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Report

Project Recommendations for Response to Oil Spills from Condensates and Light Crude Oils

Thin Oil Film (TOF) project

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ABSTRACT

Abstract heading

This Project Recommendation is a guide for assistance in establishing operational oil spill response strategies for thin oil films of condensates and light crude oils. The Recommendations are based upon the results and findings from the TOF project. Here we describe a method for predicting the efficiency of different oil spill response options using the SINTEF Oil Weathering Model (OWM) with a chosen "standard" subsea release scenario as an example. The response options include mechanical recovery, low-dosage dispersant application and high-capacity water flushing (mechanical dispersion) by use of Firefighting monitors or bow-mounted booms.

In order to use the methodology described in this report as a basis for preparation of oil spill contingency plans, the user must base the analyses on relevant Defined Hazard and Accident situations (DHA; in Norwegian DFU – Definerte Fare- og Ulykkessituasjoner). If initial release conditions give thin oil films, the analyses provided here will give a precise time window for relevant oil spill response options. This methodology can be implemented into future weathering studies for thin oil films of condensates and light crude oils and provide comprehensive recommendations for oil spill response.

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1 Abbreviations, Acronyms and Symbols

°C	Degree Celsius
m^3	cubic meter
>	greater than
<	less than
mm	millimeter
m	meter
µm	micrometre
m/s	meter per second
mPa.s	millipascal second (= cP, centipoise)
w/o	water-in-oil
wt.%	weight percent
API	American Petroleum Institute
BAOAC	Bonn Agreement Oil Appearance Code/Correlation
CTC	Continuous oil true colour
DCTC	Discontinuous oil true colour
Fi-Fi	Fire Fighting
GOR	Gas-Oil-Ratio
HSE	Health, Safety and Environment
NOFO	Norsk Oljevernforening for Operatørselskap / Eng. Norwegian Clean Seas Association for Operating Companies
OOW	Oil-on-Water
OWM	Oil Weathering Model
PPE	Personal Protective Equipment
TOF	Thin Oil Film
TVOC	Total Volatile Organic Compounds
VOC	Volatile Organic Compounds

2 Introduction

2.1 Background

The Petromaks2 Research Project *"Formation and behaviour of thin oil films and evaluation of response methods including HSE"* (hereafter called "TOF project") is a 3–year R&D project (2014-2017) funded by the Research Council of Norway and members of the oil industry (Aker BP, Centrica, Eni Norge, ENGIE E&P Norge AS, Shell Technology Norway, Statoil, and Total E&P Norge). The TOF project aims to acquire new knowledge to provide more efficient and safe oil spill response to releases of condensates and light crude oils that may lead to large areas of thin oil films on the sea surface, particularly in calm sea conditions. As a part of the oil producer's release approval for operating the oil fields, the Norwegian Authorities are requiring documented routines for evaluating, planning, and if needed, strategies for responding to acute releases of condensates and other petroleum products that may form thin oil films on the sea surface. It is therefore important to have a good understanding and documentation of the properties, fate and behaviour of oils that produce thin oil films under calm sea conditions. It is also important to understand how potential response options could be modified or customized to deal with such spilled oils.

Seven oils classified as condensates and light crude oils were studied in the TOF project, together with the "reference" oil Statfjord C Blend, a medium light emulsifying crude. We have extensive documentation on Statfjord both from weathering studies in the laboratory and behavior in the field (both experimental field trials and experience from real incidents). In addition, Åsgard Blend (a blend of light crudes and condensates) was used as a test oil during an experimental field trial being an integrated part of the NOFO Oil-on-Water (OOW) field trial at the Frigg field in June 2016. This report on "Project Recommendations for response to oil spills from condensates and light crude oils" (hereafter referred to as Recommendations) is based on laboratory and field studies from the TOF project, previous weathering studies, and knowledge about the possibilities and limitations with existing oil spill response methods. Recommendations are based on the following reports and publications from the TOF project (reference to oil weathering reports for the oils included in the TOF project is made in Ramstad *et al*., 2016):

"Thin oil films – Properties and behaviour at sea. Laboratory studies and oil weathering predictions." SINTEF report no.: F27897. 25th October 2016. (Ramstad *et al.*, 2016).

"Full-scale field testing of thin oil films from releases of light crude oil at sea. NOFO Oil-on-Water field trial in 2016." SINTEF report no.: 2017-00030. 12th May 2017. (Daling *et al*., 2017).

"Oil Spill Field Trial at Sea: Measurement of Benzene exposure". Paper published in Annals of Work Exposure and Health. 2017 (Gjesteland *et al.*, 2017).

"Determinants of Airborne Benzene from condensates and light crude oil spills on water." Journal of Occupational and Environmental Hygiene (JOEH). In progress. (Gjesteland *et al.*, 2017).

"Numerical modelling of (thin) oil films". SINTEF report no.: F27348. 11th December 2015 with extensions in 2017. (Brönner *et al.*, 2017).

"Gravity spreading of waxy crude oils on calm water". In preparation for Marine Pollution Bulletin. (Brönner *et al.*, 2017).

"Light Crude Oil Slicks Behaviour and Effect of Response Options during Full-scale Field Experiments". Proceedings from AMOP 2017 (In press). Daling *et al*., 2017).

"Mekanisk dispergering av tynne oljefilmer". SINTEF report no.: OC2017 A-125. (Sørheim *et al.*, 2017).

"TOF Summary Report". In preparation (Sørheim *et al.*, 2017).

