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# Report

## Summary report

Petromaks 2 Thin Oil Films


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**ABSTRACT**

The Petromaks 2 Research Program *"Formation and behaviour of thin oil films and evaluation of response methods including HSE"* (TOF project) has been a 3-year Research & Development project (2014-2017). This report summarize the main research conducted and the results, and refers to reports, memos, and publications/manuscripts from the TOF project.

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## 1 Preface and Acknowledgement

### *Preface*

The Petromaks 2 Research Program *"Formation and behaviour of thin oil films and evaluation of response methods including HSE"* (hereinafter called the TOF project) has been a 3-year Research & Development project (2014-2017). The TOF-project has been funded by the Research Council of Norway (RCN) and the oil industry (AkerBP, Centrica, Eni Norge, ENGIE E&P Norge AS, Shell Technology Norway, Statoil, and Total E&P Norge).

The TOF project was initiated as part of the oil producers release approval for operating 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 under certain spill release situations 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 behavior of such oils when spilled at sea. Oils that produce thin oil films under calm sea conditions are of particular interest, as well as potential response countermeasures, modified or customized, to deal with such spilled oils.

Thin oil films in this context are defined as oil films having initial thicknesses from 5 µm (0.005 mm) up to 200 – 300 µm (0.2 – 0.3 mm). Thicknesses below 5 µm normally have very short lifetimes on the sea surface, do not likely produce significant environmental effects on biota (e.g. sea birds, see e.g. French et al., 1997), and are not considered to be combatted by any known response technology.

Condensates and / or light crude oils have been obtained from oil companies and have been included as test oils in laboratory studies and full-scale field testing from this project. Seven oils (classified as condensates and light crude oils) were studied in the TOF project, as well as a "reference" oil Statfjord C Blend, which is a medium light emulsifying crude oil. We have extensive documentation on Statfjord crude oil both from weathering studies in the laboratory and behaviour in the field (field trials and incidental spills). In addition, the NOFO Oil-on-Water (OOW) field trial at the Frigg field in June 2016 also tested Åsgard Blend (a blend of light crude oils and condensates).

The TOF project has contributed to advancing the knowledge of the fate and behavior of thin oil films at sea. Knowledge derived from this project is considered equally as important to the oil industry as to organizations responsible for oil spill preparedness and oil spill contingency plans. Moreover, the TOF project acquired new knowledge to provide more efficient and safe oil spill response to releases of condensates and light crude oils to mitigate thin oil films on the sea surface, particulary for oils with a certain lifetime. Under certain release conditions, these oils may lead to large areas of thin oil films on the sea surface a short time after release.

In this project a comprehensive laboratory study has been performed focusing on behaviour of thin oil films and testing of response concepts. The study of behaviour was performed on a 200 µm oil film from the 8 oils included. The results have been important for understanding processes like emulsification and solidification of such thin oil films, and have been used as input for development of the methodology for establishing recommended oil spill response strategies for thin oil films. Besides, it contributed to selection of one oil type for use in the field trial in 2016, with properties and behaviour relevant for condensates and light crude oils. The laboratory testing of response concepts was performed to optimize the methodology for high-capacity water flushing as a basis for constructing a prototype bow-mounted flushing boom. The optimization included parameters like nozzle type, spraying angle, water pumping capacity etc. The 2016 field trial contributed to testing of the prototype and was a first verification of the water flushing technology.

The health risk for personnel involved in oil spill has been investigated as a part of a PhD-study, with focus on measurements of volatile hydrocarbons from airborne benzene and human exposure.

The trajectory model (OSCAR) has been improved based on both literature review and spreading experiments (rheology/yield-stress properties) of wax enriched oil residues.

Finally, based on findings from the TOF project combined with previous oil weathering studies and knowledge about the possibilities and limitations with existing oil spill response methods, recommendations for establishment of oil spill response strategies for condensates and light crude oils, hereinafter called "Recommendations" (Singsaas et al., 2017) has been prepared.

This report summarizes the background, key findings, definitions, descriptions, and results from the TOF project.


## *Acknowledgements*

The authors want to thank the Research Council of Norway (RCN) and the seven oil companies for funding the TOF project. The oil companies are listed alphabetically as followed with the contact persons in brackets:

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Research partner Alun Lewis Oil Spill Consultant is acknowledged for his valuable input in form of scientific discussions and contribution into this project. Alun Lewis exhibits long experiences and knowledge in oil spill response from field trials.

The participants from the reference group Hans Jensen at NOFO (The Norwegian Clean Seas Association for Operating Companies), Rune Bergstøm at Norwegian Coastal Administration (NCA), Francois X. Merlin oil spill consultant, and Øistein Johansen (Johansen Environmental Modeling Consulting) have also contributed with their valuable expertise, discussions and assistance during the project period.

We want to acknowledge NOFO for organizing and contributing financially to the OOW trial in June 2016. We would also like to acknowledge the NCA for their contribution with vessels and remote sensing aircrafts in Norway, Finland and the Netherlands during the OOW. In addition, we want to acknowledge Jason Engineering AS for developing and implementing response concepts on the vessel MS Strilborg.

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## 2 Executive summary - Key findings and main achievements

- The TOF project has provided valuable knowledge about the fate and behavior of different condensate and light crude oils. This knowledge can improve the oil spill response of thin oil films on the sea surface
- Eight oils (condensates, light crude oils, and a reference oil) were studied in the TOF project). In addition, Åsgard Blend (a blend of light crudes and condensates) was used during an experimental field trial in June 2016 (NOFO Oil-on-Water (OOW)
- Laboratory experiments of weathered condensates and light crude oils have shown different behaviours of the oil´s residue, and also formed a basis for selection of an oil type for the field trial
- The field trial supported the behaviour of the representative test oil from laboratory experiments, in addition to document and observe the fate and behaviour of the thin oil film in more realistic (oceanographic and weather) conditions, which was not possible to test in the laboratory
- The new response concept of high-capacity water flushing (mechanical dispersing) was tested in laboratory experiments with use of spray nozzles in SINTEF tower basin. Its potential for combating thin oil films was also demonstrated in a full-scale test in conjunction with field trial in 2016
- The field trial clearly demonstrated the efficiency of the high-capacity water flushing (mechanical dispersion) technology. This new concept could be a valuable addition to standard response options, such as low-dosage dispersant treatment. These response concepts were developed in cooperation with Jason Engineering AS through a technology program funded by NOFO Oljevern 2015-WP048
- Improvements of the oil spill trajectory model (OSCAR) with implementation of an updated gravity-spreading model in (research version) to give more reliable modelling of surface behaviour on oils producing thin oil films when spilled at sea. The temperature and salinity profiles can now be imported into the model and is available in the currently official release version. In addition, the coverage of surface oils by defined oil film thicknesses has also been implemented to the OSCAR model (release version) from this TOF project
- A PhD-study has demonstrated the need of using personal protection equipment (PPE). Gloves and mask are recommended for at least 1-hour after a spill i.e. an operation at least 1-hour oil drifting distance from an ongoing release. These results demonstrated the importance of monitoring human exposure to airborne hydrocarbons by stationary and personal (environmental and biological) monitoring, and volatile oil components (VOCs including carcinogentic hydrocarbon benzene)
- A methodology to prepare recommendations for response to oil spills from condensates and light crude oils, hereafter called Recommendations has been developed. The methodology is based on laboratory and field studies from the TOF project, previous weathering studies, and existing oil spill response methods. The physicochemical properties of the oils from this project have been used to categorize four different classes of condensates and light crude oils. The methodology developed will be a useful tool in contingency and response planning, and for recommending response options for relevant releases under specific scenarios
- The Recommendations have been used to give examples of possible oil spill response strategies for the different classes of oils based on a defined standardized underwater release scenario

# 3 Introduction

## 3.1 Background

Marine spills of light crude oils and condensates, which lead to the formation of large spreading of thin oil films at sea, have gained increased attention from the oil industry and the Norwegian Environmental Agency (NEA). On the Norwegian Continental Shelf, condensates and light crude oils are expected to increase in production; resulting in increased transportation of condensates and refined oil products. For oil spill contingency planning, it has been assumed that oil slicks from such oils may form thin oil films (typically less than 0.1-0.2 mm in thickness). This thickness is below the regarded minimum thickness for effective oil spill recovery, but the oil poses a risk to wildlife (e.g. seabirds) under calm sea conditions. These surface oil spills are assumed to have short lifetimes under rougher sea conditions due to natural dispersion and dilution caused by wave activity. Monitoring of oil (surface oil and naturally dispersed oil) is a common response to these thin oil films. Although, different oil types vary in their physicochemical properties and thus their behaviour. As such, the oil industry and the NEA are interested to improve response strategies to determine the fate and behaviour for oil types assumed to give of thin oil films of varying properties.

During response, condensates and light crude oils can create health risks due to the high content of volatile components. Accurate exposure information is a crucial element to ensure that exposures are correctly monitored and characterized. Health risk must be communicated appropriately, and evidence-based decisions are necessary to protect the health and safety of oil spill response workers. These risks have been poorly described in previous oil spill field studies. The knowledge obtained about the behaviour of condensates and light crude oils from this project will assist:

- The oil industry and public responders to develop improved procedures for oil spill contingency and response strategies
- Oil spill response manufacturers for development of more efficient mitigation technology
- Research organisations and consultants to provide more detailed and realisitc simulations of oil spill trajectories
- Public agencies to provide appropriate regulations for oil spill contingency

## 3.2 Objective

The main objective within this TOF project is to increase the efficiency and safety of oil spill response operations during releases of condensates and light crude oils that may lead to thin oil films on the sea surface. In order to obtain this objective the following secondary objectives were fulfilled:

- Improved understanding of the formation and behaviour of thin oil films and the potential for water-in-oil (w/o) emulsion formation and solidification of the residues from condensates and light crude oils with different physical-chemical properties. This includes the assessment of new and improved oil spill response concepts and countermeasure strategies for thin oil films
- Assessment of the potential human exposure to volatile compounds during oil spill response operations in order to characterise the risk as a function of oil composition, weathering time and sea temperature (temperate versus Artic conditions)
- Refined algorithms in oil trajectory models in order to give more reliable predictions of the lifetime and behaviour of thin oil films and formation of "windrows" consisting of solidified wax and/or enriched oil residues, and to assess the efficacy of response options for various spill scenarios

# 4 Thin oil films – What are they and when can they arise?

Thin oil films may arise from several oil spill scenarios, such as subsurface releases, but also from specific surface releases dependent on the size and release conditions of the spill. In a subsea release, free gas and gas-to-oil ratio (GOR) may contribute to the buoyancy of the rising oil plume, and release depth may play a significant role in the formation of thin oil films at the surface. Condensates and light crude oils are normally characterized by a high portion of light compounds (40–80%; boiling point < 150-200°C). When spilled in the marine environment, these oils could generate thin oil films under calm conditions (non-breaking waves; < 5 m/s wind speed).

In a surface release, the initial film thicknesses may be in the mm range, and the light components will likely evaporate within a few hours (< 0.5 – 1 day) after release. The fate and behaviour of the remaining surface residue will depend highly on the physicochemical properties of the residue.

In this TOF project, the definition of thin oil films are based on a practical oil spill response/oil behavior approach rather than a strict scientific definition. It has been demonstrated from laboratory studies and during experimental field trials that oil films with a thickness below 0.1 – 0.2 mm (100 – 200 µm) will have less capability to form water-in-oil (w/o) emulsions. The oil layer will be too thin to encapsulate water droplets into the oil. Although, it is possible for thin oil films to increase their thickness under certain oceanographic conditions. Therefore, this project defined this oil films as initial thicknesses from 5 µm (0.005 mm) up to 200 – 300 µm (0.2 – 0.3 mm). Thicknesses below five micometres normally have very short lifetime on the sea surface, are regarded as not giving any significant environmental effects on biota (e.g. sea birds) (French et al., 1997), and is not considered to be combatted by any known technology.

## 4.1 Bonn Agreement Oil Appearance Correlation (BAOAC)

The visual appearance of oil slick at sea can be an indication of the oil layer thicknesses. The BAOAC (Lewis, 2007) was developed to visually describe and calculate oil slicks from aircrafts. Table 4-1 shows how the oil appearance can be visually described, and what the different codes means with respect to estimated quantities and thicknesses. Sheen and rainbow is not included in the definition of thin oil film in this project, as it has short lifetime on the sea surface

**Table 4-1 Bonn Agreement Oil Appearance Correlation (BAOAC)**

| Code | Oil appearance | Quantity, $m^3/km^2$ | Thickness (µm) |
|---|---|---|---|
| 1 | Sheen (Silvery / Grey) | 0.04 – 0.3 | 0.04 – 0.3 |
| 2 | Rainbow | 0.3 – 5.0 | 0.3 – 5.0 |
| 3 | Metallic* | 5.0 - 50 | 5.0 - 50 |
| 4 | Discontinuous true oil colour (DCTC)* | 50 - 200 | 50 - 200 |
| 5 | Continuous true oil colourcolor (CTC) | > 200 | > 200 |

**Green colour covers code 3 and 4 for oil films from TOF project*

Thin oil film, as defined above, therefore covers codes 3 and 4 in the BAOAC. Figure 4-1 shows a picture of a spill from an underwater pipeline rupture, indicating a possible visual appearance of the thicknesses associated with codes 1-4
.

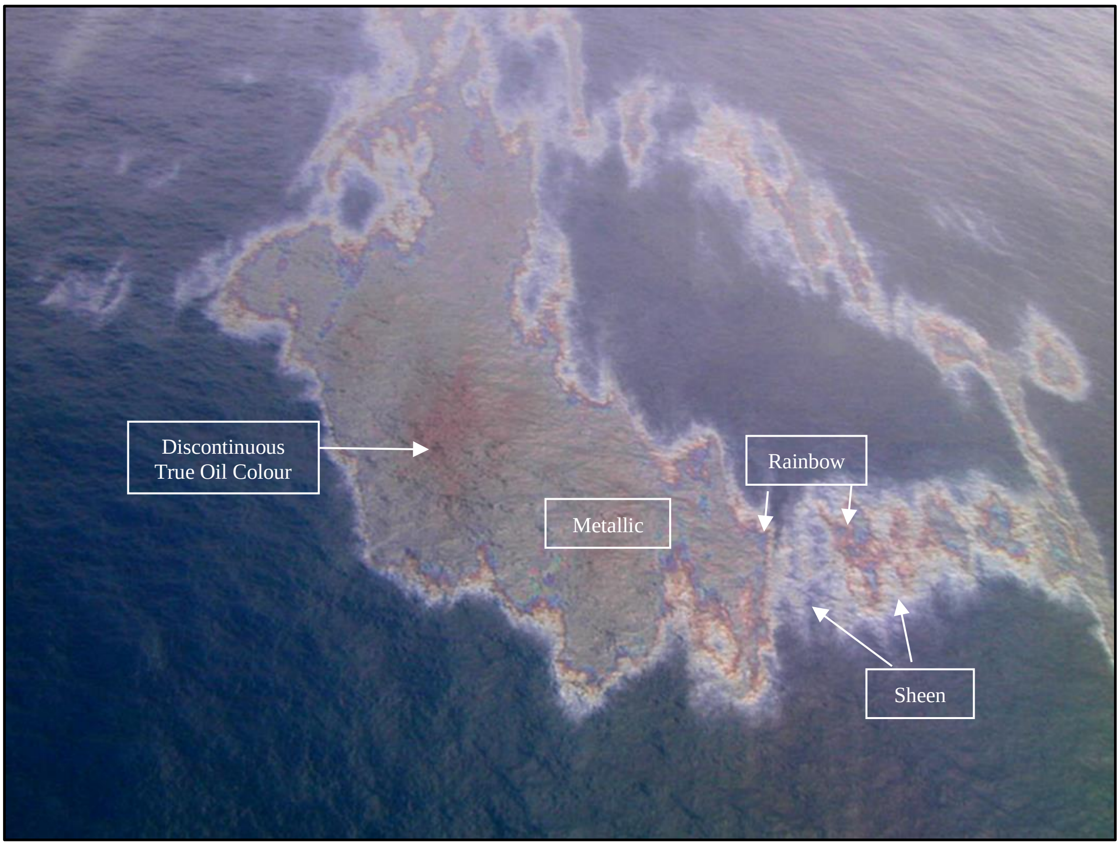


**Figure 4-1** **Example of BAOAC categories from an underwater leakage after a pipeline rupture**

## 4.2 Definition of condensates and light crude oils

In the literature, oils are commonly described as light, medium and heavy crude oils. The American Petroleum Institute (API) definition is based on the oil density (API-gravity), where oil densities < 0.87 g/mL is defined as light crude oils. In general, a condensate is defined as a low-density hydrocarbon liquid that generally occurs in association with natural gas. Its presence depends on temperature and pressure conditions in the reservoir, which allows condensation of liquid from vapour. Condensates are not only generated in the reservoir, they are also formed when liquid drops out, or condense from a gas stream in pipelines and oil/gas processing facilities.

A general definition of light crude oil is a liquid petroleum that has a low density and flows freely at room temperature. It has a low viscosity and low density due to the high proportion of light hydrocarbon fractions. It generally has a low wax content.

In the TOF project, we have characterized the tested oil based on its weathering behavior at sea. The oils are categorised as condensates, light crude oils and crude oil, based on their physicochemical properties (i.e. density and evaporation) and their ability to form w/o-emulsions. Typically, condensates exhibit high degree of evaporation, and do not normally form w/o-emulsions. Light crude oils may form stable (via wax content) and/or unstable w/o-emulsions, which may be easily broken. Crude oils may also form slightly stable to very stable w/o-emulsions.

Moreover, the oils from the TOF project have been categorized into different classes based on the physicochemical data of the fresh oil and the evaporated residues given in Section 5.2, as a basis for Recommendations given in Section 11.

## 4.3 Potential for emulsification and solidification of oil at sea

When oil is spilled on the sea surface, its behavior changes throughout the weathering process and affects the efficiency of oil spill countermeasures. Oil weathers through a variety of different processes and environmental conditions. Surface-active compounds (asphaltenes and resins) present in oil will promote the formation of w/o emulsions and contribute to stabilizing the emulsion. These components contain both hydrophilic and hydrophobic groups. Oils that contain large amounts of wax and small amounts of asphaltenes can form w/o emulsions stabilized by wax structures formed by precipitated wax. Wax stabilized emulsions are characterized by large water droplets and are normally stable, although they may break down when stress is applied and/or when the emulsion is heated.

Solidification at sea occurs after the evaporation of volatile compounds. The solidified residue that remains has a high pour point, typically 5-15°C above the sea temperature. Waxy condensates and light crude oils are known to solidify at sea.

## 4.4 Spreading and formation of windrows and bands

Oil spread out on the sea surface to thicknesses that depends on the physical properties of the oil (under prevailing temperature and release conditions). Figure 4-2 from Daling et al. (2003) illustrates how the thickness of non-emulsifying oil and an emulsifying oil change over time. A non-emulsifying/non-solidifying oil would continue to spread out to a thin sheen, which would subsequently be naturally dispersed. Over time, an emulsifying oil would increase in thickness as water is incorporated into the emulsion to form a thicker continuous slick of emulsified oil. The high viscosity of the w/o emulsion would inhibit further spreading and the emulsified slick would gradually break down into progressively smaller pieces/patches of w/o emulsion on the sea surface. The eventual fate of the small pieces of w/o emulsion is to be converted into smaller highly viscous lumps.

