OOW 15.03									

Aerial Monitoring – day 2 Wednesday 15th June, afternoon

Local Time	**14:00**	**14:10**	**14:20**	**14:30**	**14:40**	**14:50**	**15:00**	**15:10**	**15:20**	**15:30**	**15:40**	**15:50**	**16:00**
UTC	12:00	12:10	12:20	12:30	12:40	12:50	13:00	13:10	13:20	13:30	13:40	13:50	14:00
Activity													
Aircraft		NETHERLANDS OOW 15.04											
Local Time	**16:00**	**16:10**	**16:20**	**16:30**	**16:40**	**16:50**	**17:00**	**17:10**	**17:20**	**17:30**	**17:40**	**17:50**	**18:00**
UTC	14:00	14:10	14:20	14:30	14:40	14:50	15:00	15:10	15:20	15:30	15:40	15:50	16:00
Activity						4.4 releas	herder on sea surface						
Aircraft					FINLAND OOW 15.05								
Local Time	**18:00**	**18:10**	**18:20**	**18:30**	**18:40**	**18:50**	**19:00**	**19:10**	**19:20**	**19:30**	**19:40**	**19:50**	**20:00**
UTC	16:00	16:10	16:20	16:30	16:40	16:50	17:00	17:10	17:20	17:30	17:40	17:50	18:00
Activity	Remnants of 3.3				More FiFi	More FiFi							
Aircraft	FINLAND												

Total data haul

	Aircraft	Local time		Gb	folders	files
		Images				
Tuesday 14th		**First**	**Last**			
OOW14.01	Norway	08:12	09:34	3.90	25	115
OOW14.02	Finland	10:12	11:58	3.93	9	352
OOW14.03	Netherlands	13:44	14:31	2.99	14	216
OOW14.04	Norway	16:01	17:37	10.0	60	254
OOW14.05	Finland	17:51	19:28	2.94	9	322
Wednesday 15th						
OOW15.01	Norway (1)	08:33		0.725	14	69
OOW15.02	Norway (2)		11:23	5.19	35	146
OOW15.03	Finland	12:38	13:43	3.23	9	253
OOW15.04	Netherlands	14:22	15:29	0.725	14	69
OOW15.05	Finland	17:04	18:48	3.10	9	155
				36.73	**198**	**1,951**

PRELIMINARY SUMMARY OF DATA GATHERED

Tuesday 14th					
Event at sea	**Aircraft**	**Start**	**Video / FLIR**	**Photos**	**UV/IR scans**
Local (UTC)		**Local Time**			
08:45 - 08:50 (06:45 - 06:50) **Slick 3.1 release** **Start 08:43:16 @ N60°0.0799' E2°23.429'** **Stop 08:50:32** **@ N60°0.0960' E2°23.910'**	**Norway**	**08:12**	15 videos (each of HDTV, HDIR and HDZ) From **08:12** to **09:34** Local Time		
10:03 - 10:09 (08:03 - 08:09) **Slick 3.2 release** **Not observed**					
Dispersant spray 1 10:28 - 10:31 **Dispersant spray 2 10:39 - 10:42** **Dispersant spray 3 10:44 - 10:45** **Dispersant spray 4 10:48 - 10:51** **Flushing with water 11:05 - 12:00**	**Finland**	**10:08**	20 videos (Visual and FLIR) From **10:12** to **11:58** Local time		
13:21 - 13:23 (11:21 - 11:23) **Slick 4.1 release** **Not observed**	**No aircraft on-site because of failure of air traffic control in western Norway from approximately 11:00 to 13:00 local time. No aircraft take-offs allowed between these times.**				
13:53 (11:53 - ?) **Herding** **14:10 - 14:15** (12:10 - 12:15) **First ignition** **14:14 - 14:28** (12:14 - 12:28) 3 separate burns in slick **14:35 - 14:45** (12:35 - 12:45) Second burn	**Netherlands**	**13:44**	38 videos (Visual and FLIR) From **13:44** to **15:31** Local time	A total of 157 photographs	