Condensates and light crude oils often contain low amounts of heavy compounds (e.g. asphaltenes and resins) that may produce water-in-oil (w/o) emulsions and contribute to the stabilisation of such emulsions. It has been demonstrated in laboratory experiments that some of the tested condensates do not form w/o emulsions or they give emulsions with very low stability (low viscous emulsions that are easily broken). Such oils are also characterized by low viscosity residues and in a spill situation (e.g. subsea releases), the oils may spread over the sea surface and form thin oil films that are easily dispersed into small oil droplets by wave action. However, other condensates and light crude oils may form residues on the sea surface after evaporation having the potential to form of w/o emulsion.

Waxes are another group of oil compounds playing an important role in the fate and behaviour of oils in an oil spill situation. Many condensates on the Norwegian Continental Shelf contain relatively high amounts of wax. As the wax-rich condensate evaporates on the sea surface, the pour point increases and the oil residue may potentially form solidified lumps, especially in winter temperatures and calm weather conditions. Compared to thin low-viscous oil films, these solidified residues (e.g. lumps/flakes) may be present on the sea surface for a longer time and can be spread and distributed over larger areas, which increases their potential to reach shorelines or other environmentally sensitive resources. In northern and Arctic areas solidification may also be a challenge due to low sea water temperatures.

2.2 Recommendations – what are they?

The Recommendations include a guide 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.
- To document the feasibility of existing technologies and novel response technologies for thin oil films.
- To improve and increase 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 different classes of condensates and light crude oils, being defined in this project. In addition, a methodology for development of a recommended response strategy for thin oil films (< 0.2 – 0.3 mm), based on relevant release scenarios, has been developed. The SINTEF Oil Weathering Model (OWM) has been used to give examples of possible oil spill response strategies for the different classes of oils based on a defined "standard" subsea release scenario.

The main goal of the Recommendations is to mimic a subsea release, 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 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
3. A relevant subsea release based on DHA (DFU) for the oil in question

Thin oil films in this context is 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 are normally present for a short time on the sea surface, and are regarded as insignificant in regard to environmental effects on biota (e.g. sea birds (French *et al*., 1997). It is 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.

To exemplify the methodology developed, predictions of weathering properties and oil film thickness of the oils included in the TOF project have been prepared from the SINTEF OWM using the "standard" subsea release scenario described in section 4.1 and a set of criteria for efficiency of different response options. However, the release scenario plays an important role for the initial oil film thickness after an oil spill and it is necessary to do analysis of each individual oil to be able to more precisely describe possible response options and strategy.

3 Human safety and exposure

The aim in a spill situation is to be able to work as close as possible to the source. However, due to hazards related to the potential for explosion and personnel exposure to volatile chemicals, a minimum operational distance from the source of release should be maintained. In areas where human exposure is possible, it is important to allow for evaporation of the lightest components before response actions are taken. Appropriate personal protective equipment (PPE) should be used when working close to source and/or downwind of the spill (Gjesteland *et al.*, 2017).

3.1 Human exposure during response operations

A PhD study has been performed as part of the TOF project with the title: "Air monitoring of volatile organic compounds with respect to risk of human exposure during oil spill response operations offshore". Currently, this study is not formally published, but some of the preliminary data indicates that concentrations of volatile and hazard components, with special attention on benzene, are decreasing rapidly after an oil spill.

During the field trial in 2016, measurements of Total Volatile Organic Compounds (TVOC) (no single VOC components) was performed on the Åsgard Blend light crude oil and the heavier asphaltenic Grane Blend crude oil (Gjesteland *et al.*, 2017). Figure 3.1 shows data from these measurements, performed by use of photoionization detectors (PID), and illustrates that one hour after the release only minor concentrations of TVOC were measured for both oil types.

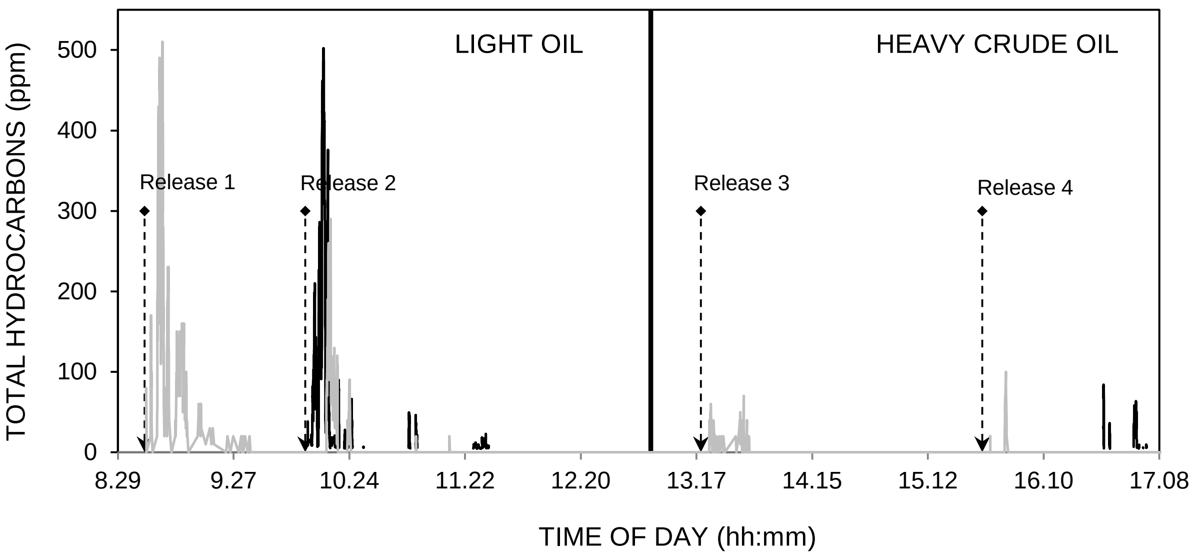


Figure 3.1 Measured total volatile organic compounds (TVOC) during the field trial in 2016 from release of light and heavy crude oil, by continuous monitoring by PID from a MOB (Man Over Board) boat close to the oil slicks (from Gjesteland et al., 2017).