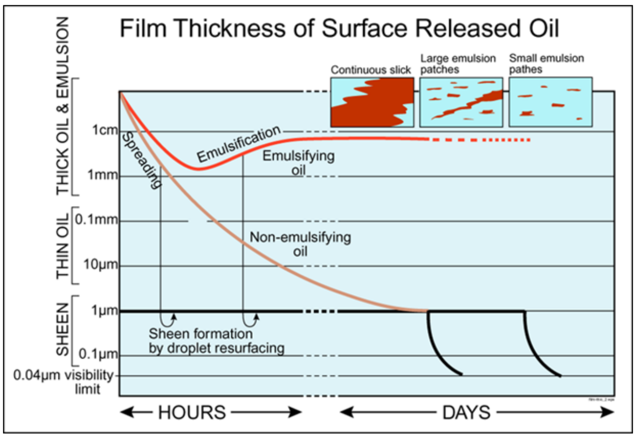


**Figure 4-2** **Film thickness of surface released oil**

A feature that is often, but not always, observed for oil spills at sea are the formation of long, narrow linear features aligned with the wind that contain relatively thick oil separated by areas of thinner oil. This feature is often referred to as *"windrows"* and seem to appear at wind speeds above 5 m/s. Langmuir circulation is such a feature that gives long narrow lines of oil. Langmuir circulation is often invoked as the explanation for the formation of "*windrows*" of thicker oil under breaking wave conditions, but this has not been firmly established. The phenomenon of Langmuir circulation has also been evaluated for oil modelling of surface oil (see Section 10). Even under calm sea conditions, thin oil films may have the potential to be concentrated into areas of bands.

The phenomenon of such bands was observed during the field trial (see Section 8) as part of the NOFO OOW 2016. Such bands were seen for the reference (untreated) slick after a few hours on the sea surface under calm (< 5 m/s wind speed) sea conditions, where the initial thin surface oil (< 0.2-0.3 mm) became "contracted" into bands with 1-2 mm oil thicknesses (see the TOF 3.1 slick in Figure 4-3).

Furthermore, the oil residue from such bands reached a high pour point and started to solidify, leading to a slow break up and an extended lifetime of the surface oil. Such bands have also previously been observed in real incidents under calm weather conditions (e.g. Macondo and the Exxon Valdez incidents). The TOF 3.2 slick (Figure 4-3) was in an early phase after release treated with dispersant followed by additional turbulence mixing with water flushing. The slick dispersed into the water column, but and a small fraction of very thin oil film was left on the surface that broke-up easily under breaking wave conditions.

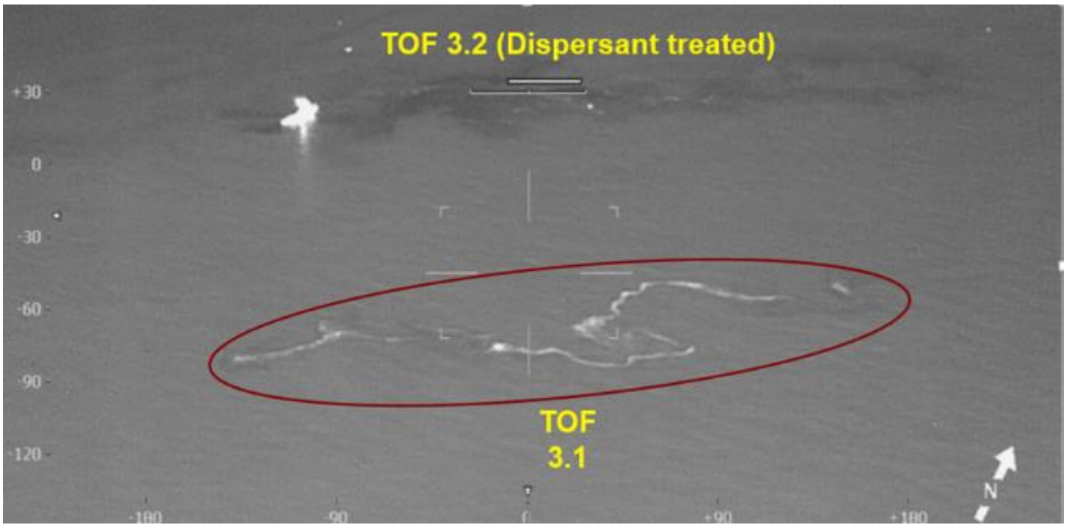


**Figure 4-3** **Overview FLIR image taken both the non-treated 3.1 slick (red circle) slick with the characteristic bands and the dispersant treated 3.2 slick in the background (©Finnish Border Guard / SYKE)**

# 5 Selection of crude oils and condensates for the laboratory studies

The behavior and properties of eight oils (condensates, light crude oils, and a reference oil) were studied in the TOF project. The selection of the oil in this TOF project was based on the following main 3 criteria:

1) Previously prior laboratory weathering study of the oils existed
2) Oils that represented the majority of condensates and light oils under production in the Norwegian sector, with respect to their physicochemical properties
3) Condensates/oils currently in production

Previous weathering studies have shown that the fate and behavior of the selected oils were strongly influenced by weathering processes. Based on the criteria listed above, the selected oils were condensates: Atla, Alve, Marulk, Ormen Lange, and Skarv; and light crudes: Gjøa and Vale. Statfjord C Blend was chosen as the reference crude oil. Figure 5-1 shows visual samples of the fresh oils that have been studied in the TOF project.


*A: Skarv*
*B: Atla*
*C: Alve*
*D: Marulk*
*E:OrmenLange*
*F:Gjøa*
*G: Vale*
*H:Statfjord C Blend*

**Figure 5-1 Samples of the fresh oils studied in the TOF project**

## 5.1 Physicochemical properties

The weathering, fate and behavior of thin oil films, as well as the characteristics of their surface residues were documented by physicochemical analysis and visual observations.

Figure 5-2 shows an overview of the crude oils categorized into groups: *Paraffinic, Waxy, Naphthenic, and Asphaltenic crudes*. The same figure presents the distribution of the condensates used in this project based on their increasing solidifying residue properties.

Table 5-1 gives an overview of the physicochemical properties of the fresh oils and their corresponding evaporated residues. In addition, the Åsgard Blend oil was used during the field trial in 2016. Selected physicochemical properties of the oils are discussed below.

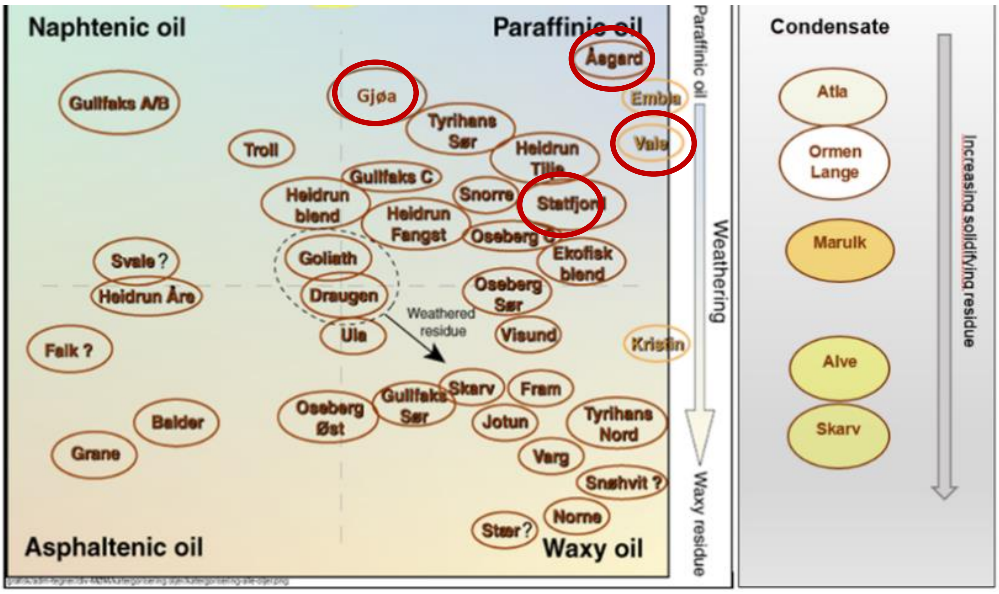


**Figure 5-2** Categorization of condensates based on increasing solidifying residues. The crude oils are marked with red circles. Note: Åsgard in this figure represents the Åsgard Light crude oil and not the Åsgard Blend used during the field trial in 2016

**Table 5-1** Physicochemical properties of the oils included in the TOF project (NA: not analyzed, ND: not detected)

| Oil name | Residue | Evap. (vol.%) | Residue (wt.%) | Density (g/mL) | Pour point (°C) | Viscosity (mPa.s), 13°C, 10s$^{-1}$ | Viscosity (mPa.s), 5°C, 10s$^{-1}$ | Asphaltnes (wt.%) | Wax (wt.%) | Yield stress (Pa), 13°C | Yield stress (Pa), 5°C |
|---|---|---|---|---|---|---|---|---|---|---|---|
| Atla | Fresh | 0 | 100 | 0,746 | -36 | 1 | NA | 0,02 | 0,5 | NA | NA |
| | 150°C+ | 62 | 41 | 0,809 | -24 | 2 | 2 | 0,04 | 1,2 | NA | NA |
| | 200°C+ | 78 | 25 | 0,826 | -9 | 4 | 5 | 0,07 | 2,1 | NA | NA |
| | 250°C+ | 88 | 14 | 0,842 | 3 | 8 | 50 | 0,12 | 3,7 | NA | NA |
| Marulk | Fresh | 0 | 100 | 0,759 | <-36 | 1 | 1 | <0.01 | <0.01 | ND | ND |
| | 150°C+ | 53 | 50 | 0,811 | -12 | 3 | 4 | 0,01 | 0,01 | ND | ND |
| | 200°C+ | 69 | 34 | 0,829 | 0 | 5 | 6 | 0,01 | 0,01 | ND | 0,3 |
| | 250°C+ | 80 | 22 | 0,842 | 6 | 9 | 22 | 0,02 | 0,02 | ND | 0,3 |
| Ormen Lange | Fresh | 0 | 100 | 0,75 | -33 | 1 | NA | <0.01 | <0.01 | NA | NA |
| | 150°C+ | 54 | 50 | 0,795 | -21 | 2 | NA | 0,01 | <0.01 | NA | NA |
| | 200°C+ | 70 | 33 | 0,809 | -12 | 3 | NA | 0,01 | <0.01 | NA | NA |
| | 250°C+ | 82 | 18 | 0,820 | -6 | 5 | NA | 0,02 | <0.01 | NA | NA |
| Gjøa | Fresh | 0 | 100 | 0,836 | <-36 | 5 | 4 | 0,03 | 1,5 | ND | ND |
| | 150°C+ | 25 | 78 | 0,866 | -24 | 14 | 25 | 0,03 | 1,9 | ND | ND |
| | 200°C+ | 36 | 67 | 0,879 | 3 | 34 | 57 | 0,04 | 2,2 | ND | ND |
| | 250°C+ | 48 | 56 | 0,892 | 12 | 98 | 428 | 0,05 | 2,6 | ND | ND |
| Alve | Fresh | 0 | 100 | 0,796 | 0 | NA | 12 | 0,03 | 5,0 | ND | ND |
| | 150°C+ | 39 | 64 | 0,836 | 12 | 9 | 765 | 0,05 | 7,8 | ND | 1,8 |
| | 200°C+ | 52 | 51 | 0,849 | 18 | 78 | 912 | 0,06 | 9,8 | 0,8 | 1,8 |
| | 250°C+ | 63 | 40 | 0,857 | 21 | NA | 2050 | 0,08 | 13 | 0,3 | 0,9 |
| Skarv | Fresh | 0 | 100 | 0,829 | 6 | 6 | 98 | 0,01 | 2,2 | ND | 1,8 |
| | 150°C+ | 31 | 71 | 0,857 | 15 | 47 | 201 | 0,02 | 3,1 | 1,8 | 2,8 |
| | 200°C+ | 55 | 48 | 0,882 | 21 | 191 | 604 | 0,03 | 4,5 | 2,8 | 1,8 |
| | 250°C+ | 69 | 33 | 0,897 | 27 | 627 | 4426 | 0,04 | 6,6 | 1,8 | 13 |
| Vale | Fresh | 0 | 100 | 0,816 | -9 | 37 | 169 | 0,03 | 3,3 | 1,2 | 0,4 |
| | 150°C+ | 27 | 77 | 0,851 | 6 | 189 | 1183 | 0,04 | 4,3 | 0,5 | 2,9 |
| | 200°C+ | 40 | 64 | 0,866 | 18 | 1169 | 4105 | 0,05 | 5,1 | 3,1 | 6,6 |
| | 250°C+ | 53 | 51 | 0,879 | 27 | 5098 | 15172 | 0,06 | 6,4 | 21 | 40 |
| Statfjord C Blend | Fresh | 0 | 100 | 0,834 | -9 | 12 | 60 | 0,16 | 4,1 | ND | ND |
| | 150°C+ | 23 | 80 | 0,869 | 12 | 146 | 385 | 0,2 | 5,1 | 0,5 | 0,8 |
| | 200°C+ | 34 | 70 | 0,883 | 21 | 679 | 2682 | 0,23 | 5,8 | 1,2 | 3 |
| | 250°C+ | 44 | 60 | 0,897 | 27 | 2578 | 9577 | 0,27 | 6,8 | 5,4 | 26 |
| Åsgard Blend (full-scale field trial) | Fresh | 0 | 100 | 0,78 | -36 | 1 | NA | NA | 3,9 | 0,2 | NA |
| | 150°C+ | 50 | 55 | 0,845 | 6 | 16 | NA | NA | 7,1 | 0,3 | NA |
| | 200°C+ | 63 | 41 | 0,866 | 15 | 132 | NA | NA | 9,5 | NA | NA |
| | 250°C+ | 72 | 32 | 0,883 | 24 | 707 | NA | NA | 12 | 3 | NA |

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### True Boiling Point (TBP)

The True Boiling Point (TBP) / distillation curve is obtained by measuring the vapour temperature as a function of distilled oil (vol.%). The distillation curves for the oils used in this project are given in Figure 5-3. The lightest condensates (by density), Atla and Ormen Lange (yellow and light blue lines) exhibit the highest evaporative loss, whereas Statfjord C Blend (blue line) (reference crude oil) has the lowest evaporative loss due to higher content of heavier components.

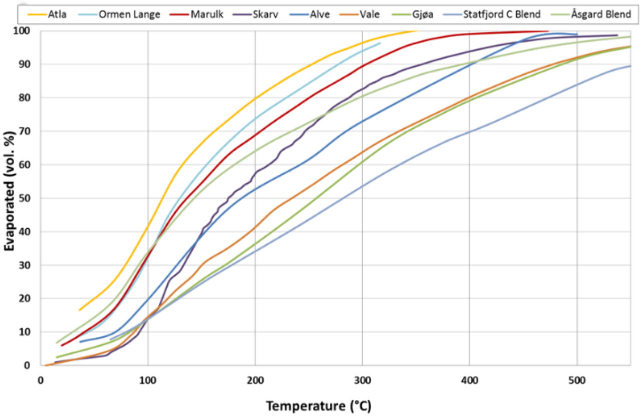


**Figure 5-3** **Distillation curves of the project oils**

### Density

The density of an oil is the ratio between mass and volume expressed (*e.g.* g/mL or kg/m$^3$). The density of hydrocarbons increases with increasing molecular weight. In American literature, the density of the oil is often expressed as API gravity (Equation 1). The density of fresh oils normally lies in the range of 0.78 to 0.95 g/mL that corresponds to 50 to 10 °API. The span in densities of the project oils are shown in Figure 5-4. Gjøa and Statfjord C Blend exhibit the highest densities > 0.83 g/mL, whilst the condensates Atla, Ormen Lange and Marulk have the lowest densities (< 0.76 g/mL).

**Degree API gravity = (141.5 / Specific Gravity) -131.5 (1)**

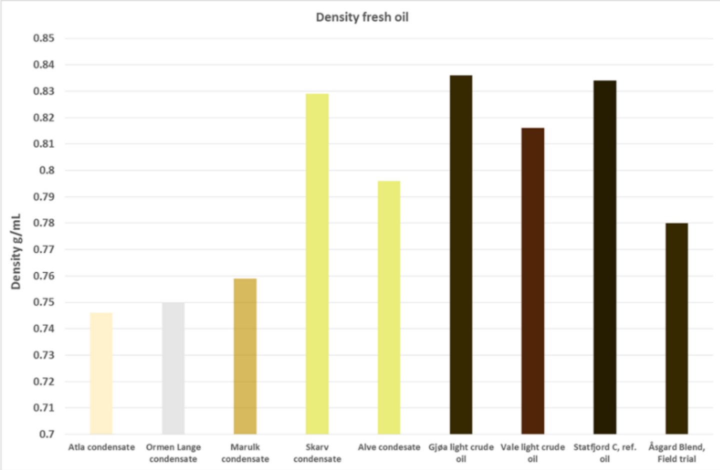


**Figure 5-4** **Variation of densities of the project oils (fresh oils)**

### Pour Point

The temperature at which oil ceases to flow when cooled without disturbance under static and standardized conditions in the laboratory is defined as the oil's *pour point*. This parameter determines the temperature at which the oil becomes semi-solid. The pour point of an oil with high wax-content increases with evaporation. The lower weight compounds contribute to keeping the wax in solution, and when they evaporate the residue solidifies. The pour points of the 250°C+ residue of the project oils are given in Figure 5-5.

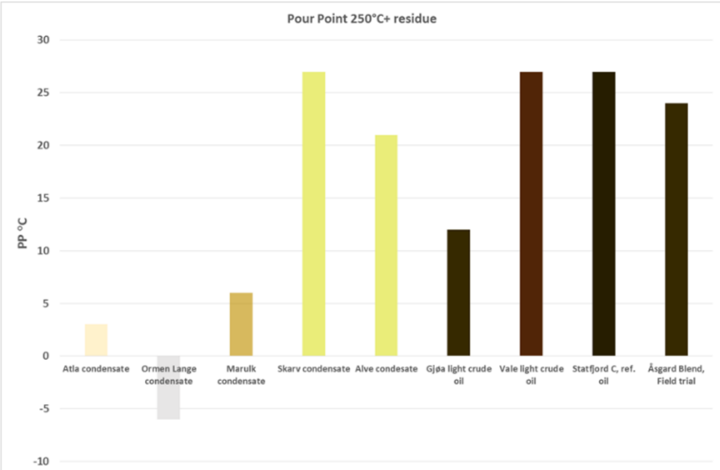


**Figure 5-5** **Pour point of the project oils from the 250°C+ residues**

### Yield stress /rheological property

The yield stress (Pa) is defined as the stress that must be applied to an oil /emulsion to make it begin to flow. Yield stress was measured on the fresh and the 250°C+ residue at 5 and 13°C, and was found to be insignificant for Atla, Ormen Lange, Marulk and Gjøa. These oils are also regarded as Newtonian, because their viscosities are independent of the shear rate, which is typical for low viscous oils with low wax content. Yield stress was significant for the Alve, Vale, Skarv, and Statfjord C Blend oils, particularly for the 250°C+ residue at 5°C. These oils are regarded as non-Newtonian due to their higher wax content. Yield stress rheology is assumed to be an important parameter for surface spreading Brönner et al., (2017). For OSCAR modelling, see Section 10.

## 5.2 Classification of condensates and light crude oils

According to the Recommendations given by Singsaas et al. (2017), the oils from this TOF project have been classified into four oil classes based on physicochemical data for the fresh and evaporated oil residues. Table 5-2 gives an overview of the different classes with the physicochemical criteria used in the classification.

**Table 5-2 Physicochemical data as a guide for classification of condensates and light crude oils**

| Class | Density g/mL | Evap. 200°C, % | PP* 200°C, °C | Asph. 200°C, wt% | Wax 200°C, wt% |
|---|---|---|---|---|---|
| **1** | < 0.80 | > 60-70 | < 0 | < 0.02 | < 2 |
| **2** | < 0.85 | > 30 | < 5-15 | < 0.05 | < 3-5 |
| **3** | < 0.85 | > 50 | > 15 | < 0.05 | > 5 |
| **4** | < 0.85 | < 30-50 | > 15 | > 0.05 | > 5 |

**Pour Point*

The defined classes are:

### Class 1: Non-emulsifying /-solidifying oils

Class 1 represents light condensates with a high degree of evaporation. Residues from these oils will not form w/o emulsions and they will not solidify on the sea surface due their low pour points and low concentrations of wax and asphaltenes. In breaking wave conditions (wind speed > 5 m/s), the oils will have a short lifetime on the sea surface due to the high degree of evaporation and natural dispersion. Physicochemical data for the condensates Marulk, Atla and Ormen Lange have been used as examples when defining this class.