15:00 - 15:30 (13:00 - 13:50) Residue in sorbent boom					
15:00 - 15:30 (13:00 - 13:30) Sorbent booming of residue **15:40 - 15:43** (13:40 - 13:43) **Slick 4.2 release**					
16:05 - 16:20 (14:05 - 14:20) MOB B, 1st. sampling of surface oil **16:33 – 16:35** (14:33 - 14:35) MOB– C splitting the slick, Flare put in down-wind area **16:34: – 16:40** (14:34 - 14:40) Main burn **17:00** (15:00) New flares. New ignition **17:00 – 17:06** (15:00 - 15:06) Second burn **17:25 - 17:45** (15:25 - 15:45) Dispersant on unburnt area	**Norway**	**16:01**	17 videos (each of HDTV, HDIR and HDZ) From **16:01** to **17:37** Local time	A total of 12 photographs	
KV Sortland (16:13) Strilborg in 3rd oil slick **18:08** (16:08) (dispersing remnants of 4.2 slick) Slick 3.1 and 3.2 **18:31** (16:31) Desmi boom failure **18:55** (16:55) Desmi boom failure **19:00** (17:00) Desmi boom failure **19:25** (17:25)	**Finland**	**17:51**	20 videos (Visual and FLIR) From **17:51** to **19:28** Local time		27 UV/IR Line scans between **17:59** and **19:25** Local time

Wednesday 15th					
Event at sea **Local** (UTC)	**Aircraft**	**Start** **Local Time**	**Video/FLIR**	**Photos**	**UV/IR scans**
	Norway (1)	**08:00**			
	Norway (2)	**10:00**			
09:07 Current Buster **09:09** Current Buster **09:19** Current Buster (Stril Luna) **09:22** Strilborg / KV Sortland W342 **09:27** Current Buster / Bøen LJSY **09:43** Current Buster **09:50** Current Buster **10:03-10:09** KV Sortland 3.3 release MOB **10:06:30 10:06:45** **10:11** slick **10:37** Current Buster			19 videos (each of HDTV, HDIR and HDZ) From **08:33** to **11:23** Local time		
Aircraft tasked to slicks in UK waters Fi-Fi from Strilborg **13:14** (11:14) Strilborg Fi-Fi **13:31** (11:31)	**Finland**	**12:05**	6 videos (Visual and FLIR) From **12:38** to **13:43** Local time	73 photos from **12:58** to **13:40** Local time	9 UV/IR Line scans between **12:45** and **13:20** Local time
	Netherlands	**14:05**	7 videos (Visual and FLIR) From **14:22** to **15:29** Local time	28 photos from **14:09** to **15:02** Local time	
16:49 Expt. 4.4 Release 4 L of Herder **Remnants of FiFi slick** **18:40:-18:50** More FiFi treatment. Guided to area by the Finnish aircraft.	**Finland**	**16:05**	10 videos (Visual and FLIR) From **16:45** to **18:48** Local time	8 photos 4 photos of herder 4 photos of oil 8 photos pf FiFi	9 scans of herder 2 scans of oil

Appendix D Drone operations

By Torbjørn Houge
MARITIME ROBOTICS AS

During the exercise, Maritime Robotics provided drone flight support to document aspects of the trials. Drones flown were 2 camera drones and 1 drone flying with smoke sampler equipment. The following outlines which flew at which trials (experiments), and an estimate on how much documentation is available for each trial. The smoke sampler drone flew during the burns on day 1. Because of the nature of the flight profile, it is impossible to know exactly how much sampling time was done for each burn.

The video drones collected video of the oil slicks, herding and burning. In the table below page, the recording time will be documented.

Drone flights and trials (experiments):

Trial	Drone	Description	Time	Video
3.1	Video drones Smoke sampler drone	Drone flights for pilot calibration and video angle testing. No video.	-	-
3.2	None		-	-
HERDER/ BURNING 4.1	Video drones Smoke sampler drone	4 video drone sorties. Results of herder application on video. Video of burning. Smoke sampling 10-15min.	14:00 – 14:30	20 min
HERDER/ BURNING 4.2	Video drones Smoke sampler drone	Large continuous film clips, 2 gaps between flights. 3 video drone sorties. Shows mob boat splitting the slick, then burning. Smoke sampling 10-15min.	15:51 – 17:08	32 min
HERDER/ BURNING 4.3	Video drones Smoke sampler drone	Large continuous film clips, 2 gaps between flights. 3 video drone sorties. Video of release, herding and burn. Smoke sampling 10-15min.	19:04 – 20:07	35 min
TOF 3.3 FIFI	1 Video drone	Problematic to fly drone off the ship which is spraying with water. Wind close to margins made drone flights hard when ship was going against the wind. 1 video drone sortie.	12:52 – 13:05	13 min
HERDER in water	Video drone	Approximately 40min flying during this test. 2 video drone sorties.	16:44 – 17:16	31 min

General comments

Drone flights have low priority for the ship, so ship behaviour is not optimal. The large amounts of metal and machinery affects the compass in the drones, at times to the degree that the drones will not accept taking off. Oil visibility depends on weather, angle and light conditions, so it varies between video clips.

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