These data indicate that in low wind conditions (5 m/s and below), one hour after oil release, most of the volatile organic compounds have been evaporated. The results from the field trial are supported by findings from laboratory studies performed prior to the field trial. In the case of a continuous release (e.g. a blowout), the evaporation is expected to be similar to an instantaneous release (a batch release with shorter duration) over time. Based on these results, one-hour drifting time has been suggested as a minimum "safety" border regarding human exposure. However, working downwind the oil slick PPE should be mandatory at this recommended distance from the source. We also recommend that workers should change exposed clothing after working hours.

3.2 Flash point and explosion hazard

A subsea blowout may lead to high volume releases of "free" gas (mainly methane) associated with the oil/condensate. Depending on water depth, there could be a substantial risk of fire and explosion, and historically several blowouts incidents have been accompanied with fires at the blowout location (e.g. IXTOC in 1979 and Montana spill in 2009). Other release scenarios may also include risk for release of "free" gas.

If "free" gas is not associated with an oil release, the flash point of the oil is the most important parameter when evaluating potential explosion hazard. On the sea surface, the flash point should be above seawater temperature to avoid explosion and fire hazard. Figure 3.2 illustrates how we can predict the flash point for the Gjøa oil (surface release) using the SINTEF OWM. On the sea surface, the flash point exceeds the seawater temperature for one hour due to evaporation of the lightest components. This is also valid for the other oils included in this project.

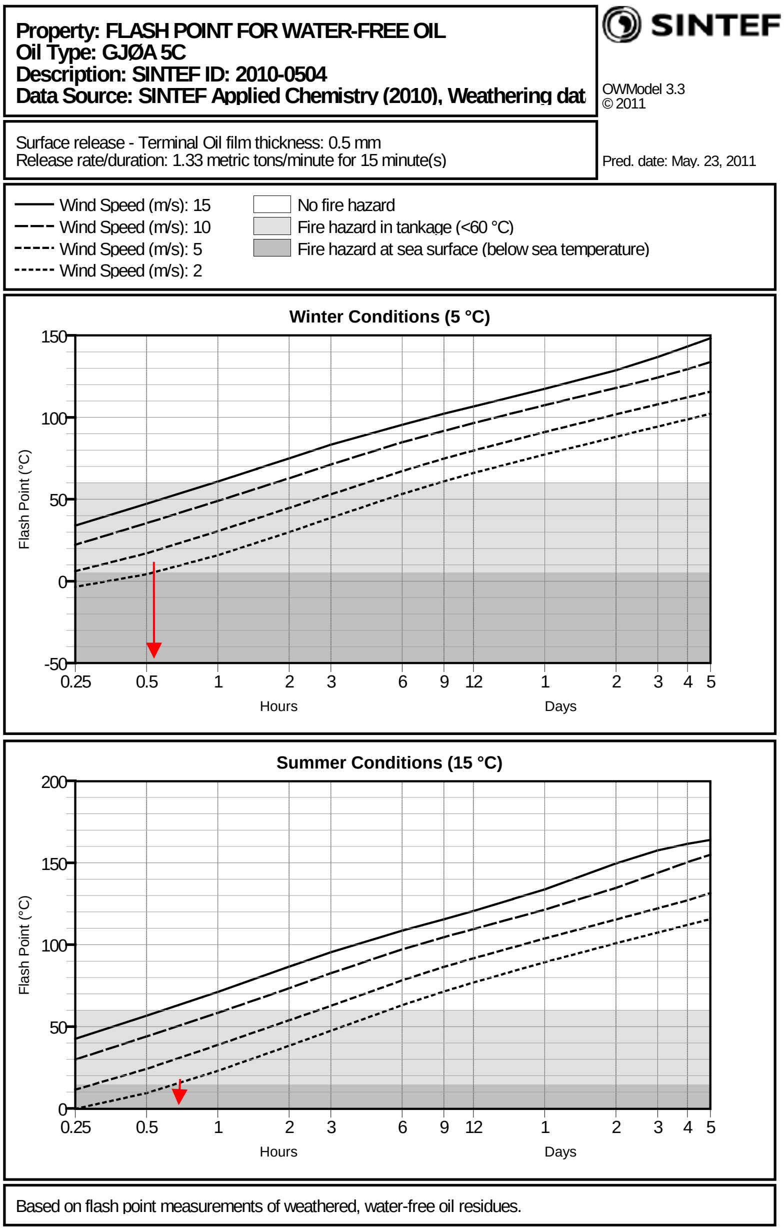


Figure 3.2 Predictions of flash point for Gjøa at two different seawater temperatures indicating where the flash point exceeds the seawater temperature at 2 m/s wind speed.

Today, 1000 m "safety" zone has been used as a rule of thumb in Norway, based on computation of gas dilution with different gas rates and GOR. An operational evaluation by responders is always performed at the site. Explosimeters must be continuously used as experience shows that a risk can exist for varying release rates of gas. This should also be a subject for discussion among the oil companies, as there seems to be a lack of documentation today when "free" gas is involved.