### Class 2: Low-emulsifying oils

Class 2 represents condensates and light crude oils with a low to medium density and evaporation. The wax and asphaltene contents are slightly higher than Class 1, which indicate that oils in this class may form unstable w/o emulsions on the sea surface provided that the initial oil film thickness is higher than 0.1 mm. The oils will normally not solidify within the first day, due to the relatively low pour point of the residues. The lifetime on the sea surface is expected to be longer than for Class 1 oils. Physicochemical data for Gjøa have been used as an example when defining this class.

### Class 3: Solidifying oils

Class 3 represents more waxy condensates and light crude oils, which after a release may evaporate to residues with high pour points. Over time, the residues will start to solidify on the sea surface to form lumps/flakes with differentiating sizes depending on the sea conditions and the rheological properties of the solidified residue. These oils/residues will not form typical w/o emulsions. The lifetime on the sea surface will be longer than for Class 1 and the oils may persist on the sea surface for some time even at higher wind speeds (> 10 m/s), due to solidification. Physicochemical data for Alve and Skarv have been used as examples when defining this class.

### Class 4: Emulsifying paraffinic crude oils

Class 4 represents light crude oils with medium density and evaporation, and higher asphaltene and wax contents than the other classes. Provided an initial oil film thickness above 0.1 mm, oils in this class may have a tendency to form w/o emulsion after an oil spill to sea with varying viscosity and stability. Even if the pour point rises with time on the sea surface, the emulsions formed will retard the tendency to solidify. Although, under very calm conditions (e.g. 2 m/s wind speed) solidification may appear. Provided initial oil film thicknesses are low (0.05 mm and below), these oils may neither form w/o emulsions nor solidify. Physicochemical data for Vale and Statfjord C Blend have been used as examples when defining this Class.

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# 6 Laboratory testing – Behaviour of thin oil films from condensates and light crude oils

The laboratory testing was conducted to study the characteristics and behaviour of surface residues from thin oil films in calm weather conditions. Weathering of thin oil films from fresh oil was also assessed over time. To compare physicochemical properties, a set of standardized tests were conducted on all oils.

## 6.1 Closed experimental system

The principle of the closed experimental system, defined as the tilting cylinder method, is shown in Figure 6-1. This method was used to characterize the properties of thin oil films from the different weathered oil residues.

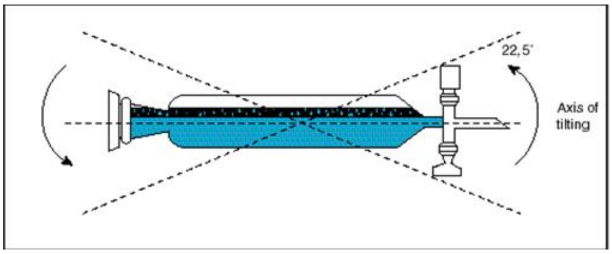



**Figure 6-1 Principle of the tilting cylinder method**

The experimental system was modified to give an equal tilting of 16 degrees in both directions. The results from these experiments were mainly based on qualitative observations (video and photo documentation). Figure 6-2 exemplifies the tilting cylinder method in the experiment. Procedure and description of the tilting cylinder method (aka rocking table test) are given in a separate Project Memo (D2-3).

**Figure 6-2 Examples from the tilting cylinder method /rocking table test of different oils/residues from the TOF project**

## 6.2 Open experimental system

In an oil spill situation at sea, weathering processes occur simultaneously and are interrelated. The weathering processes of thin oil films were simulated using two open experimental systems: 1) MNS chamber and 2) flume basin. To simulate calm weather conditions with none breaking waves, which is a prerequisite for extended lifetime of thin oil films, modifications of the experimental systems were performed. Procedures and descriptions of the modified open experimental systems are given in Project Memo (D3-1).

The MNS test (Mackay and Szeto, 1980) is one of the regulated methods for testing dispersant effectiveness in Norway. The energy input in this system is applied by blowing air across the oil/water surface, and generates a circular wave motion (see Figure 6-3 for the principle of the MNS test). The "standard" energy used for dispersant testing is estimated to correspond to a medium to high sea state (breaking wave conditions). A modified procedure with reduced applied energy was developed for adjusting the MNS method for studying the weathering, fate and behaviour of thin oil films under calm conditions.

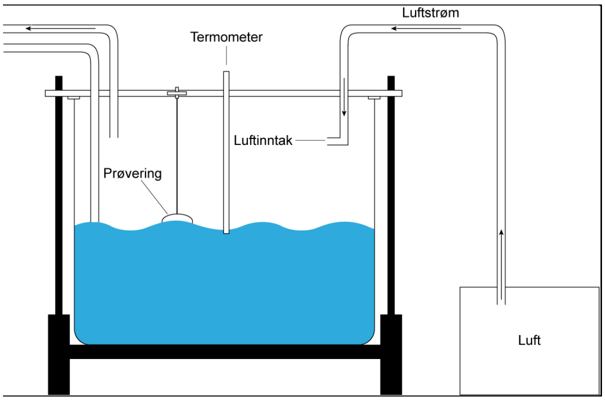



**Figure 6-3 Standard MNS chamber**

For larger scale weathering studies under calm sea conditions, the SINTEF meso-scale flume was used. The technical modification is given in Project Memo (D3-2). One liter of fresh oil was applied to the water's surface in the flume basin. Compared to the MNS chamber, the oil volume was increased to accommodate additional sampling and to ensure a larger volume of oil remained at the end of the experiment. A schematic drawing of the experimental flume basin is presented in Figure 6-4. Approximately 5 $m^3$ of seawater circulated in the 10-meter long flume, which was located in a temperature controlled room. Two fans were placed in a covered wind tunnel, controlling the wind speed and orientation.

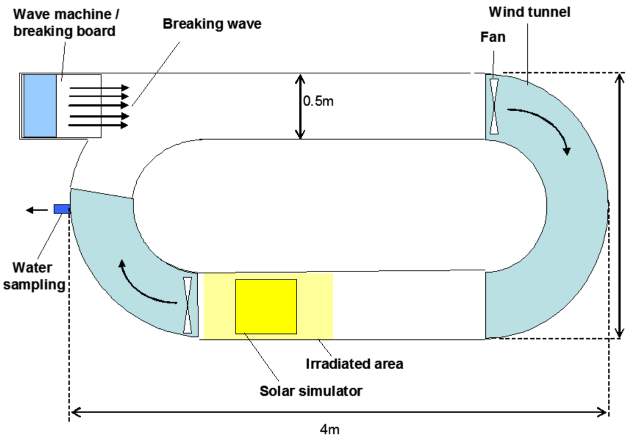



**Figure 6-4** **Schematic drawing of the flume basin**

## 6.3 Laboratory results

### 6.3.1 Characteristics of surface residues from thin oil films

The characteristics of surface residues of the project oils from the closed experimental system were studied after disturbing the surface film with applied tilting energy (see Section 6.1 for method description). The aim was to study formation of solidified lumps /emulsions on the water surface and the tendency for dispersion of oil droplets into the water phase. A large series of experiments, were performed:

- Weathering degree: 200ºC+ and 250ºC+ residue, and selected photooxidized residues. The 150ºC+ residue was not included in these experiments since this weathering degree (e.g. evaporative loss) is expected to occur within very short time at sea (less than 1 hour).
- Initial oil film thickness of 200 µm was used as the target default average film thickness from these experiments. Film thicknesses of 50, 100, 500 and 1000 µm were partly tested in selected test series.
- Energy exposure: Thin oil films are expected to be generated under calm weather conditions (typical non-breaking waves; < 5 m/s wind speed). Thin oil films are expected to be naturally dispersed in breaking wave conditions (> 5 m/s wind speed). The energy exposure was controlled by the tilting frequency, and the standard tilting frequency was defined at 12 rpm (defined as number of strokes per minute). Exposure time: 18 hours.
- Test temperature: 13 and 2°C represents respectively typical North Sea summer temperature and Arctic climate conditions, *e.g.* in the Barents Sea.

Results and description from these laboratory experiments can be found in Ramstad et at. (2016) and Project Memo (D2-4).

#### *Atla, Alve, Marulk and Skarv (condensates)*

The condensates did not show any significant water-uptake at 2 or 13°C. Atla and Marulk did not show any solidification/formation of lumps on the water surface, and easily formed dispersed droplets into the water phase with the applied standard tilting frequency. Marulk showed a slight tendency to form a "loose" emulsion at 2°C, but the negligible water-uptake indicated no significant emulsification. Skarv and Alve exhibit high pour points and formed solidified flakes.

#### *Gjøa and Vale (light crude oils)*

Gjøa and Vale formed "loose" emulsions. Vale formed lumps and solidified at 2°C, whilst Gjøa did not show any solidification at 2 and 13°C. However, the photooxidized residue of Gjøa formed stable emulsion at 13°C with water content ~ 54 vol. %.

#### *Reference Statfjord C Blend*

Statfjord C Blend showed water-uptake (20-30 vol. %) and emulsification. Similar to Vale, the Statfjord emulsion also solidified at low temperature (2°C). The oil solidified on the water surface and formed lumps from weathered residues (200 and 250°C+), including the photooxidized residue.

## 6.3.2 Weathering of thin oil films

Weathering of thin oil films from the eight oils were studied using the modified MNS test and flume basin simulating very calm sea conditions. The oils/condensates were applied onto the water phase by generation of small oil droplets by pumping the oil through a syringe, followed by surfacing and spreading to generate initial thin oil films. The results from this study has been reported in Ramstad et al., 2016 and Project memo (D3-2).

In the initial phase of the experiments (30-60 minutes), the sampling and monitoring were focused on quantification of evaporation of selected volatile hydrocarbons (VOC) with respect to potential human exposure (see Section 9). Weathering parameters, such as evaporation, solidification, dispersion/entrainment and emulsification were observed, monitored, and characterised over 18 hours.

The experiments were performed at 2 and 13$^{o}$C, with wind speeds of 1 and 3 m/s, and oil film thicknesses of 100, 250, and 500 µm. After the 18 hours of weathering, the applied energy was increased successively to simulate breaking wave conditions, and the breakup of the surface oil film and dispersion of oil droplets into the water column was studied (see Figure 6-5). Samples were taken during the experiments to monitor the evaporation process (using gas chromatographic analysis, GC/FID) and to quantify oil film thicknesses.

The appearance of the initial oil films varied from a uniform film to patches that solidified after a short time. The lighter condensates, Marulk, Atla and Ormen Lange individually spread into a homogenous film and their thickness initially sustained the calm experimental period. Oils with higher pour points, Vale, Atla , Skarv and crude Statfjord C Blend, had heterogenous films. The appearance and properties of these oils changed significantly during the experimental period, and some oils started to solidify (Skarv, Alve, Vale), whereas others remained as uniform liquid films on the water's surface (Ormen Lange, Atla and Marulk).

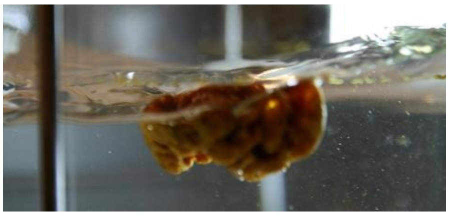
| | | | |
|---|---|---|---|
|  | Gjøa – droplet generation |  | Alve – solidified (apparent) film broke up and formed solidified droplets |
|  | Marulk, Atla and Ormen Lange – small oil droplets |  | Skarv – solidified surface film was broken up into "flakes" (not droplets) of solidified oil |
|  | Vale – generation of one large lump |  | Statfjord C Blend– initial generation of one large lump, which was broken up into smaller but still relative large droplets/lumps |

**Figure 6-5** **Behaviour of oil film residues with breaking wave conditions in the MNS chamber applied after 18 hours weathering at calm conditions**

No natural dispersion or emulsification was observed during the experimental period with low wind speeds. The light oils and condensates had varying concentrations of light compounds, so the volume that evaporated ranged from 50 to 98% (18 hours). In addition to oil type, the evaporation was also affected by the oil film thickness, temperature and wind speed.

All the oil were tested in the modified MNS chamber. In the MNS test, no stable emulsions were generated during the short period with breaking waves (30 minutes), which was in accordance with the closed system experiments using evaporated residues. The solidified oils/condensates generated a limited number of relatively large lumps. The liquefied films generated smaller oil droplets under exposure, which resurfaced and generated a "new" film after termination of the exposure.

In the flume basin experiments there were significant water quantities in the samples, which were probably due to the higher exposure in the area close to the wave generator with some accumulation of oil, allowing water incorporation in the oil phase. The stability of these "emulsions" was however not quantified, but from observations they appeared to be unstable. However, it was observed some challenges using the flume basin to study thin oil films mainly caused by the wall-effects, where the films easily were sticked to the surrounding flume wall. This phenomenon was not, however, observed in the MNS-test. Therefore, only a selection of oils were tested in the flume basin.

Sorbent pads was used to evaluate the adhesion properties of a selection of different oil residues by visual documentation to test the adhesion to a relevant skimmer material. This is illustrated in Figure 6-6 for Gjøa and Skarv from the flume experiments. The colour intensity of the oil residue was in general very weak and was difficult to identify on the pad surface. After careful examination, it was concluded that the adhesion properties of the tested residues were independent of the oil properties.

Gjøa (Flume experiment) Skarv (Flume experiment)

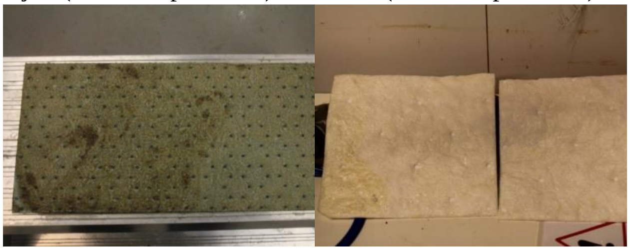


**Figure 6-6** **Adhesion of oil residue to sorbent pads at the end of the experimental period**

Some of the oil residues generated during the weathering in the flume basin and from the MNS experiments were evaluated for dispersibility with the field dispersion (FET) test using Dasic NS dispersant. The oil residues from the flume experiments at 13°C, including Gjøa, Skarv and Statfjord C Blend showed good dispersibility. Similar results were observed in the MNS experiments at 2°C for Statfjord C Blend and Gjøa, whereas the high-waxy residue of Vale showed limited effectiveness of dispersant.

### 6.3.3 OWM predictions and summary of oil properties

The initial oil film thickness from an oil spill may vary depending on many factors. The way the oil is released (oil spill scenario) is of upmost importance to the formation of the oil film. A subsea release from a depth less than 400 - 500 m will typically give lower initial film thicknesses than a surface (e.g. platform) release. For a subsea release, the water depth, release conditions (amount, release diameter etc.), and gas-to-oil ratio (GOR) are important for the subsequent film thickness formation on the sea surface.

The SINTEF Oil Weathering Model (OWM) was used to visualize how physicochemical properties influence weathering behavior. A standard scenario was chosen to simulate an initial thin film thickness lower than 250 µm for all eight oils. Oil film thickness represented thin thicknesses anticipated shortly after an subsea release. Under a given set of defined release parameters, the OWM predicts the change in the oil's properties and behavior over time on the sea surface. The input parameters are given in Table 6-1. Figure 6-7 shows examples of oil weathering predictions at 13°C and 5 m/s wind speed for the eight oils. For a more extent overview of OWM predictions, see Ramstad et al., 2016.

**Table 6-1** **Release parameters for OWM predictions**

| OWM Release input parameters | Numbers and units |
|---|---|
| Release rate | 250 $m^3$ for 1 hour (equals to 6000 $m^3$/d) |
| Gas-to-oil ratio (GOR) | 50 |
| Water depth | 300 m |
| Temperature | 2 and 13°C |
| Wind speed | 2 and 5 m/s |

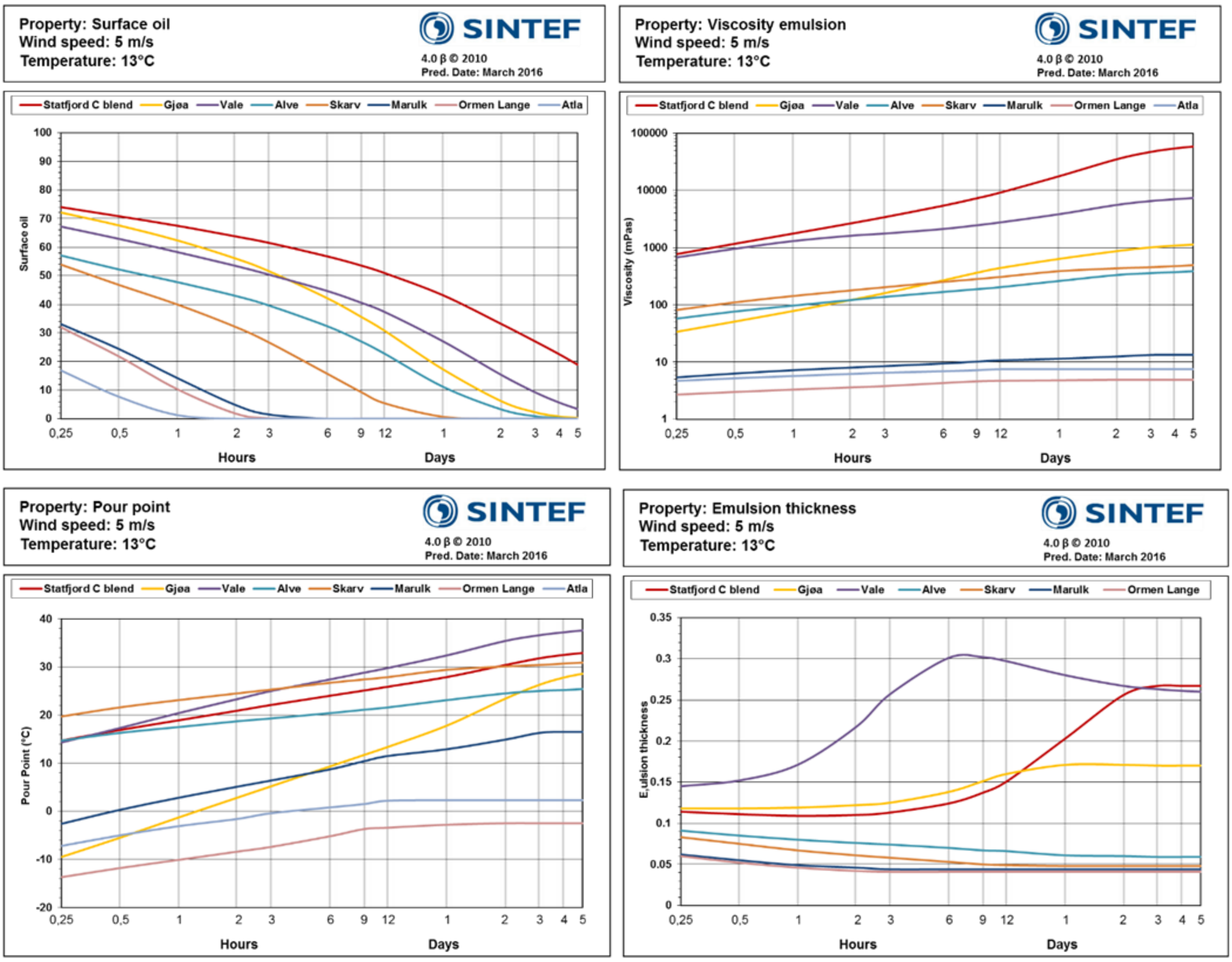



**Figure 6-7** **Examples SINTEF OWM prediction of surface oil (mass balances), viscosity emulsions, pour points and emulsion film thicknesses at 13°C and 5 m/s wind speed for the 8 oils for comparison. Predictions based on standard subsea release (see Table 6-2)**

### *Summary of the oil properties*

**Atla**, **Ormen Lange** and **Marulk** residues have a low density, low wax and asphaltene content, and will not generate water-in-oil (w/o) emulsions. They have a low pour point with no yield stress, and can therefore undergo further spreading at the sea surface.

These oils will have a rapid evaporation and the oil films of these residues will easily be dispersed/entrained into the water column by (increasing) wave exposure.