Based on our evaluation of the potential for human exposure to volatile components (e.g. BTEXs and PAHs) and the potential for explosion (associated with evaporation of volatiles from the oil slick), for safe operations we recommend a one hour drifting time, as a minimum, downwind from an oil release. As a rule of thumb, a one hour drifting time equals approximately 500 m at 5 m/s wind speed and 1 km at 10 m/s wind speed. In these Recommendations (section 6) we have used one hour as a "safety" zone. This zone is based on measurements of the rapid dilution of VOCs demonstrated in both laboratory and field experiments in the TOF project and the predicted flash point for the oils included in the TOF project. If a high amount of "free" gas is associated with the oil release, it may be necessary to extend the "safety" zone 1 – 2 km downwind (e.g. 2 – 4 hrs. at 5 m/s wind speed).

Care must be taken when operating close to the "safety" zone and obtaining continuous in-situ measurements of potential explosion hazard (explosimeter) and use of PPE, as mentioned above, should be mandatory.

4 Methodology and input information used as basis for the recommendations

A methodology for classification of condensates and light crude oils based on physicochemical properties and for development of a recommended response strategy by use of the SINTEF OWM has been developed. Figure 4.1 gives an overview of the methodology.

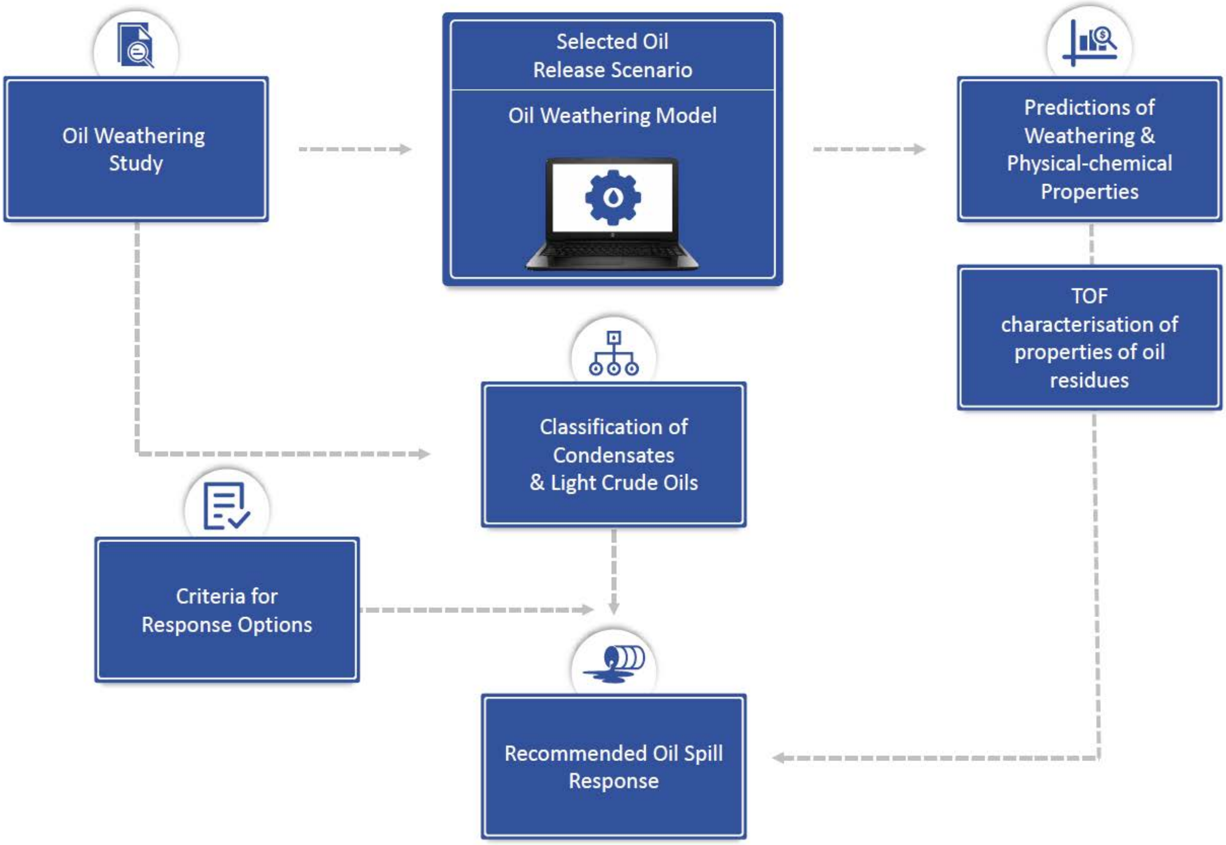


Figure 4.1 Sketch of the methodology used for classification of condensates and light crude oils and development of recommended response strategy for thin oil films.

An oil weathering study of the oil in question is a prerequisite for using this methodology. Results from the weathering study will typically give physicochemical properties for the fresh oil and oil residues, needed for classification of the oil. The weathering study also gives input needed to prepare predictions of weathering properties by use of the SINTEF OWM, which is a basis for the development of recommended response strategies. A relevant oil release scenario must be selected as a basis for running the SINTEF OWM.

4.1 "Standard" oil release scenario

The initial oil film thickness from an oil spill may vary depending of many factors. The way the oil is released (oil spill scenario) is of great importance for the initial oil film thickness formation. 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 amounts, and GOR are important for the subsequent oil film thickness formation on the sea surface.

As an example of using the described methodology, a "standard" oil release scenario has been defined as basis for the SINTEF OWM predictions. Table 4.1 gives an overview of the parameters used in the "standard" scenario. The SINTEF OWM predicts physicochemical and weathering data for the bulk phase of the oil at different time steps. A release of 250 m^3 for one hour was selected which equals 6000 m^3/day in a blowout situation. The GOR was set to 50 for all oils included in the TOF project. Some of the oil fields for the oils included in this project have a very high GOR (above 1000) which is expected to give lower film thickness than predicted by use of the "standard" scenario. This underlines the need for doing analysis for each individual oil using relevant DFU's.

Table 4.1 Release parameters used in the OWM predictions.

OWM – Release input parameters	Numbers and units
Release amount and duration	250 m^3 for 1 hour (equals 6000 m^3/d)
Gas-to-Oil Ratio (GOR)	50
Water depth	300 m
Sea water temperature	2 and 13°C
Wind speed	2 and 5 m/s

4.2 Classification of condensates and light crude oils

Based on physicochemical data for fresh oil and evaporated residues for the oils included in the TOF study an approach for the classification of condensates and light crude oils has been developed. Table 4.2 gives an overview of the different classes with physicochemical data used in classification of the oils.

Table 4.2 Physicochemical data as a guide for classification of condensates and light crude oils

	Density, g/mL	Evaporation 200°C, %	Pour point, 200°C, °C	Asphaltenes, 200°C, wt%	Wax, 200°C, wt%
Class 1	< 0.80	> 60-70	< 0	< 0.02	< 2
Class 2	< 0.85	> 30	< 5-15	< 0.05	< 3-5
Class 3	< 0.85	> 50	> 15	< 0.05	> 5
Class 4	< 0.85	< 30-50	> 15	> 0.05	> 5

The classes defined, based on physicochemical properties, 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 concentration of wax and asphaltenes. In breaking wave conditions (wind speed > 5 m/s), the oils will have 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. Even if the pour point rises with time on the sea surface, the emulsions formed will retard the tendency to solidify. However, under very calm conditions (e.g. 2 m/s wind speed) solidification may appear. Provided initial very low oil film thicknesses (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.

4.3 Criteria for safety and oil spill response options

Examples of possible oil spill response strategies for the four classes were based on the location of the "safety" zone and the efficiency of the response, which included the predicted physicochemical and weathering properties of the oils (Figure 5.2 – 5.7). These criteria are based on laboratory and field experiments, including the 2016 TOF field experiment. The potential for human exposure was documented through laboratory and field experiments as part of the PhD study in the TOF project. Possibilities and restrictions with using the high capacity water-flushing (mechanical dispersion) was documented throughout these meso-scale experiments and verified in the field during the TOF project and in a SINTEF project performed as part of the NOFO "Oljevern 2015" program. Use of dispersants has been tested and verified through numerous previous laboratory and field studies and was also tested during the 2016 field trial. The time-window for use of dispersants on different oils is normally predicted as part of weathering studies by use of standardized testing procedures. For mechanical recovery, there is less "published" documentation regarding efficiency related to oil film thickness and weathering properties. However, NOFO has extensive experience with mechanical recovery and some of the criteria used here are based on experiences from numerous OOW field trials and oil spill incidents.

4.3.1 "Safety" zone for explosion hazard and human exposure

After an acute oil spill a "safety" zone must be established early on and downwind from the spill site due to the evaporation of the light oil components or release of "free" gas (mainly methane) related to a blowout. This is based on the risk for explosion/fire and the health of the personnel involved in the oil spill response operations.

Criteria used:

- Explosion/fire hazard: For oil drifting on the sea surface, no explosion/fire hazard is expected when the oil's flash point is above the temperature of the seawater. For thin oil films, this seem to happen within a drifting time of one hour from the spill site.
- Human exposure: It is recommended that the concentration of VOC components is below the occupational exposure limits (OEL) before entering a spill area. Based on laboratory or field measurements, the

concentration of a thin oil film will be below these limits within one hour after release (Gjesteland *et al*., 2017).

In the Recommendations (chapter 6) one hour is set as the minimum drifting time (from the source) before any oil spill response operations are initiated. However, the following precautions must be taken:

- Prior to the initiation of spill response operations, an operational evaluation including human health and safety must always be conducted at the site.
- Explosimeters must be utilized continuously and one should be aware of the possibility for varying release rates of gas.
- The release of "free" gas associated with the oil spill (e.g. a blowout situation) must be monitored. This may also include the risk for fire at the spill location, which will likely reduce the risk of an explosion further downwind the spill site. However, the release of "free" gas may extend the "safety" zone and must be continuously evaluated on site.
- PPE, especially gas masks and protective clothing, should be mandatory when working in proximity to the "safety" zone.

4.3.2 Mechanical recovery

Traditional mechanical recovery systems are sensitive to thin oil films spread over large areas, and given such conditions, efficiency may be significantly reduced. In addition, the viscosity of the oil or the w/o emulsion is important for potential boom leakage. An oil or a w/o emulsion with a viscosity lower than 1000 mPa.s is commonly thought to promote leakage, but factors like operational speed and weather conditions also play a role and must therefore be considered during a booming operation.

Criteria used:

- Oil film thickness: A thickness above 0.1 – 0.2 mm is required as a minimum for confinement in a boom. The following criteria are used for mechanical recovery:

Oil film thickness	Evaluation
< 0.1 mm	Mechanical recovery is judged not applicable
0.1 – 0.2 mm	Mechanical recovery is feasible, with expected reduced efficiency
> 0.2 mm	Mechanical recovery is judged applicable

- Oil viscosity: A minimum viscosity of 1000 mPa.s is beneficial for effective confinement in a boom at wind speeds above 5 – 10 m/s (breaking waves conditions). At low wind speeds (2-5 m/s), oils with viscosities below 1000 mPa.s can be confined if the operational towing speed is low. Assuming low operational speed and calm sea conditions, it may be possible to contain an oil with a lower viscosity (e.g. 250 mPa.s); however, this has not been verified in the laboratory or the field.