**Alve** and **Skarv** residues have high wax content. They have a yield stress, which will restrict spreading at the sea surface. The evaporated residues have a high pour point that may result in solidification. The residues do not take up water for emulsion formation. The fate of the solidified oil film is dependent on the environmental conditions. Under calm condition, the evaporation will probably be slowed down due to the solidification, and spreading of the oil may be restricted. The solidified film could be accumulated in *e.g.* windrows. Under increasing wave exposure, the solidified residues will be entrained into the water column as solidified lumps or large droplets/"flakes".

**Gjøa** and **Vale** are representatives for oils that have potential for water uptake and emulsion formation, as shown in the standard weathering studies. The water uptake is however dependent on the initial oil film thickness and wave energy exposure. The emulsion generated had a high water content with limited stability. In the laboratory studies performed in this project, with very calm condition, no water uptake with these residues was observed.

Gjøa and Vale are, however, different with respect to chemical composition and physical properties. The properties of Vale residues are also similar to Alve, Skarv and Statfjord C Blend (reference oil) residues with high wax content and a high pour point and may be solidified under calm wind conditions, whilst the emulsion properties are more similar to the Statfjord C Blend.

## 6.4 Further use of findings from the laboratory study

All the oils included in the laboratory study have previously been subjected to a weathering study. In a "traditional" weathering study the oils are tested as if they form a relative thick oil film (e.g. 20 mm). Predictions of weathering properties by use of the SINTEF OWM are based on a surface release with an initial oil film thickness of 20 mm. In this study, we modified some analytical methods used in previous weathering studies to accommodate lower oil film thicknesses. The intention was to study whether a low oil film thickness under low energetic conditions (simulating calm sea conditions) would have the same behavior as predicted in the weathering studies for a thicker oil film. The initial thicknesses used in the three test apparatuses (tilting cylinder, MNS apparatus and flume basin) was approximately 200 µm. The findings indicated:

- Water-in-oil emulsification. Even with this thin oil film (200 µm), Gjøa, Vale and Statfjord C blend showed a tendency to form w/o emulsions. Gjøa residue formed loose emulsions with low stability. Vale residue formed more paraffinic emulsions similar to Statfjord emulsions (in viscosity). None of the light condensates showed a similar tendency. This confirms that an oil film thickness of 200 µm may be sufficient for emulsion formation. It is assumed that at oil film thicknesses below 100 µm, an oil is not capable of forming w/o emulsions because the oil droplets formed are too small for incorporation of water when re-surfacing.
- Solidification may appear if the pour point of an oil residue increases to 5-15°C above the sea water temperature. It may be more pronounced at calm sea conditions (low wind speed and wave activity). It has been demonstrated in this project that residues from Skarv, Alve, Vale and Statfjord C Blend may have a potential for solidification (solidified flakes) even with a low initial oil film thickness (200 µm). It is assumed that if an oil film is observed as "metallic" (5-50 µm), which is at the lower end of the definition of thin oil films in this project (5 to 200-300 µm), the oil properties will not have any influence on the rheology of the modelled film.
- A defined subsea release scenario was chosen as input to the SINTEF OWM. The scenario, presented in Table 6-1, gave a low predicted initial oil film thickness for all the oils included in the TOF study. Given these input data the predictions showed that the light condensates (Atla, Ormen Lange and Marulk) have a short lifetime at the sea surface, even under low wind conditions (5 m/s). Alve and Skarv will not form any w/o emulsion, but the lifetime on the sea surface will be longer as

the residues may solidify under calm conditions at low sea water temperature. The predictions indicate that Gjøa may form a loose emulsion given the conditions described in this scenario, with very low viscosity, indicating that it is easily broken. Vale and Statfjord C blend may form slightly more stable w/o emulsions with higher viscosities. The predictions verified the findings from the laboratory study that initial film thickness above 100 µm can cause w/o emulsification, but that initially thin oil films from many condensates and light crude oils can have a short lifetime at the sea surface.

- The laboratory study was used to perform a comprehensive analysis of volatile and toxic compounds as part of a PhD study. The focus was on human exposure to contaminants in oil spill response operations. The laboratory data were used as a basis when measuring Total Volatile Organic Compounds (TVOC) during experiments performed as part of the NOFO field trial in 2016. The final publication of results will take place in 2018.
- Findings from this laboratory study contributed to evaluation and selection of oil spill response concepts (see Section 7) and together with the tower basin testing it was an important basis for planning, selection of test oil (Åsgard Blend) and performance of the field testing during the NOFO 2016 field trial.

# 7 Testing of response concepts and construction of operative prototypes

## 7.1 Evaluation of concepts

As a part of the TOF project, several response concepts for treating thin film films (0.2 - 0.3 mm) were evaluated as possible methods, either as a stand-alone method or in combination with others. The possible response concepts that were evaluated and discussed are summarised as followed:

- No response, only monitoring (natural dispersion/evaporation). Lifetime on sea surface will depend on the properties of the residue and the weather conditions
- Dispersant application at low dosage (e.g. based on present boom systems)
- Mechanical dispersion (artificial turbulence or energy)
- Sorbent booms, "loose" sorbents, pads
- Combinations:
  - Dispersant booms
  - In-situ burning (ISB)
  - Bubble booms (limited area and swath width)-potential in ice
  - Spreaders (thinners)
  - Herders in combination with dispersant application, ISB and /or mechanical recovery

The most important aspects for choosing response concepts were based on the two main factors: 1) to enhance natural dispersion of the oil film into the water column, and 2) utilize existing equipment to deliver high-capacity water flushing from existing pump systems from Fi-Fi monitors and fire extinguishing systems currently installed on oil spill response vessels and on larger coastguard vessels. In addition, the well-known strategy to use such artificial energy to enhance natural dispersion in combination with use of dispersant was considered as a relevant method for treating thin oil films in an early phase after a spill.

Mechanical dispersion by use of high-capacity water flushing as a standalone method, or in combination with use of low dosage dispersant application were therefore concluded as the two main concepts that were decided to be further developed and customized as a combination of using existing technology and equipment.

## 7.2 Theoretical evaluation and laboratory testing of nozzles

Theoretical evaluation and laboratory testing of different types of nozzles were carried out as part of the TOF project. The objectives were to investigate the potential of using high-capacity water flushing from nozzles for mechanical dispersion of a thin oil film at sea. In addition, Johansen (2015) has given a theoretical evaluation of the concept for use of a vertical water jet for mechanical dispersion of thin oil films (a part of Project Memo D3-5). The theoretical evaluation implied that water flushing was a promising concept for breaking-up a thin oil film, but designated experiments were recommended to determine the criteria for optimal water flow rates.

### *Evaluation and laboratory testing of nozzle concepts*

Nozzle types were evaluated for oil droplet size distribution after treatment of an oil film with water flushing. Seven smaller nozzles of different sizes, angles and configurations were tested in the SINTEF minitower.. In addition, 4 larger nozzles types were also tested in the SINTEF tower basin to document droplet penetration rates with different test settings (i.e. nozzle velocities, tilting angles, and water flow rates). Examples from the basin testing of the nozzle concepts are given in Figure 7-1 and Figure 7-2.

Figure 7-1 shows a schematic illustration and photo documentation of tracer particles (3 mm polyethylene particles) interacting with the water jet generated by the nozzle. The preliminary findings showed that both the nozzle application and nozzle velocities were important factors for breaking up a thin oil film.

Figure 7-2 shows experiments using the different nozzles. Based on the initial laboratory testing, the "Veejet 750" nozzle type with a spreading angle 25° was considered the most promising for breaking-up thin oil films. This nozzle type was also installed on the full-scale prototype boom manifold and tested prior the field trial (see Section 7.3).

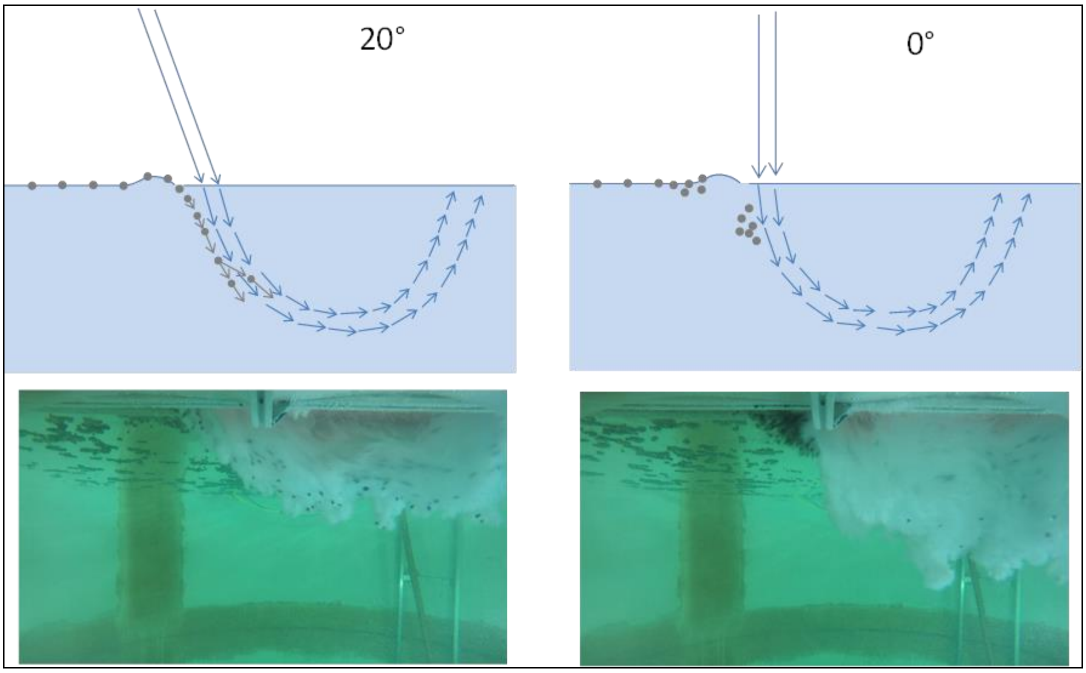



**Figure 7-1** **Schematic illustration and photo documentation of tracer particles interaction with the water jet with nozzle angels of 20 and 0°**

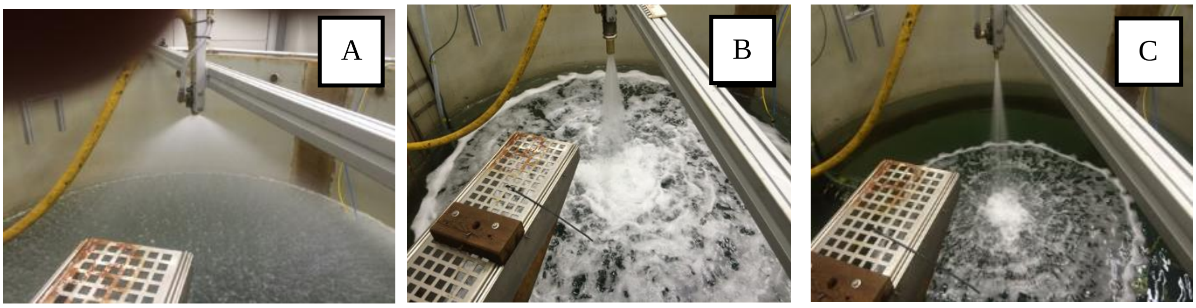



**Figure 7-2** **Testing of nozzle concepts in the SINTEF tower basin A) full jet 120°, B) Flat jet (25°)-most promising C) Full cone nozzle (less penetration-no further testing**

### *Testing of high volume nozzle treatment of thin oil films with full-scale experimental condition*

In order to further evaluate the efficiency of the "Veejet 750" nozzle, it was installed on the high-capacity nozzle manifold at MS Strilborg (Section 7.3). Water flow and nozzle height above the water surface was varied in different experiments. Water flows of 200, 300 and 400 l/min were used in these experiments, where 300 l/min flow per nozzle were used during the full-scale field trial (Section 8).

In addition, the nozzle heights were varied from 0.5, 1 and 1.5 m, which represents the varying operative water flushing heights in the field. These experiments showed that high-capacity water flushing has a potential to break-up a thin oil film of Åsgard Blend to droplets in the range of 70-100 µm with water flows of 300-400 l/min. The operative nozzle height is recommended to be 1-1.5 m above the sea surface for optimal effect. The experiments were a part of NOFOs technology development program Oljevern 2015 (Sørheim et al., 2017)

### *Calculation and effect of weathering degree on water droplets*

The experiments in the SINTEF tower basin as described above have been done with injection of fresh Åsgard Blend. An increase in the droplet size distribution and reduction of treatment efficiency should therefore be expected with weathering at sea, but this has not been systematically tested. However, the median droplet size distribution (d50) as a function of the oil viscosity has been calculated using a modified *Weber equation* (Wang and Calabrese, 1986) verified for subsea blowouts. Droplet sizes from high-capacity water flushing were calculated using the SINTEF OWM by connecting droplet size calculations to predictions of oil emulsion viscosities. It should be noted that the calculation has not been demonstrated experimentally, but should be considered as a preliminary indication of the expected development of the median droplet size with increasing viscosities during weathering of oil at sea.

To generate oil droplet sizes (d50) <70-100 µm (see red line in Figure 7-3) for optimal efficiency with application of high-capacity water flushing for a weathered oil of Åsgard Blend, the viscosity of oil / emulsion should be less than 150-250 mPa.s. This indicate an effective time window of < 5-6 hours at 2 m/s wind speed, and correspondingly 2-3 hours at 5 m/s. The potential for high-capacity water flushing to break-up an oil film into smaller drops for effective treatment is therefore linked to an early phase (i.e. hours after a spill of a light crude oil / condensate in calm weather conditions). This was also documented in the field (see Section 8).

Validation is recommended through laboratory experiments on a wider range of oils (with different viscosities) to obtain a robust operational time window for high-capacity water flushing.

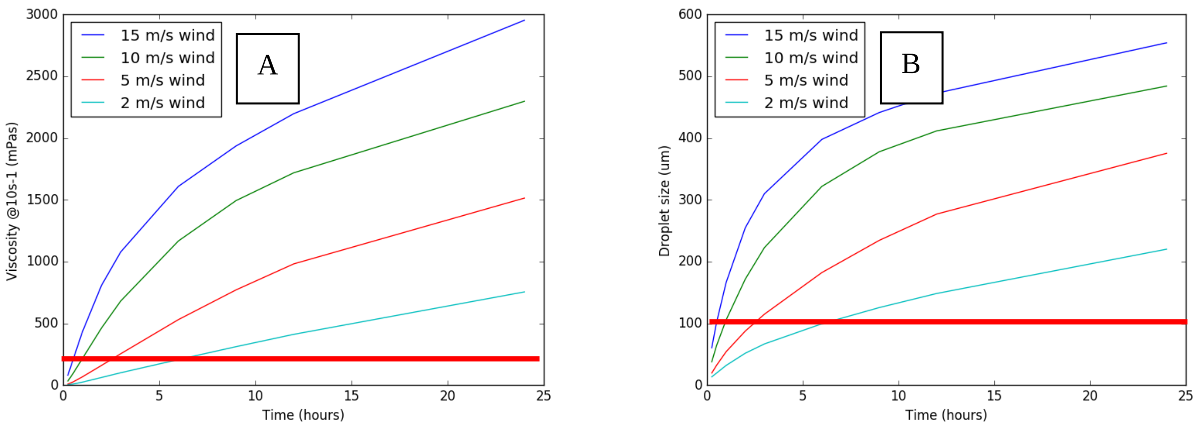



**Figure 7-3** **A: Predicted viscosities (shear rate 10 $s^{-1}$) for Åsgard Blend. Red line shows the viscosity limit of 250 mPa.s for optimal dispersion with high-capacity water flushing B: Calculated median droplet size d (d50) based on viscosities and densities. Red line shows the maximum droplet size (< 100 µm) for optimal dispersion**

## 7.3 Construction, installation and preliminary testing of prototypes

The development and customizing of the concepts were conducted as a separate part of NOFOs technology development program Oljevern 2015 (Sørheim et al., 2017). Here, the main objective was to develop both simplified and cost-effective solutions with high-capacity water flushing to reduce the potential of environmental damage from thin oil films at sea. The concept of mechanical dispersion with the use of high- capacity water dosing was developed for this purpose. The main delivery under the NOFO Oljevern 2015 program WP-048 was to develop and test the two prototypes for mechanical dispersion of thin oil films consisting of the following equipment solutions:

1) A high-capacity boom (manifold) with water flushing that can be placed in the bow (front) of the vessel according to the same principle as today's dispersant spraying system on oil spill response vessels
2) Construction of deflector nozzle (so-called "nebb") that can be mounted on the Fi-Fi monitors

Both prototypes were developed and constructed in cooperation with Jason Engineering AS. A container based system including both the high-capacity boom manifold for water flushing, and high-and low dosage boom manifold for application of dispersant was constructed. Figure 7-4 shows the container based system and the deflector nozzle. The prototypes were installed on MS Strilborg (see Figure 7-5), and their general functions (without oil) were tested in Hammerfest in May 2016 prior to the NOFOs field trial in June 2016. The defector nozzle showed a reduced efficiency and a two-phase splitting of the vertical water jet. The deflector nozzle was therefore stripped down from the Fi-Fi monitor system and was not further used in the field trial.

The concepts of high-capacity water flushing from both the nozzle boom manifold and Fi-Fi monitors (without mounted deflector nozzle) were tested with a light crude oil/condensate of Åsgard Blend during the field trial as a part of the TOF project (see Section 9).

**Figure 7-4** **Left: A complete container based bow boom system for mechanical dispersion by high capacity water flushing and use of dispersants. Right: Deflector nozzles**


**Figure 7-5** **Response systems installed on MS Strilborg for treatment of thin oil films:**
**1): High/low dosage dispersant spraying system,**
**2): High capacity water flushing boom,**
**3): Fi-Fi monitors**

# 8 Field verification NOFO Oil-on-Water (OOW) field trial 2016

## 8.1 Main objectives for the field trial

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 or condensates, which is not possible to perform in laboratory laboratories experiments
- To study and document the formation of bands/windrows of thick oil, which can be an important factor for the behaviour and persistence of spilled condensates or light crude oils
- To test and document the operative efficacy and capabilities of response options based on recommendations and laboratory results. Laboratory and field-testing of response concepts was also conducted as a part of the NOFO Oljevern 2015 program *"Mechanical Dispersion of Thin oil films"* funded by NOFO (see Section 7.3)
- To characterize personal exposure to airborne hydrocarbons by stationary and personal (biological) monitoring of volatile oil components (VOCs) under relevant oil spill response conditions (see Section 10)

## 8.2 Releases and treatment strategies

As an integrated part of the NOFO 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), see properties in Table 5-1 were conducted:

- TOF 3.1: Reference slick without any response treatment. Released day 1, under non-breaking wave conditions.
- TOF 3.2: Released day 1, under non-breaking wave conditions. Treated 1-1.5 hours after release with a low concentration of dispersant, followed by high-capacity bow boom water flushing
- TOF 3.3: Released day 2, under breaking wave conditions. Treated with water flushing from Fi-Fi monitors 3-4 hours after release

Figure 8-1 illustrates the order of the oil releases and the release strategy. To allow the 10 m$^3$ of oil to spread to an average film of 0.2 – 0.5 mm. The slicks were released over a distance of 500 m within 5 min.

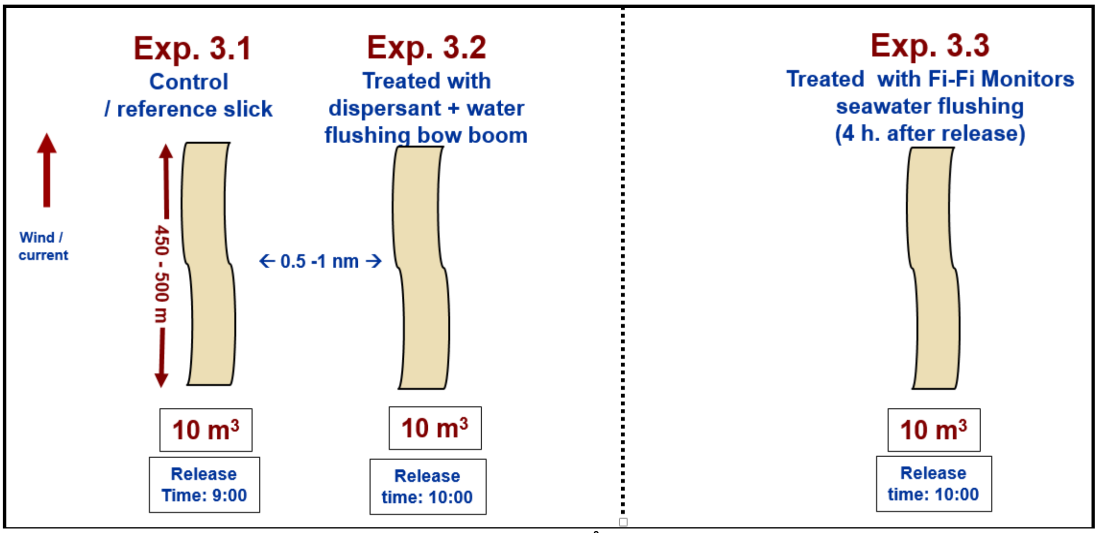



**Figure 8-1** Schematics of the three releases with Åsgard Blend. Exp.3.1 and 3.2 were releases performed June 14[t.h.] ("Day 1") under non-breaking wave conditions and Exp. 3.3 released June-15[th] ("Day 2") under breaking waves conditions

## 8.3 Vessels and Monitoring Platforms

Two response vessels contracted by the Norwegian Coastal Administration (NCA) were allocated for the field experiments:

1) The Norwegian coastguard vessel KV Sortland (see Figure 9-2 A) was the 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) and an Aerostat (Ocean Eye™ with visual and Infrared (IR) video cameras, Figure 8-2 C)
2) MS Strilborg (Figure 8-2 B) is a response and emergency towing vessel. Two sampling boats, (MOB (Man Over Board)) boats operated from on MS Strilborg were used for ground truth sampling (surface oil and water column) and air monitoring

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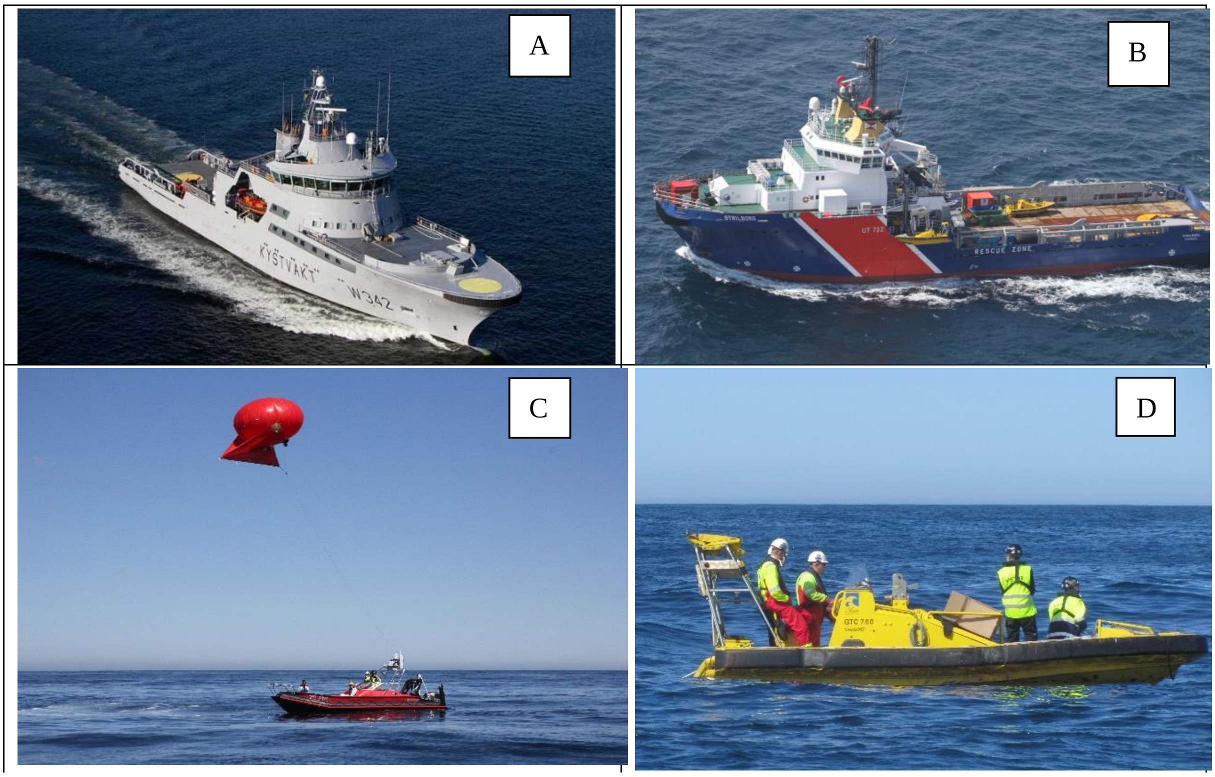



**Figure 8-2** **Vessels involved in the TOF- experiments: A): KV Sortland (command vessel), B): Strilborg, C): USV with Aerostat, D): Sampling boat (MOB-B boat from MS Strilborg)**

Additionally, surveillance aircraft from three countries participated during the trials in monitoring the spreading / behaviour of the slicks, and in documenting effects of the response treatment. A range of sensors available in the aircraft were used for documentation, including:

- Side Looking Airborne Radar (SLAR)
- Electro Optical and Infrared (EO/IR) HD video camera
- (IR / UV) Line scanner
- Visual estimation of oil layer thickness according to the Bonn Agreement Oil Appearance correlation (BAOAC)

Synthetic Aperture Radar (SAR) pictures from satellites acquisitions gave valuable documentation of the overall spill site area, while visual monitoring from drones provided detailed documentation of the surface spreading and oil distribution within the individual slicks.

The total volatile organic compounds (TVOC) concentrations in the air were monitored by the use of eight photoionization detectors (PID) placed on different platforms (sampling boats and vessels) operating close to the oil slicks. In addition, human exposure to aromatic volatiles (BTEX: benzene, toluene, ethylbenzene, xylenes: and naphthalenes) was measured by use of Thermal Desorption Tubes (ATD) and urine samples collected before and after work shift of personnel on sampling boats and vessels. This is a part of the PhD-study and reported in separate papers, see Section 10.

The ground-truth sampling from the MOB boats included:

- Surface oil slick thickness measurements (synchronized to aircraft monitoring)
- Surface sampling for physicochemical characterization of oil properties on site (i.e. viscosity, water content, emulsion stability, dispersibility field test, and post laboratory analyses of evaporative loss and density)
- Water column: Oil concentration by Ultra Violet Fluorimetry (UVF) plus chemical analysis of water samples and *in-situ* oil droplet size distribution measurements by using a LISST-100 instrument towed at 1 m water depth.

## 9.4 Main findings from the field testing

A substantial amount of quality data was collected from the various monitoring platforms during the two-day field trial. Comprehensive planning and agreeable prevailing weather conditions allowed the completion of three out of four planned experiments with Åsgard Blend. The data and results from the field trial are reported in Daling et al., 2017 [a)], and published in Daling et al, 2017 [b)].

### *Behaviour of Åsgard Blend at sea*

The spreading and weathering behavior of spilled Åsgard Blend was documented in both non-breaking (< 5 m/s wind speed) and breaking wave conditions (> 5 m/s wind speed). The oil was released to produce initial average oil thicknesses of 0.2 to 0.5 mm. During and after the release, measurements were made of the TVOC concentrations in the air, and the plumes of volatile compounds were also detected remotely by IR/FLIR sensors on the aircraft and Aerostat during and after release. As much as 50 vol.% of this light crude / condensate blend evaporated in the first 2 to 3 hours on the sea. The initial spreading behavior of the oil was in accordance with the prior-modelled spreading behavior. However, within two hours on the sea surface, the reference slick (TOF 3.1) had become "re-distributed" into areas of very thin oil films (sheen, rainbow metallic) and smaller areas of thick oil residue (1 to 2 mm) that formed narrow bands (IR white in Figure 8-3 A/B/C, below). These bands contained more than 80% of the total oil volume, but cover less than 20% of the IR-detectable slick area. During the day, the oil residue in these bands increased in pour point and started to solidify, which prolonged its break-up and extended its lifetime. Patches of surface residue were detectable through the next day even under breaking wave conditions.

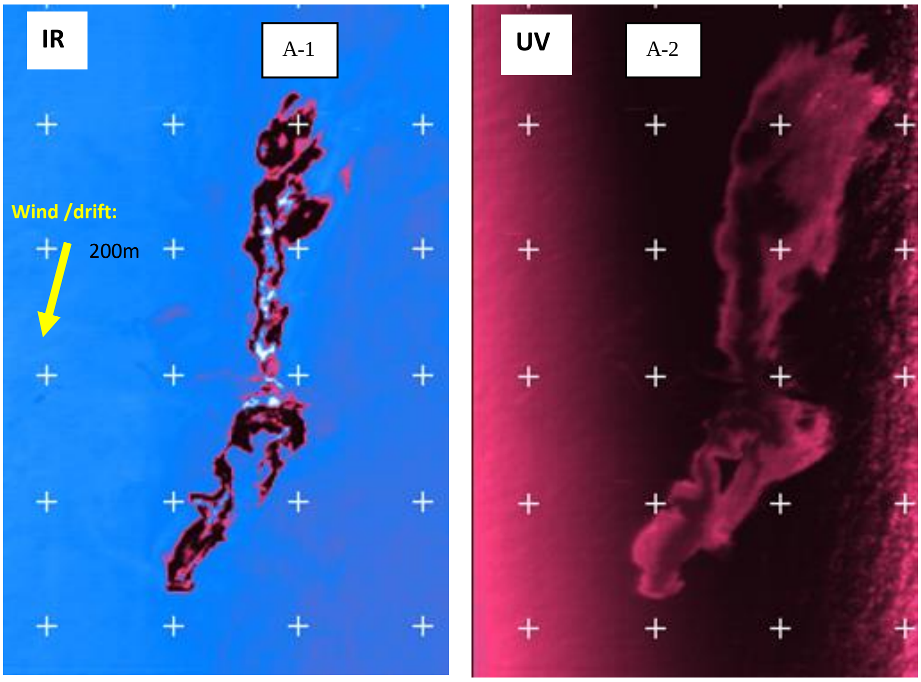



**Figure 8-3 A-1/A-2** **IR /UV line images of TOF 3.1 slick after 1 hour**

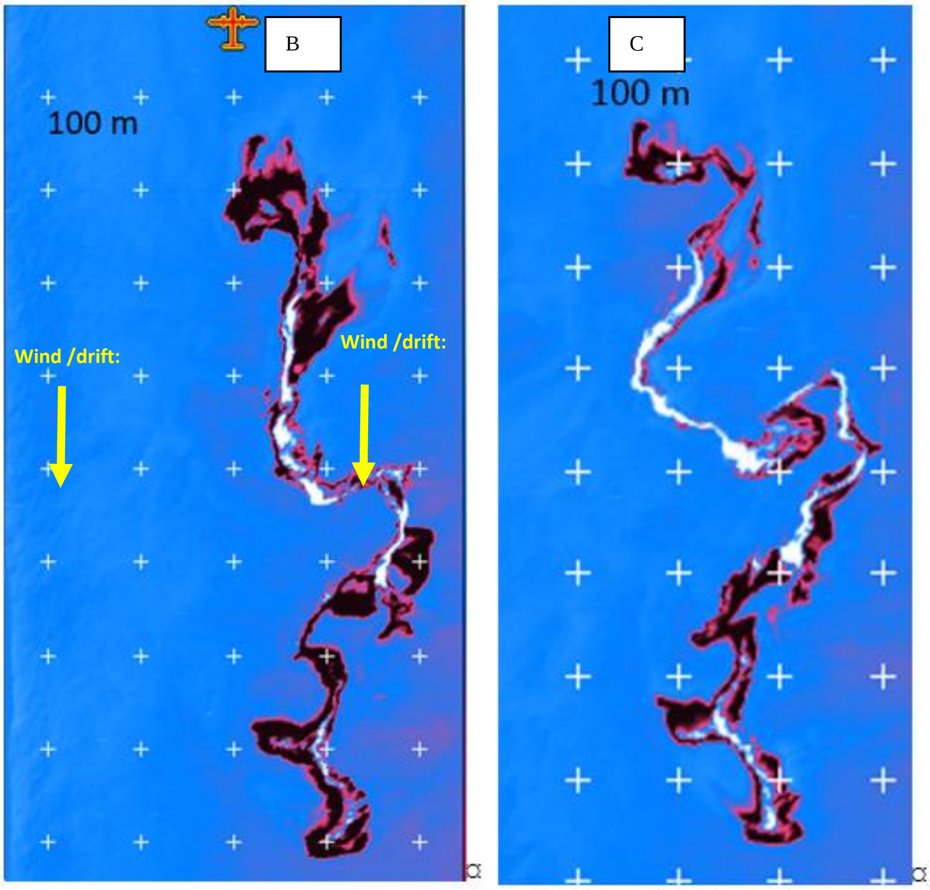



**Figure 8-3 B/C** **Surface behaviour of reference slick (TOF 3-1): B: IR image 1.5 h and C: IR image 12 h after release. Shows contraction into narrow bands (IR white) of 1-2 mm thick oil residue**

### *Effect of response treatment*

Three novel response techniques were tested during the field trials:

i. low-dosage dispersant treatment, followed by
ii. high-capacity water flushing from bow-mounted boom, and
iii. water flushing by using Fi-Fi monitors

Mechanical dispersion by using high-capacity water flushing and mechanical dispersion using Fi-Fi monitors was tested in a full-scale field trial. The high-capacity water flushing system was not tested as a stand-alone / independent response technology. Results from laboratory basin experiments with similar nozzles and test conditions as in the field (Sørheim et al., 2017), indicated that this system has the potential to be an effective response option for dispersing weathered oil residues with viscosities of in the range of 150 - 300 mPa.s without using dispersants.

Although not tested under optimal conditions (due changes in the field plan, a decision taken by the on-scene commander) the Fi-Fi monitor water-flushing response was effective. The testing clearly demonstrated its potential for reducing the persistence of spilled light crude oils /condensate on the sea surface.

For the TOF 3.2 slick, dispersant application followed by high-capacity water flushing (0.5 to 1 hour after the dispersant treatment) was found to be extremely effective. The majority of oil was dispersed as small oil droplets (70 to 100 µm) in the water column (see aerial photo in figure 8-4).

Low dispersant concentrations (DOR 1:300 to 1:400 for the thickest oil) were sufficient to disperse light crude oil. Only a thin oil film remained after the dispersant treatment (see IR image of TOF 3.2 slick versus the reference TOF 3-1 slick in Figure 8-5).

Effective dispersion was achieved by combining the low-dosage dispersant treatment with artificial turbulence. This turbulence was 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.

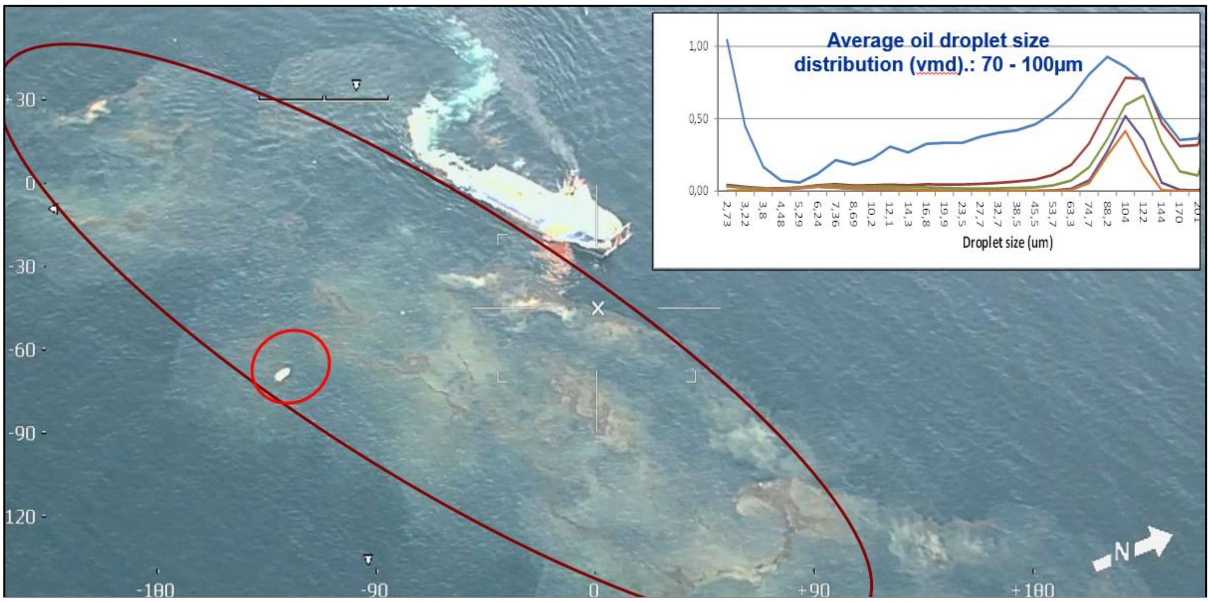



**Figure 8-4** **Aerial photo just after the low-dosage dispersant application. Sampling boat (red circle) monitor the dispersed oil concentration and oil droplet size distribution in the water column**

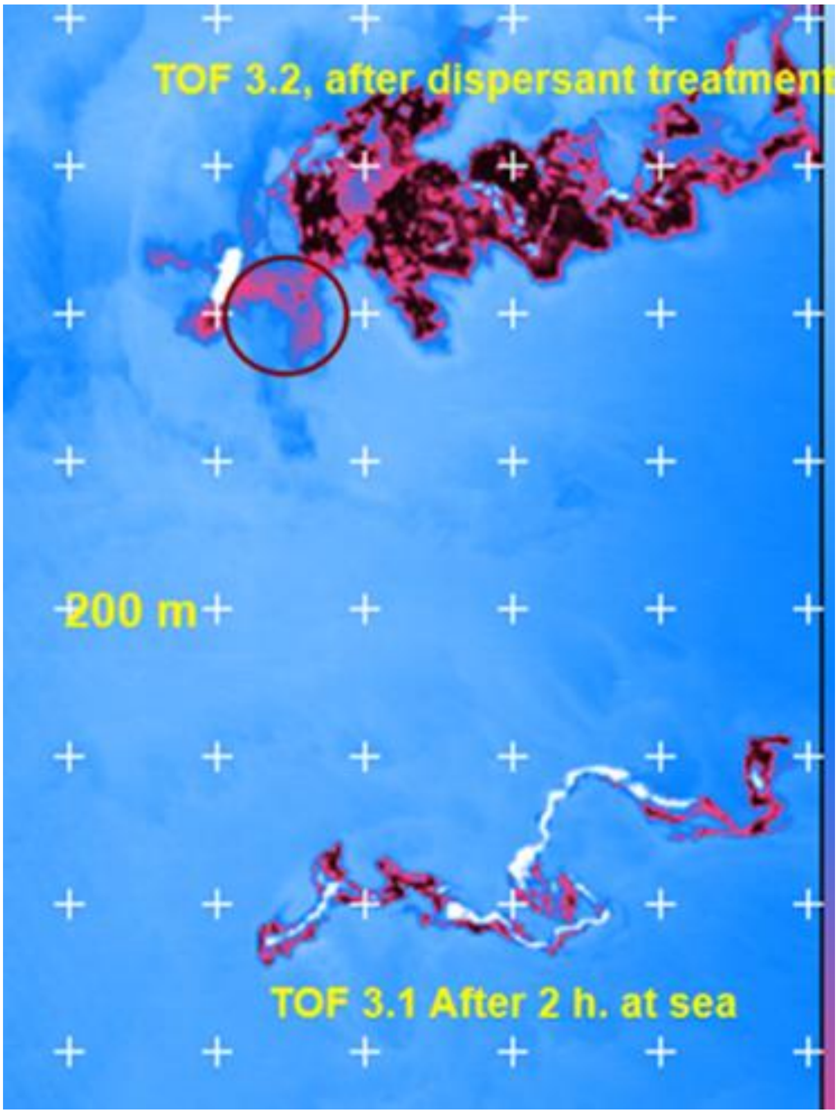



**Figure 8-5** **IR images after low-dosage dispersant treatment of the TOF 3.2 slick compared to the non-treated TOF 3.1 reference slick with the characteristic "bands" of thick oil**

The next day, the TOF 3.3 slick was released under breaking wave conditions. The oil was allowed to weather on the sea in breaking waves for 3 to 4 hours before water flushing using Fi-Fi monitors was initiated. The oil had weathered and emulsified to a viscosity of 330 mPa.s (at shear $10s^{-1}$), which is slightly above the recommended upper viscosity limit for water flushing recommending.