Oil viscosity	Evaluation
< 250 mPa.s	Mechanical recovery is judged not applicable
250 – 1000 mPa.s	Mechanical recovery is feasible, with expected reduced efficiency
> 1000 mPa.s	Mechanical recovery is judged applicable

Oils with high initial pour points (e.g. Skarv and Alve) may tend to solidify, particularly at low temperatures and/or calm wind conditions. Solidified oil lumps may reach thicknesses above 0.1 – 0.2 mm and confinement in a boom is possible, but reduced efficiency is expected due to spreading.

4.3.3 Use of dispersants

When dispersants are applied to a surface oil slick, a minimum oil film thickness is required for the dispersant to interact with the oil and to minimize the penetration into the underlying seawater (herding). Using a low-dosage application boom system, which is relevant for thin oil films, the required minimum film thickness is lower than the commonly used high-dosage system (0.05 mm for low-dosage versus 0.1 mm for high-dosage). Reduced efficiency by use of dispersants should be expected for oils that have solidified on the sea surface. However, combining dispersant application with artificial turbulence (e.g. high-capacity water flushing) can extend the window of opportunity. Use of water flushing after dispersant application may also be necessary at low wind speeds (< 5 m/s), for all oils, due to low wave energy, or oils with a pour point exceeding (> 5-15°C) the sea water temperature.

Criteria used:

- Oil film thickness: A thickness above 0.05 – 0.1 mm is required as a minimum for treatment by the low-dosage application boom system. The following criteria are applied for use of chemical dispersants:

Oil film thickness	Evaluation
< 0.05 mm	Use of dispersants is judged not applicable
0.05 – 0.1 mm	Use of dispersants is feasible, with expected reduced efficiency
> 0.1 mm	Use of dispersants is judged applicable

- Dispersant efficiency as a function of oil viscosity: Viscosity is specific to the type of oil and is based on standardized testing and predictions of dispersibility from weathering studies:

Dispersibility from weathering studies	Evaluation
Poorly/not dispersible	Use of dispersants is judged not applicable
Reduced dispersibility	Use of dispersants is feasible, with expected reduced efficiency
Dispersible	Use of dispersants is judged applicable

- Pour point: At low wind speeds and low seawater temperatures, the pour point should be taken into consideration. When the pour point increases to 5-15°C above seawater temperature it is expected that use of dispersants is not feasible. This is also dependent on the possibility for supplying artificial mixing energy, e.g. by use of high-capacity water flushing.

Pour point	Evaluation
> 15°C above sea water temp	Use of dispersants is judged not applicable
< 5°C above sea water temp	Use of dispersants is judged applicable

Predictions of the window of opportunity for use of dispersants are often included in weathering studies. For condensates, were such data are not available, they are expected to be dispersible unless there is a possibility for solidification due to high pour point.

4.3.4 High-capacity water flushing (mechanical dispersing)

This is a "new" technology that has been tested in the laboratory and was used in the field during the NOFO OOW field trial in June 2016 (Daling *et al*., 2017). It is often referred to as mechanical dispersing and consists of high-capacity water flushing by use of fire-fighting (Fi-Fi) systems available on many supply vessels or bow-mounted booms connected to existing pump systems available on response vessels. The Fi-Fi systems can have a capacity of 3600 m^3 seawater per hour and bow-boom can has a capacity of 16 m^3 seawater per minute. The principle is based on that the high-capacity water flushing will disperse the thin oil film into the water column giving droplets sizes similar to chemical dispersions (< 100 µm).

The most important parameters for the use of high-capacity water flushing are oil film thickness, viscosity and pour point. This technology can be used at oil film thicknesses lower than any other response method. Mechanical dispersing seems to be sensitive to oil/emulsion viscosity, but can be used in combination with chemical dispersants at higher viscosities. For oils with a tendency to solidify on the sea surface it is expected that water flushing can be used in an early phase prior to solidification.

Criteria used:

- Oil film thickness: This technology is judged to cover an oil thickness area of 0.005 – 0.20 mm (5 – 200 µm). The following criteria are used for oil film thickness:

Oil film thickness	Evaluation
> 0.2 mm	Use of water flushing is judged not applicable
< 0.2 mm	Use of water flushing is judged applicable

- Oil viscosity: A viscosity of 250 mPa.s is used as an upper limit for effective treatment by water flushing. This limit is based on results from laboratory studies and the 2016 field trial. The following criteria are used:

Oil viscosity	Evaluation
> 250 mPa.s	Use of water flushing is judged not applicable
150 – 250 mPa.s	Use of water flushing is feasible, with expected reduced efficiency
< 150 mPa.s	Use of water flushing is judged applicable

4.3.5 Summary of criteria for response

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

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

4.4 Remote sensing and monitoring

Remote sensing consists of systems that can detect and monitor oil slicks on the sea surface and dispersed oil droplets in the water column. Surface monitoring can be performed from satellite, aircraft, helicopter, aerostat, oil platform and ships while subsea monitoring can be performed by dedicated instruments operated from a ship or small boats. There are several different systems and sensors being used and NOFO has an overview of the available systems and which ones are currently used in Norway.

Remote sensing and monitoring plays an important role in the recommendations given for the all the 4 classes defined in this report. It will always be performed as a part of any oil spill response operation, for instance as a tool for guidance in use of mechanical recovery, chemical dispersants or high-capacity water flushing. It can still, in selected situations, be evaluated as the only possible response to oil spills from condensates and light crude oils if the lifetime on the sea surface is very short, due to oil characteristics, weather conditions etc.