The experiment indicated that water flushing could effectively disperse low viscosity oils/residues before they have become semi-solid.

It is therefore important to emphasize that high-capacity water flushing by use of bow-mounted boom and/or Fi-Fi monitors may have a short "time window" for use and therefore require a rapid decision for use in a spill situation.

The response technique tested in the field clearly showed the potential for developing operational response strategies with high encounter rates to significantly reduce the persistence of light crude oils/condensates on the sea surface in calm weather conditions.


**Figure 8-6** **Water flushing using SB Fi-Fi monitor on MS Strilborg. Drone video by Maritime Robotics (A) and ©Finnish Border Guard / SYKE (B)**

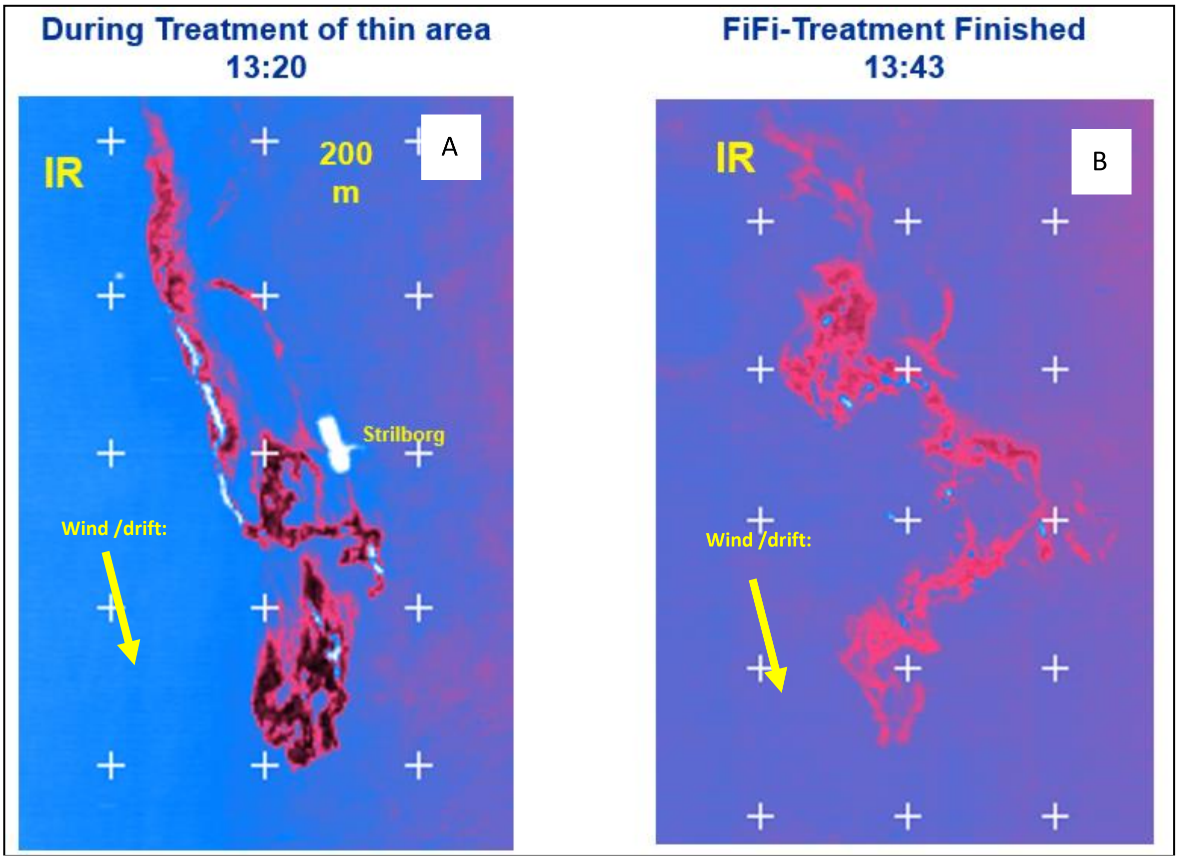



**Figure 8-7** **IR-line scanning images demonstrate the effect of Fi-Fi water flushing of the TOF 3.3 slick. A: In an early phase of the Fi-Fi water flushing (1st. sortie). B: Slick 25 min. later (after finishing the flushing operation)**

## 8.5 Documenting response efficieny in future field trials

The field trial in the North Sea (2016) yielded unique documentations of spreading and behaviour of oil slicks (Åsgard Blend) under non-breaking (calm weather conditions) and breaking waves conditions. The tested high capacity water flushing response techniques clearly illustrated their response potential for light crude oils and condensates under calm weather conditions.

The documentation gained through the field-testing are valuable for forming robust oil spill contingency planning and optimizing response strategies during real spill incidents. The field trial clearly showed the importance of combining complementary observations from different monitoring platforms and sensors. This coordination is crucial for efficient response operations.

Future field trials could optimize the operational capabilities and encounter rates of the response concepts developed and demonstrated through this TOF project. Moreover, high-capacity water flushing should be implemented in future contingency plans to mitigate thin oil films from light crude oils/condensates spilled on the sea surface, especially in calm weather conditions.

# 9 Analysis of volatile and toxic compounds-PhD study

A PhD study, titled *Air Monitoring of Volatile Organic Compounds with Respect to Risk of Human Exposure* was conducted to assess the potential exposure to volatile compounds during response operations of condensates and light crude oils spilled at sea.

The PhD study included laboratory experiments using the modified MNS test chamber (see Section 6.2) to measure the air concentration of benzene, toluene, ethylbenzene, xylenes (BTEX), naphthalene and n-hexane evaporated from a thin oil film. The experiments were conducted in conjunction with the weathering experiments of thin oil films described in Section 6.3.2. The main objective was to determine the impact of possible determinants such as water temperature, oil group, pour point, viscosity, wax and benzene, on air concentrations of benzene with increasing time after an oil release. The data have not been published, but the paper is under preparation and more detailed results from this study are planned in 2018.

Another focus of the PhD study was the potential for human exposure to chemical hazards during response operations. During the NOFO field trial in 2016, measurements of Total Volatile Organic Compounds (TVOC) was performed on the Åsgard Blend light crude oil and the heavier asphaltenic Grane Blend crude oil (Gjesteland et al., 2017). The data published indicate that concentrations of volatile and hazard components, with special attention on benzene, are decreasing rapidly after an oil spill.

## 9.1 Human exposure

### 9.1.1 Sampling methods

The air concentration of total volatile organic compounds (TVOC) during oil release was measured with real-time photoionization detectors (PIDs) calibrated with isobutylene. The PIDs were placed on the main deck of the two response vessels and in the three MOB boats participating in the releases.

BTEX, naphthalene and n-hexane was measured with passive thermal desorption tubes (ATD) packed with Tenax TA. The tubes were attached in the participants breathing zone, outside of the half-mask (Figure 9-1). The equipment was delivered and analyzed by SINTEF Molab Oslo.

Biological uptake of benzene was measured by collecting urine samples of the participants before and after work shift. The equipment was delivered and analyzed by the Health and Safety Laboratory in England.

**Figure 9-1** **Protective half-mask, nitrile gloves and air sampling tube (ATD) attached to helmet (photo: Norwegian Coastal Administration, Espen Reite)**

### 9.1.2 Results and conclusions

*TVOC*

During the releases of Åsgard Blend, the air concentration of TVOC increased from 0 to about 500 ppm immediately after release, but rapidly decreased to zero within the first hour (Figure 9-2). The concentration was highest in the MOB boats working close (<50 m) and downwind to the oil slick. The response vessel (MS Strilborg) detected TVOC for only a few minutes when passing downwind of the oil slick during the second release of Åsgard Blend. The release vessel (KV Sortland) detected TVOC in air for less than a minute after release of Grane Blend, but this may be due to handling the oil release equipment.

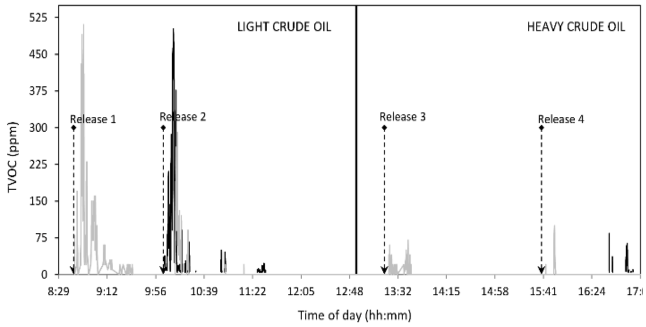



**Figure 9-2** **Air concentration of total volatile organic compounds (TVOC) measured by MOB A (grey) and MOB C (black) during release of light and heavy crude oil (Gjesteland et al., 2017)**

### *Personal air measurements*

Personal exposure to benzene was highest for participants in the MOB boats working close (<50 m) and downwind of the oil slick (Figure 9-3). On day 1 the benzene level for some participants was close to the Norwegian 12-hr occupational exposure limit (OEL) of 0.6 ppm. On day 2 the benzene exposure was above the OEL for four participants. Thus, the measurements indicated that protective equipment should be used. The exposure on the two response vessels was equivalent to background levels of benzene. Exposure to toluene, ethylbenzene, xylenes, naphthalene and n-hexane did not exceed respective OELs. See Gjesteland et al., 2017 for more detailed information on these results.

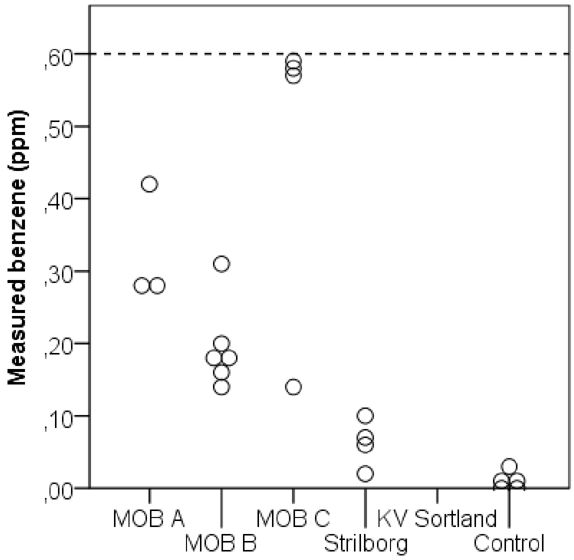



**Figure 9-3** **Personal exposure to airborne benzene as a time-weighted average arranged by the participants' location. The Norwegian 12-hr exposure limit is indicated with a dotted line (Gjesteland et al., 2017)**

### *Biological measurements*

More detailed information about these results will be published in 2018.

## 9.2 Recommendations human exposure from field trial

The measurements showed that the exposure to TVOCs and benzene during a bulk spill of fresh crude oil at sea is highly dependent on the type of oil. Exposures during a heavy crude oil release appear to be low, while exposures during a light crude release appear to be significant (up to five times higher). Personal protective equipment (PPE), especially half-masks, are recommended the first hour after the release of light crude oils when working close or downwind of the oil slick. The mask must be stored in an airtight place when not in use. These measurements indicate that for bulk spills of fresh crude oil at sea the exposure to fresh crude oil rapidly declines with time after release. For a continuous spill, the exposure time close to where the oil is surfacing would be longer. Thus, cleanup should preferably be carried out at a distance (minimum 1 hour drifting time) from the source where benzene and other hydrocarbons have already evaporated. Use of PPE is also strongly recommended during a continous spill.

# 10 Oil spill trajectory modelling

One of the main challenges in oil spill modelling is output of model results and visualization versus reality. In this project, we aimed to developing refined sub-models in the oil trajectory modelling system for more reliable predictions of the lifetime and behaviour of thin oil films from condensates and light crude oils. The refined models were developed especially for solidified wax and/or enriched oil residues for a complete assessment of response options and their efficiency for various spill scenarios. This to provide a better estimate for spreading and calulation of oil film thicknesses. The new sub-models have been integrated with SINTEF's OSCAR (Oil spill contingency And Response) model. The oil spill modelling work is summarized as followed:

1) A literature review was performed focusing on [I)]spreading of oil on the sea surface, [II)]Langmuir circulation and its relevance for oil spill and contingency modelling, and [III)]rheology properties as wax appearance temperature, yield stress, and viscosity and their role for surface spreading and solidification of thin oil films. This has been reported by Brönner et al., 2017 [a)]
2) Improvement of oil spill modelling by implementing temperature and salinity in the OSCAR model. Temperature and salinity govern the properties that are important for spreading of oil on the sea surface and in the water column. This has been reported in Brönner et al., 2017 [b)]
3) Spreading experiments of oils with non-Newtonian behavior (waxy oils) were investigated in a laboratory study. The experiment setup is described in Project Memo (D3-3)
4) Based on the spreading experiments (see point 3, above), an updated spreading model (yield stress inhibited spreading) has been developed and implemented into a Research version of OSCAR (Brönner et al., 2017 [b)]). The result and resulting updated spreading model has been summarized in Project Memo (D5-2). In addition, a manuscript has been outlined and submitted for publishing (Brönner et al., 2017[c)])

## 10.1 Literature review on modelling of (thin) surface oil

A pre-study to investigate important processes for modelling of (thin) surface oil was conducted through the TOF project. The following 3 main processes have been studied, given as:

***Part I: Spreading of oil on the sea surface*** describes observations of surface oil and thin oil films from field studies and real spill situations and discusses the relation of observed patterns in the slick with explanations (e.g. Langmuir circulation).

***Part II: Langmuir circulation and its relevance for oil spill modelling (with OSCAR)*** takes the theory and modelling approaches for Langmuir circulation further and relates these to transport modelling with OSCAR with respect to available input data, timely and spatial resolution of the two phenomena. It was concluded that even Langmuir circulation probably affects the thickness and distribution of oil on the sea surface, and is therefore a potentially important process. To date, Langmuir circulation is not included in any oil spill model, including OSCAR, mainly due to scaling. For example, typical Langmuir cells operate in the range of tens to hundreds of meters and length scales in field observations tend to be much smaller.

***Part III: The role of rheology for surface spreading and solidification of thin oil films*** looks into the consistency and flow of (thin) oil and discusses possibilities for improvement in oil spill modelling based on this knowledge.The OSCAR model represents oil on the sea surface as so-called "spillets", a circular representation of an oil mass with information like mass (i.e. oil type), water content, position, thickness, radius and more. In short, spreading is estimated for each spillet and a uniform thickness is calculated. The OSCAR model includes the viscosity of seawater, but not oil viscosity, and distinguishes light and heavy oils via oil density. It was therefore recommended from this pre-study to include oil viscosity/yield stress. These parameters allow the calculation of equilibrium/terminal film thickness and the transition from a spreading regime to a transport regime (break-up into patches).

## 10.2 Spreading experiments of non-Newtonian waxy oils

Spreading of waxy oils with non-Newtonian behaviour was investigated by experiments in a circular basin at SINTEF. The spreading experiments were designed to simulate radial spreading of oil released continuously on calm water. A series of model oils were used in these experiments with use of wide range diesel mixed with weathered waxy crude. The overall objective of the spreading experiments was to generate relevant and robust data on oils and mixtures of oils with different rheological properties (i.e. viscosity and yield stress). The modelled oils exhibited different non-Newtonian properties, i.e. the ability to withstand gradual deformation by increasing shear force. Yield stress (Pa), also called flow limit, is defined as the force to overcome for an oil to spread as a liquid. The flow limit affects the spreading, distribution and the terminal film thicknesses of an oil slick on the sea surface.

The spreading experiments were a part of the TOF project and were also supported by the Norwegian Coastal Administration (NCA). The findings have established a basis for upgrading and improvement of the spreading model in the oil spill trajectory model (OSCAR) (see Section 10.3). The experimental set up is described below.

### *Experimental setup*

The spreading experiments were performed in a circular test tank with a diameter of 550 cm, a height of 130 cm and a water depth of 87 cm. Oil was applied to the surface through a funnel with diameter of 10 cm. The top of the funnel was placed approximately 2 mm below the water surface. To not disturb the surface slick, the oil was pumped into the tank from the bottom with a frequency controlled displacement pump (Figure 10-1). The oil flow was measured with a Contoil flow meter and logged during the experiments.

An example release and spreading is given in Figure 10-2. The experiments were documented by photo and video. Yield stress and film thicknesses was measured by an ultrasound traducer and image processing. Surface spreading data (including yield stress and thickness) from the experiment was comparable to the proposed algorithm.

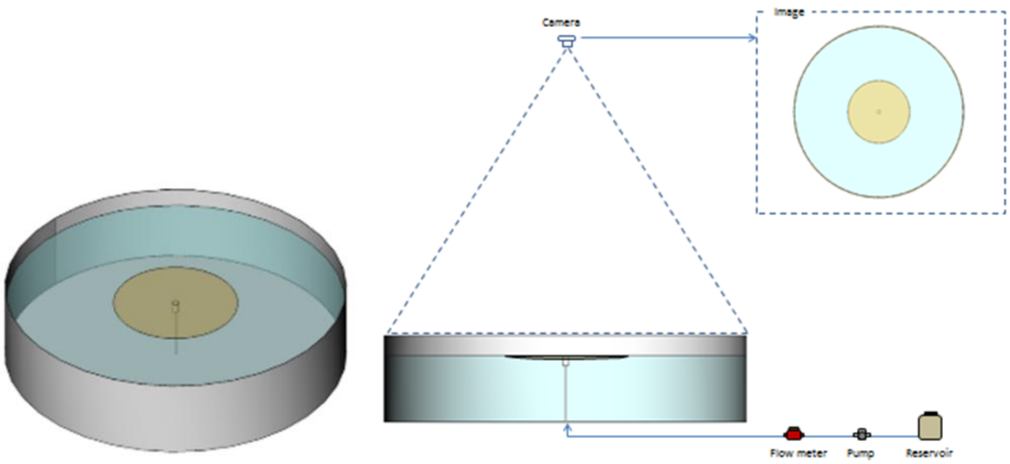
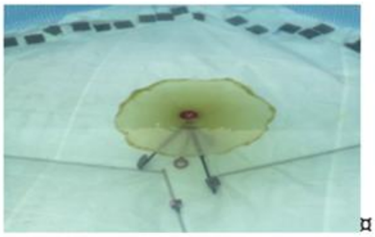



**Figure 10-1** **Experimental setup and video documentation from the spreading experiments**



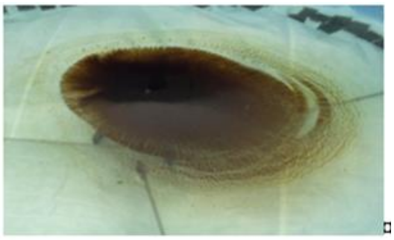


**Figure 10-2** **Example from release and spreading of oil at different time steps. The measurements were conducted after termination oil disturbing on the surface (within 2-3 minutes after release)**

## 10.3 Improvement of oil spill trajectory model (OSCAR)

The improvements of the OSCAR model through the TOF project are summarized as:

***Part I: Temperature and salinity for oil spill modelling***

The temperature and salinity profiles including oxygen (TSO) are now an implemented feature in the currently released OSCAR model, and the profiles can easily be imported via a standardized netCDF data format. Temperature and salinity of the ambient seawater are important parameters when it comes to the behavior of spilled oil in the sea. Both properties are responsible for the density of the seawater, which affects the buoyancy of the spill. Temperature of the seawater will determine its viscosity, a property that is important for oil spreading. Figure 10-3 shows an example of temperature and salinity profiles for summer and winter conditions for one of the oil (field) from the TOF project

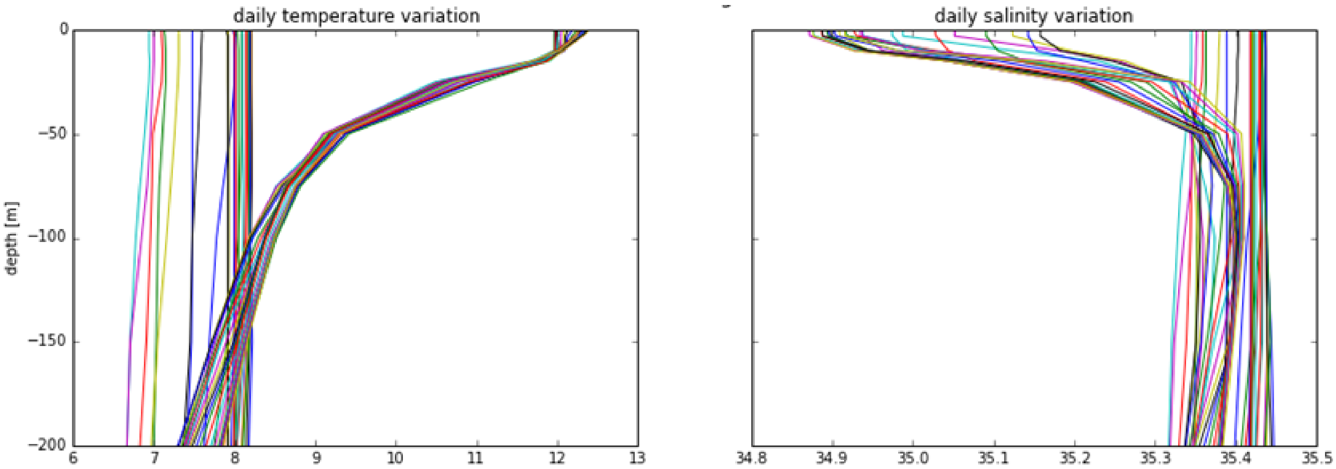



**Figure 10-3** **Example of daily and seasonal variations in temperature and salinity. The winter data (28.02.2015) is less variable due to the mixing and almost constant through the water column (straight lines on the left for temperature and on the right for the salinity) while the summer data (28.07.2015) shows variations both during the day and with decreasing depth**

### Part II: *Improved modelling of surface behaviour (solidification and spreading)*

The yield stress-inhibited spreading sub-model has now been implemented in a research version of OSCAR. This model predicts the spreading of oils in relation to weathering, wax precipitation and solidification. The viscosity of the oil is temperature dependent with lower viscosities at higher temperatures and vice versa. When the seawater temperature is close to the pour point of an oil, the oil will stop spreading.