4.5 Future use of the Recommendations

It is recommended that the methodology described is implemented in future oil weathering studies for condensates and light crude oils. In addition to the standardized surface release used as a basis for predictions today, a subsea release as described could be included with a relevant release scenario for a specific oil based on DFU's for the oil field. Specific recommendations for oil spill response to thin oil films from condensates and light crude oils may be developed from the methodology described in this report.

5 Physicochemical and weathering properties

5.1 Physicochemical properties

Seven condensates and light crude oils and a reference oil (Statfjord C Blend) were studied in the TOF project to create comprehensive recommendations and classifications. In addition, the Åsgard Blend oil was used during the field trial in 2016. All these oils have been subjected to prior oil weathering studies and Table 5.1 gives an overview of the physicochemical properties of the fresh oils and their corresponding evaporated residues.

Table 5.1 Physicochemical properties of the oils included in the TOF Project

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	N.A	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

5.2 Example of weathering properties for a "standard" subsea oil release

By use of the SINTEF OWM and the "standard" subsea oil release scenario described, predictions of selected weathering properties for the eight of the oils included in the TOF project are presented using two seawater temperatures (winter conditions (2°C) and summer conditions (13°C)) and two wind speeds (2 and 5 m/s). These predictions have been used as a basis for giving examples of possible oil spill response strategies connected to the different classes. The relevant predictions were combined with the criteria defined for the different oil spill response options in section 4.3.

Surface oil:

Given the release scenario used (subsea release), several of the oils included in this study have short predicted lifetimes on the sea surface, especially at 5 m/s wind speed.

Note that even if some of these oils are predicted to disappear from the surface before the end of the five-day simulation period, this may not be reflected in the other predictions presented in this chapter and the illustrations presented for each class in the Recommendation in chapter 6. The OWM predicts the oil properties as if the oil is on the sea surface for the entire simulation period of five days.

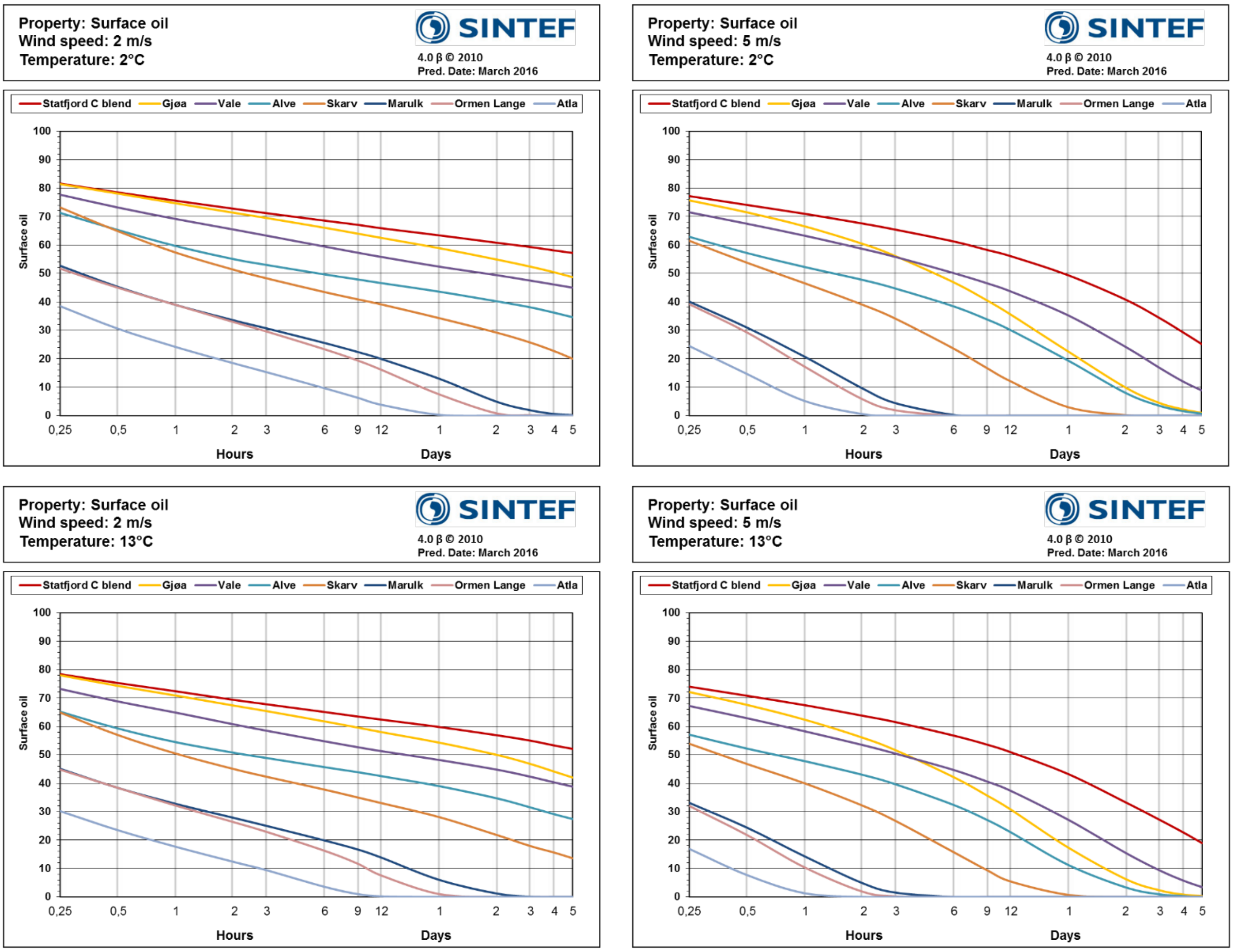


Figure 5.1 *Comparison of surface oil for Statfjord C blend (ref. oil), Gjøa and Vale (light crude oils), and the condensates Alve, Skarv, Marulk, Ormen Lange and Atla at 2 and 13°C with 2 and 5 m/s wind speeds. Predictions based on the "standard" subsea release:*
Release rate: 250 m^3 for 1 hour; GOR: 50; water depth: 300 m (Table 4.1).