Categorization of oil thickness has also been implemented into the current version of the OSCAR model. This functionality is independent of the yield stress-inhibition spreading model and will be available for all users through the netCDF export of the surface grid.

Categories of oil film thicknesses are defined by use of the Bonn Agreement Oil Appearance Correlation (BAOAC), extended above 200 µm *< 0.04 µm; 0.04 µm - 0.3 µm; 0.3 µm - 5 µm; 5 µm - 50 µm; 50 µm - 200 µm; 200 µm - 1000 µm; 1000 µm - 2000 µm; 2000 µm - 5000 µm; 5000 µm - 10000 µm; > 10000 µm*

The output from the model can now be reported for each of the thickness categories over time and per model area grid cell:

- surface_mass_distribution_by_thickness
- surface_avg_viscosity_distribution_by_thickness
- surface_avg_coverage_distribution_by_thickness
- surface_avg_water_content_distribution_by_thickness

Model outputs can assist oil spill response and contingency planning by predicting the fate of a TOF over time. With the new output we can relate thickness to other parameters. Example model outputs are shown in Figures 10-4, 10-5 and 10-6. The figures illustrate how different thickness within a single oil film can change their mass over time (Figures 10-4 & 10-5) or simulate the overall coverage and thickness (Figure 10-6).

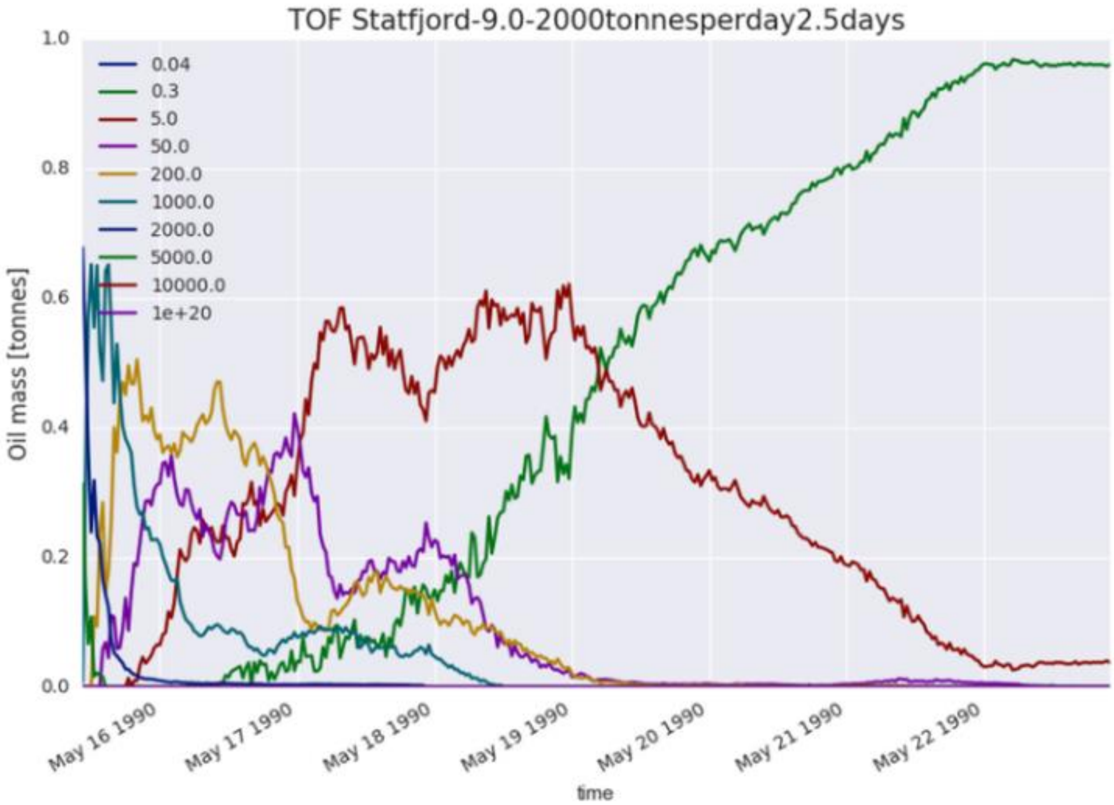



**Figure 10-4** **Example plot of mass distribution of surface oil per thickness category over time (surface_mass_distribution_by_thickness).**
**The x-axis show the time in the simulation and the y-axis fraction ([0…1]) of the oil mass. Here we look at the surface oil mass over time (simulation period), where the oil mass is distributed into the different thickness categories. For example can we see that the fraction of oil thicker than 1000µm (turquoise) is about 65% at the beginning of the simulation, but there is no oil thicker than 1000 µm after May 18, noon. This plot does giv us information about the total mass of surface oil or the spatial distribution.**

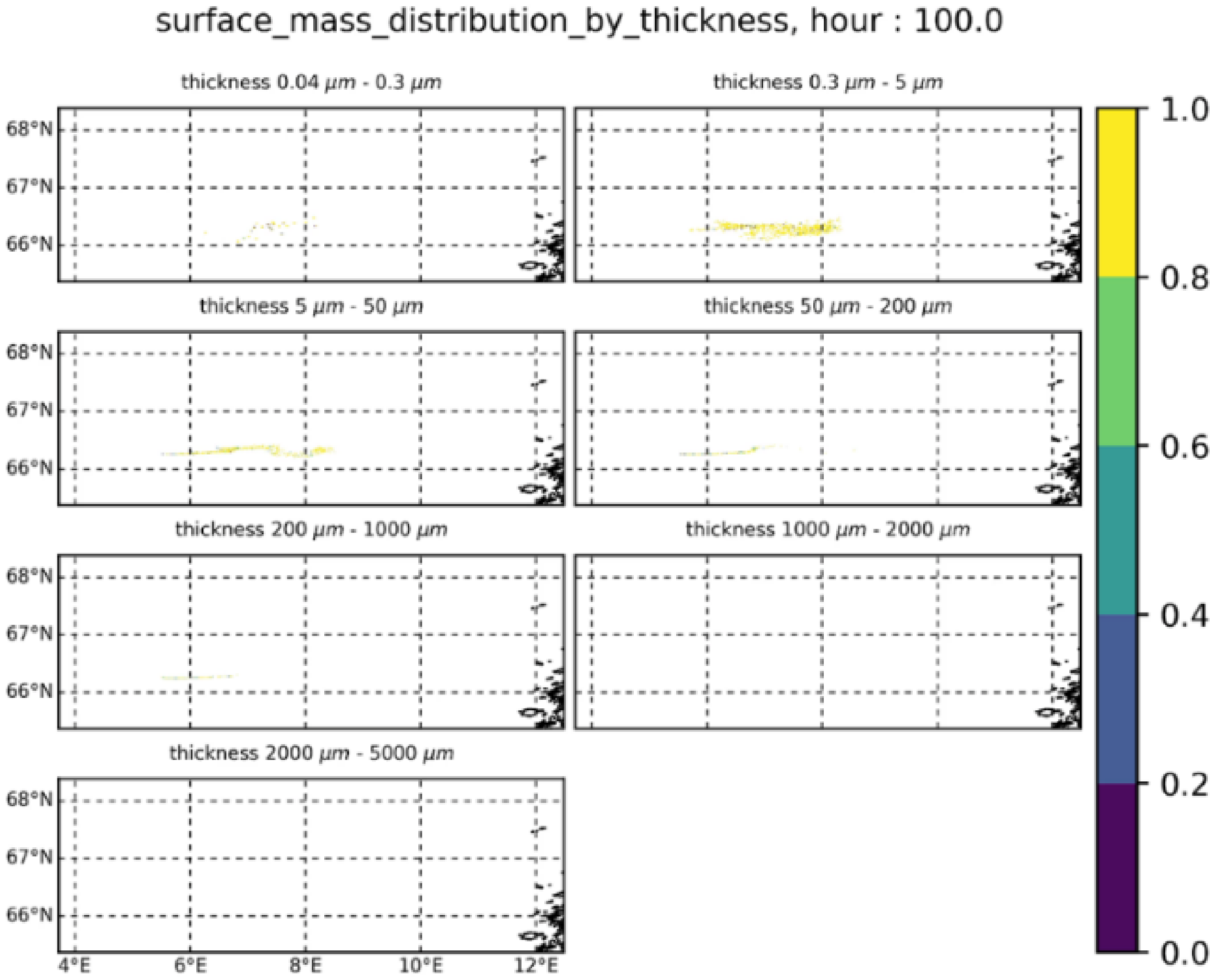



**Figure 10-5** **Example plot of the spatial distribution of mass fractions ([0…1]) of the surface oil mass at a snapshot in time (hour 100). The x-axis shows longitudes, the y-axis latitudes, the legend to the right mass fraction ([0…1]). Here we see that after 100 hours there is no surface oil thicker than 1000µm (empty panels). The spatial distribution and fraction of oil in the other thickness categories is shown in the respective panels. This plot gives information where respondable oil (of a specific thickness) is.**

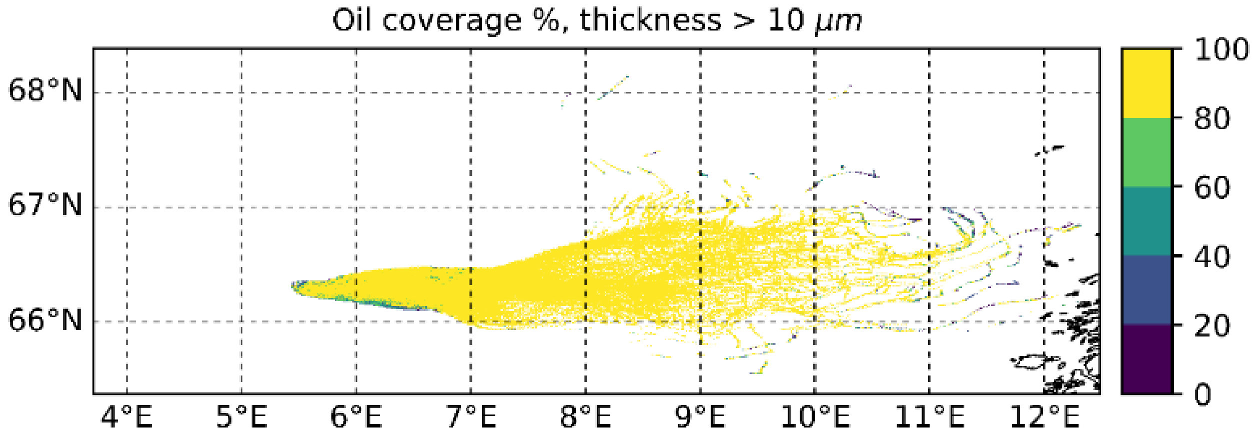



**Figure 10-6** **Example plot of maximum coverage (over time) for oil thicker than 10 µm from a single simulation ( surface_avg_coverage_distribution_by_thickness).**
**The x-axis shows longitudes, the y-axis latitudes, the legend to the right coverage in %. Here we look at how much the oil is fragmented within a cell of the model area. The yellow area is the area where there has been continuous oil during the simulation period (max over time) while at the edges we see that the oil has been fragmented.**
**A similar plot could be produced for viscosity (surface_avg_viscosity_distribution_by_thickness) and water content (surface_avg_water_content_distribution_by_thickness)**

### *OSCAR*

- Temperature and salinity profiles can now be easily imported into the OSCAR model from netCDF format, and the sub-model is available in the currently official release version of OSCAR
- The yield stress-inhibited spreading sub-model has now been implemented in a research version of OSCAR. Further testing is however, needed to document how the yield stress-inhibited spreading model interacts with the other sub models as it was out of scope for the development in this project
- It should be noted that the processes in OSCAR are calibrated towards each other and against reference cases (e.g. Macondo, Amoco Cadiz, Braer) and analytical reference cases
- Categorisation of surface oil by use of the extended (above 200 µm) BAOAC thicknesses is implemented as a new feature in OSCAR. This feature is now available in the currently official release of the OSCAR model

# 11 Recommendations for establishment of oil spill response strategies for condensates and light crude oils

A recommendation for assistance in establishing operational oil spill response strategies for thin oil films created by condensates and light crude oils has been developed through the TOF project (Project Recommendations; Singsaas et al., 2017). These Recommendations is a tool for use in contingency planning for analysis of various oil spill scenarios to assist the oil industry and oil spill responders with the following objectives:

- To establish operational oil spill response strategies for condensates and light crude oils forming thin oil films on the sea surface
- To document the feasibility of existing technologies and novel response technologies for thin oil films for a specific scenario
- To provide support for improving and increasing the reliability of oil spill response analyses and plans for specific oil fields
- To provide guidance and increase our understanding of the potential for human exposure to VOC (Volatile Organic Compounds) during oil spill clean-up from spills of condensates and light crude oils

The Recommendations are based upon results and findings from the TOF project, existing weathering data from the oils studied in the TOF project, and generic knowledge about the possibilities and limitations using existing oil spill response methods.

The eight oils studied in the TOF project were chosen based on their physicochemical properties and are examples of four classes (see Section 5.2) of condensates and light crude oils.

The Recommendations have been based on a subsea release scenario, which will initially produce thin oil films. When developing a recommended oil spill response strategy for a specific condensate or light crude oil, weathering properties should be predicted using the SINTEF OWM. Realistic scenarios must be based on relevant Defined Hazard and Accident situations (DHA; in Norwegian DFU – Definerte Fare- og Ulykkessituasjoner) including water depth, release amount/duration and Gas-to-Oil Ratio (GOR). It is important to note that these analyses can be combined with our traditional weathering analyses to simulate surface releases, and to also produce recommendations for response options for thin oil films. It is recommended that future weathering studies include three scenarios for analysis and prediction:

1. A standard surface release (a common parameter for a weathering study today)
2. The "standard" subsea release scenario described in this report used for oils expected to form thin oil films
3. A relevant subsea release based on DHA (DFU) for the specific oil in question

Thin oil films are defined as oil films having initial thicknesses from 5 µm (0.005 mm) up to 200 – 300 µm (0.2 – 0.3 mm). It was our objective to mimic low wind speeds (up to 5 m/s – non-breaking waves), under both summer and winter conditions. At higher wind speeds, many condensates and light crude oils are likely to be present for a short time on the sea surface due to natural dispersion and evaporation. The strategy and time-window for use of different response methods can vary between different oils within the same class.

For exemplifying and comparing the behaviour of different oils, a specific spill scenario was chosen for the SINTEF Oil Weathering Model (OWM), see Table 6-1 in Section 6.3.3. The predictions form a basis for recommending the response options for the different oil classes. However, the release scenario applies specific parameters that impact the initial oil film thickness, so it is necessary to analyse each oil release based on its relevant release scenario to precisely describe possible response options and strategy.

Figure 11-1 shows an overview of the methodology used for the development of the recommended response strategy for thin oil films.

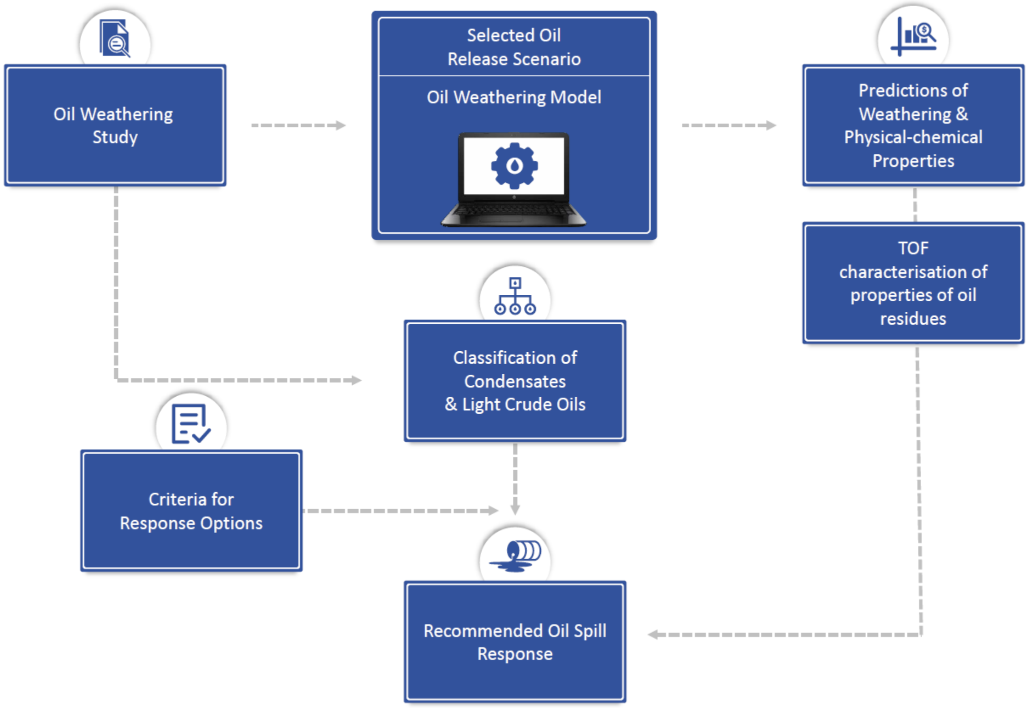



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**Figure 11-1** **Overview of the methodology used for development of recommended response strategy for thin oil film from condensates and light crude oil**

## *Input for use of the methodology*

- Oil weathering study including physicochemical properties of the oil
- Standard and a specific oil field relevant release scenario (DFU) as input to the SINTEF OWM
- Defined criteria for safety zone for explosion hazard and human exposure
- Response options and criteria for response (see Table 11-1):
  - Mechanical recovery
  - Use of dispersants
  - High-capacity water flushing (mechanical dispersing)
  - Remote sensing and monitoring
- Project recommendations for choosing the best approach for response options

Example of an oil spill response strategy is shown in Figure 11-2, and the operational criteria for different response options on thin oil films under calm weather conditions at sea is given in Figure 11-3.

**Table 11-1** **Summary of criteria for response**

| Response technique | Relevant parameters | Applicable (green) | Reduced efficiency (yellow) | Not applicable (red) |
|---|---|---|---|---|
| **Mechanical recovery** | Oil thickness<br>Oil viscosity | > 0.2 mm<br>> 1000 mPa.s | 0.1 – 0.2 mm<br>250 – 1000 mPa.s* | **< 0.1 mm**<br>**< 250 mPas** |
| **Chemical dispersants** | Oil thickness<br>Dispersibility efficiency<br>Pour point | > 0.1 mm<br>Oil specific<br><br>< 5°C above seawater temp. | 0.05 – 0.1 mm<br>Oil specific | **< 0.05 mm**<br>**Oil specific**<br><br>**> 15°C above seawater temp.** |
| **Mechanical dispersing – water flushing** | Oil thickness<br>Oil viscosity | < 0.2 mm<br>< 150 mPa.s | 150 – 250 mPa.s | **> 0.2 mm**<br>**> 250 mPa.s** |

** A lower viscosity limit of 250 mPa.s has been selected for "active booming" in a mechanical recovery operation. This is an assumption based on low sea state conditions (wind speed < 5 m/s) and reduced speed on the recovery vessel*

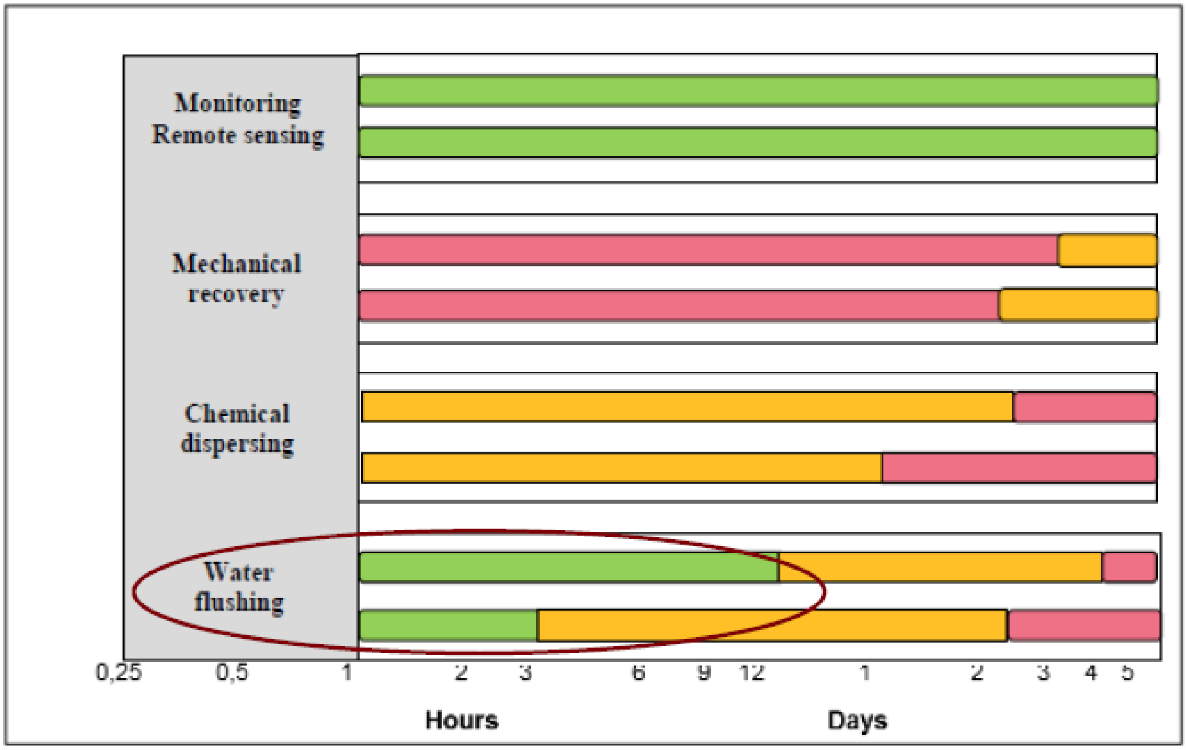


**Figure 11-2** **Example of oil spill response strategy by use of weathering data predicted by the SINTEF OWM based on a standard release scenario. The response criteria and colour coding are explained in Table 11-1. Under each response option the upper bar represents 2 m/s wind speed and the lower 5 m/s**

Figure 11-2 gives an example from the SINTEF OWM predictions of a standard underwater release. This example shows that high-capacity water flushing could be recommended as the primary response. The predicted initial film thickness is found to be too thin for mechanical recovery and dispersants. The figure also shows that the time window for water flushing is, for thiscase, the first hours after the release.In this example, which is an oil giving residues with high pour points, the wax will start to participate and the oil may therefore, start to solidify. The efficiency of the water flushing will then be reduced.

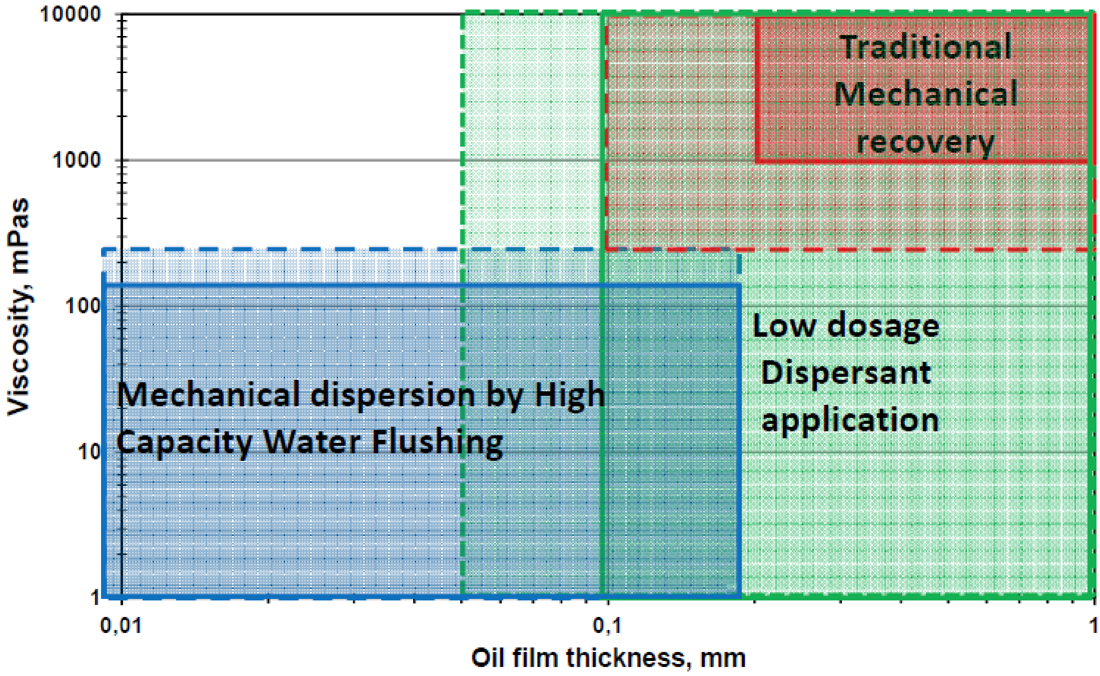


**Figure 11-3** Operational criteria used for different response options on thin oil films under calm weather conditions at sea

## 12 Conclusion and potential for further documentation for implementation of response technologies for thin oil films

Extensive work was conducted through the 3-year TOF project that produced valuable results. Knowledge concerning the fate and behavior of thin oil films, created by different condensate and light crude oils, contributes to improving marine oil spill response. The overall findings from the TOF project have given a scientific basis for recommendations concerning the treatment of marine thin-oil-films. This section summarizes achieved improvement through the TOF project.

- Current oil spill response techniques and strategies (i.e. mechanical recovery and use of chemical dispersants) have limitations for thin oil films from condensates and light crude oils. The concept of mechanical dispersing by use of high-capacity water flushing has been tested in the laboratory and was demonstrated in full scale for the first time during the field trial in 2016. Further laboratory testing on a wider range of oil types and film thicknesses will strengthen the criteria and document the efficiency for using this technology.
- Fi-Fi equipment is standard on most supply vessels operating offshore and use of existing equipment is advantageous. Fi-Fi and high-capacity water flushing booms have a potential to be implemented as an operational response in the Norwegian oil spill contingency plan.
- The methodology developed for assistance in establishing operational oil spill response strategies for use in contingency planning regarding thin oil films are based on the research and testing performed on eight condensates and light crude oils included in the TOF project. The methodology for evaluating different response options is based on the defined release scenario and the presence of thin oil films. Future use of this methodology, for a wider range of condensates and light crude oils, may contribute to further improvement and refining of the methodology.
- It is recommended that future weathering studies should include three scenarios for analysis and prediction, as a basis for recommendation of response strategy:
    - A standard surface release (a common parameter for today's weathering studies)
    - The standard subsea release scenario described in this report used for oils expected to form thin oil films
    - A relevant subsea release based on DHA (DFU) for the oil in question
- Based on laboratory and field data from the TOF project it is indicated that viscosity below 250 mPa.s is required to break up the oil into sufficiently small droplets to be dispersed by high-capacity water flushing. However, this is based on testing with only one oil type (Åsgard Blend). It is therefore recommended to perform testing with other oil types in order to obtain precise documentation of the viscosity limit.

Further refining of the water flushing technology could be documented thorough:

- Laboratory experiments: Extend the test matrix for water-flushing with the test method designed during the NOFO Oljevern 2015 program. Testing a larger range of oils and weathering degrees with a wider variation in viscosity would establish a more robust and fundamental framework as a basis for estimating the precise time-window for water-flushing.
- Field-testing: At existing offshore oil production sites, during periods of calm weather, thin oil films are formed on the sea surface 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 with the use of a remote sensing aircraft.

The promising demonstration of the of these response concepts during the NOFO Oil-on-Water field trial in 2016 should be extended at the future OOW trials. It is recommended that similar experiments be conducted, but using less persistent condensates or a surrogate distillate, such as marine gas oils.

# 13 Dissemination list

## 13.1 Project Memos

**Table 13-1 Overview of Project memos from the TOF-project**

| Project memo | Project | Title | Author (s) | Year |
|---|---|---|---|---|
| **D1-1** | P1. Mapping of variability as a basis for selection of test oils | Interfacial Tension Measurements (IFT) & TAN (Acid number) | Umer Farooq | 2014 |
| **D1-2** | P1. Mapping of variability as a basis for selection of test oils | Evaluation of Atla condensate | Kristin Rist Sørheim | 2014 |
| **D2-1** | P2. Bench-scale testing | Small-scale (closed) experimental system to study Thin Oil Films (TOF) from condensates and light crude oils - Evaluation and description | Svein Ramstad | 2014 |
| **D2-2** | P2. Bench-scale testing | Thin oil film rheology | Thor-Arne Pettersen | 2015 |
| **D2-3** | P2. Bench –scale testing | Petromaks 2 Thin Oil Films: Standard Operating Procedure (SOP) - Rocking Table Test | Irene Andreassen | 2014 |
| **D2-4** | P2. Bench-sale testing | Characteristics of surface residues from thin oil films with use of closed experimental system | Svein Ramstad, Irene Andreassen, Kristin Rist Sørheim | 2015 |
| **D3-1** | P3. Meso-scale flume experiments | Standard Operating Procedure (SOP) for weathering, fate and behaviour of thin oil films under calm condition in modified MNS | Irene Andreassen, Thor-Arne Pettersen | 2015 |
| **D3-2** | P3. Meso-scale flume experiments | Meso-scale flume experiments with TOF - Technical specification | Thor-Arne Pettersen, Kristin Rist Sørheim | 2015 |
| **D3-3** | P3. Meso-scale flume experiments | Spreading experiments model oils | Frode Leirvik | 2016 |
| **D3-4** | P3. Meso-scale flume experiments | Weathering of thin oil films in open exposure systems; properties and behaviour | Svein Ramstad, Thor-Arne Pettersen | 2016 |
| **D3-5** | P3. Meso-scale flume experiments | Testing of high volume spray treatment of thin oil films | Frode Leirvik, Øistein Johansen, Dan Krause | 2016 |
| **D5-1** | P5.Full-scale field verification | Field plan for testing and monitoring of Thin Oil Films (TOF) experiments during the NOFO OPV-2016 (week 24-25) | Per S. Daling, Kristin Rist Sørheim | 2016 |
| **D5-2** | P5.Full-scale field verification | Surface spreading of thin oil slicks | Øistein Johansen (Johansen Environmental Modeling) | 2016 |
| **D5-3** | P5.Full-scale field verification | Cruise report for experiment 3 (Thin Oil Films) and experiment 4 (herder and ISB) during the NOFO OPV-2016 (week 24) | Per S. Daling, Daniel Krause, Ingrid Gjesteland (UiB), Torbjørn Houge (Maritime Robotics), Alun Lewis, Kristin R. Sørheim | 2016 |
| **D5-4** | P5.Full-scale field verification | Summary lessons learned NOFO OPV-2016. Experiment 3 and 4 (TOF and HISB) | Per S. Daling, Daniel Krause, Ingrid Gjesteland (UiB), Vegard Hovstein (Maritime Robotics), Alun Lewis, Kristin R. Sørheim | 2016 |
| **D6-1** | P6. Improvement of oil spill trajectory modeling | Surface spreading of waxy oils | Øistein Johansen (Johansen Environmental Modeling) | 2016 |

## 13.2 Project Reports

**Table 13-2 Overview of Project reports from the TOF-project**

| Project report | Project | Title | Author (s) | Year |
|---|---|---|---|---|
| **SINTEF report F27897 (Restricted)** | P3. Meso-scale flume experiments | Thin Oil Films – Properties and behaviour at sea. Laboratory studies and oil weathering predictions | Svein Ramstad, Kristin Rist Sørheim and Per S. Daling | 2016 |
| **SINTEF report OC2017-A-2017 (Unrestricted)** | P3. Meso-scale flume experiments | Thin Oil Films – Properties and behaviour at sea. Laboratory studies and oil weathering predictions | Svein Ramstad, Kristin Rist Sørheim and Per S. Daling | 2016 |
| **SINTEF report 2017:00030 (Unrestricted)** | P5.Full-scale field verification | Full-scale field testing of thin oil films from releases of light crude oil at sea | Per S. Daling, Alun Lewis, Kristin Rist Sørheim, and Ingrid Gjesteland | 2017 |
| **SINTEF report OC2017 A-181 (Unrestricted)** | P6. Improvement of oil spill trajectory modeling | Numerical modelling of (thin) oil films- Improved behaviour and life time of thin films in the OSCAR model<br>Part I: Spreading of oil on the sea surface<br>Part II: Langmuir circulations and its relevance with oil spill modelling<br>Part III: The role of oil rheology for surface spreading and solidification of thin oil films | Ute Brönner, Alun Lewis, Øistein Johansen and Tor Nordam | 2015 |
| **SINTEF report OC 2017-F-048 (Restricted)** | P6. Improvement of oil spill trajectory modeling | Upgraded oil spill modelling with OSCAR. Surface processes and lifetime of oil on the sea surface.<br>Part II: Improved modelling for surface behaviour. Restricted | Ute Brönner and Øistein Johansen | 2017 |
| **SINTEF report OC2017 A-205 (Untrestricted)** | P7.Dissemination and communication of results | Recommendation for oil spill response of thin oil films | Ivar Singsaas, Kristin Rist Sørheim and Per S. Daling, | 2017 |
| **SINTEF report OC2017 A221 (Untresricted)** | P7.Dissemination and communication of results | Summary report | Kristin Rist Sørheim, Per S. Daling , and Ingrid Gjesteland | 2017 |

## 13.3 Publications, dissemination and conferences

**Table 13-1 Overview of publications, dissemination and conferences from the TOF project**

| Deliverable | Project | Description / Title | Format | Author (s) | Year | Comments |
|---|---|---|---|---|---|---|
| **D7-1 PhD-study** | P4. Air monitoring of volatile compounds with respect to risk for human exposure | Participation at SINTEF supervisor group of "Experts in Team" (NTNU) | Lecture | Ingrid Gjesteland | 2015 | |
| **D7-2 PhD-study** | P4. Air monitoring of volatile compounds with respect to risk for human exposure | Lecture in "Exposures after oil spills" internal education at Occupation Medical Department at Haukeland /Bergen) | Lecture | Ingrid Gjesteland | 2015 | |
| **D7-3 PhD-study** | P4. Air monitoring of volatile compounds with respect to risk for human exposure | Determinants of Airborne Benzene evaporated from thin oil film releeased on seawater - | Paper I | Ingrid Gjesteland, Bjørg Eli Hollund, Jorunn Kirkeleit, Per Daling, Kristin Rist Sørheim and Magne Bråtveit | 2017 /2018 | In progress *Hygienist journal* |
| **D7-4 PhD-study** | P4. Air monitoring of volatile compounds with respect to risk for human exposure | Oil Spill Field Trial at Sea: Measurements of Benzene Exposure | Paper II | Ingrid Gjesteland, Bjørg Eli Hollund, Jorunn Kirkeleit, Per Daling and Magne Bråtveit | 2017 | *Annals of Work Exposures and Health* |
| **D7-5 PhD-study** | P4. Air monitoring of volatile compounds with respect to risk for human exposure | Benzene Uptake during Release of Fresh Crude Oil at Sea | Paper III | Gjesteland et al | 2018 | Planned |
| **D7-6 PhD-study** | P4. Air monitoring of volatile compounds with respect to risk for human exposure | Determinants of Airborne Benzene from crude oil spills on water | Presentation | Ingrid Gjesteland | 2016 | International Conference on the Science of Exposure Assessment in Epidemiology and Practice in September 2016, Barcelona (EPICOH) |
| **D7-7 PhD-study** | P4. Air monitoring of volatile compounds with respect to risk for human exposure | Benzeneksponering under opprydning av olje til havs | Presentation | Ingrid Gjesteland | | Norsk Yrkeshygieniske Forening årskonferanse in Bergen |
| **D7-8 PhD-study** | P4. Air monitoring of volatile compounds with respect to risk for human exposure | Biological monitoring of benzene after exposure to fresh crude oil spilled at sea in an oil spill field trial | Presentation | Ingrid Gjesteland | 2018 | International Congress on Occupational Health (ICOH) in Q2 2018. |
| **D7-9** | P5. Full-scale field verification | Ground-truth monitoring and aerial surveillance | Presentation | Per S. Daling , Alun Lewis, Kristin R. Sørheim | 2017 | GOMRI conference, New Orleans, February 2017 |

| | | | | | | |
|---|---|---|---|---|---|---|
| | | documentation of oil slick behaviour and effect of response options during full-scale field experiments using light crude oils | | | | SINTEF and Alun Lewis consult |
| **D7-10** | P5. Full-scale field verification | Light Crude Oil Slicks Behaviour and Effect of Response Options during Full-scale Field Experiments | Presentation | Per S. Daling, Alun Lewis, Kristin Rist Sørheim | 2017 | AMOP conference, Calgary, October 2017<br><br>SINTEF and Alun Lewis consult |
| **D7-11** | P5. Full-scale field verification | Light Crude Oil Slicks Behavior and Effect of Response Options during Full-scale Field Experiments | Paper IV | Per S. Daling, Alun Lewis, Frode Leirvik, Thor-Arne Pettersen, Daniel Krause, Svein Ramstad and Kristin Rist Sørheim | 2017 | Proceeding Paper. AMOP conference, Calgary, October 2017<br><br>SINTEF and Alun Lewis consult |
| **D7-12** | P6. Improvement of oil spill trajectory modelling | Spreading of waxy oils om calm water | Paper V | Ute Brönner, Øistein Johansen, Frode Leirvik, Tor Nordam and Kristin Rist Sørheim | 2017 | In progress. Submitted to *Marine pollution bulletin*<br><br>SINTEF and Johansen Environmental Modeling |

## 14 References

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