Evaporation:

Evaporation is an important process for removing oil from the sea surface after an oil spill. For oils that contain a large amount of light oil components (for instance condensates), evaporation is normally rapid after a release to sea. Figure 5.1 shows that the light condensates (by density), Atla, Ormen Lange and Marulk, exhibit the highest evaporative loss, whereas Statfjord C Blend (reference crude oil) has the lowest evaporative loss due to the higher content of heavier components.

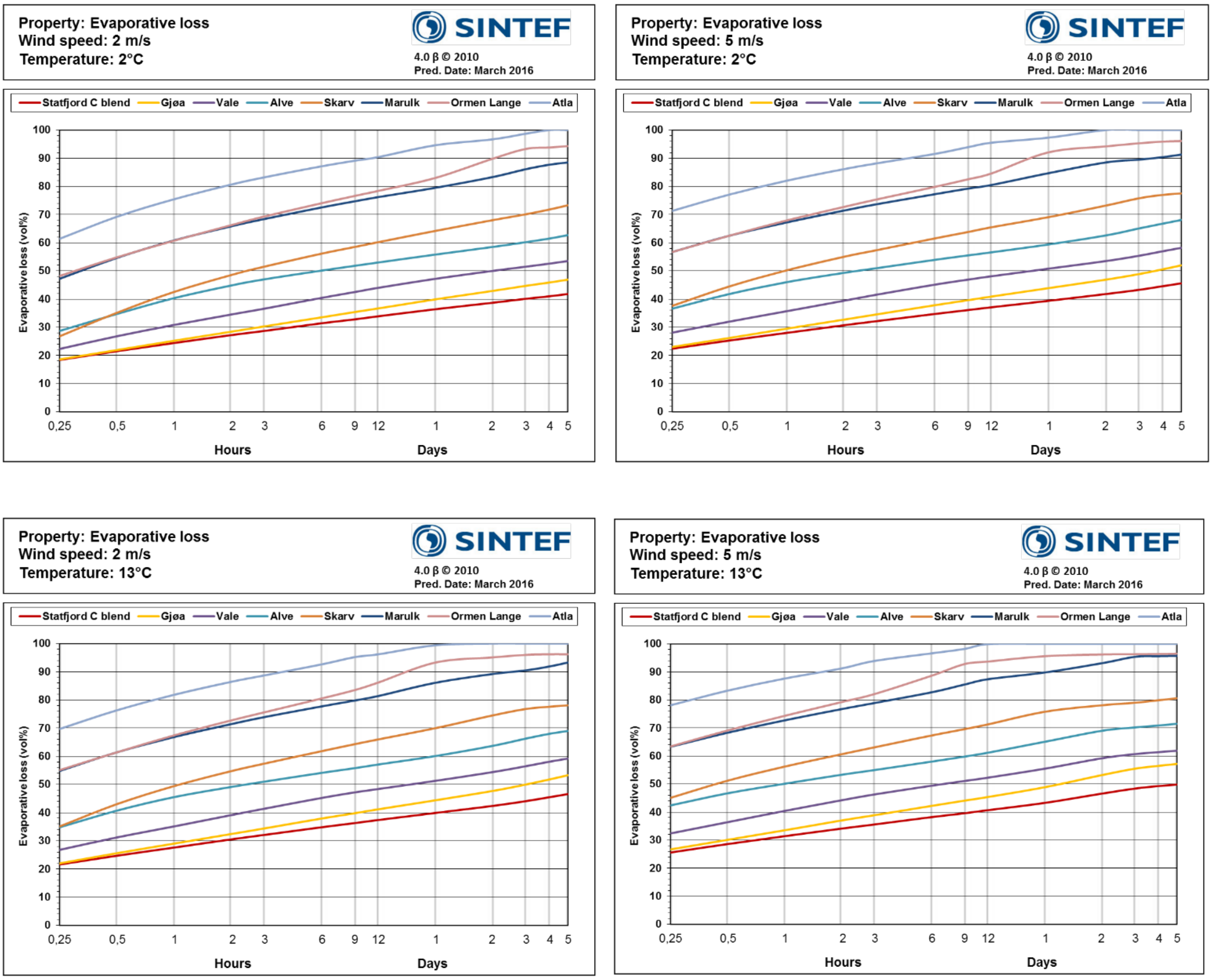


Figure 5.2 Comparison of evaporation for Statfjord C blend (ref. oil), Gjøa and Vale (light crude oils), and the condensates Alve, Skarv, Marulk, Ormen Lange and Atla at 2 and 13°C with 2 and 5 m/s wind speeds. Predictions based on the "standard" subsea release: Release rate: 250 m^3 for 1 hour; GOR: 50; water depth: 300 m (Table 4.1).

Flash Point:

The flash point for a fresh crude oil can be far below 0ºC. Immediately after release to the sea surface the lightest components will evaporate and the flash point will rise rapidly above the seawater temperature. When the flash point of an oil slick has exceeded the seawater temperature in open waters, hazards associated with explosion or fire are reduced or become non-existent. "Free" gas, often associated with continuous releases (e.g. blowout), can contribute to explosion/fire hazard, and should be evaluated separately.

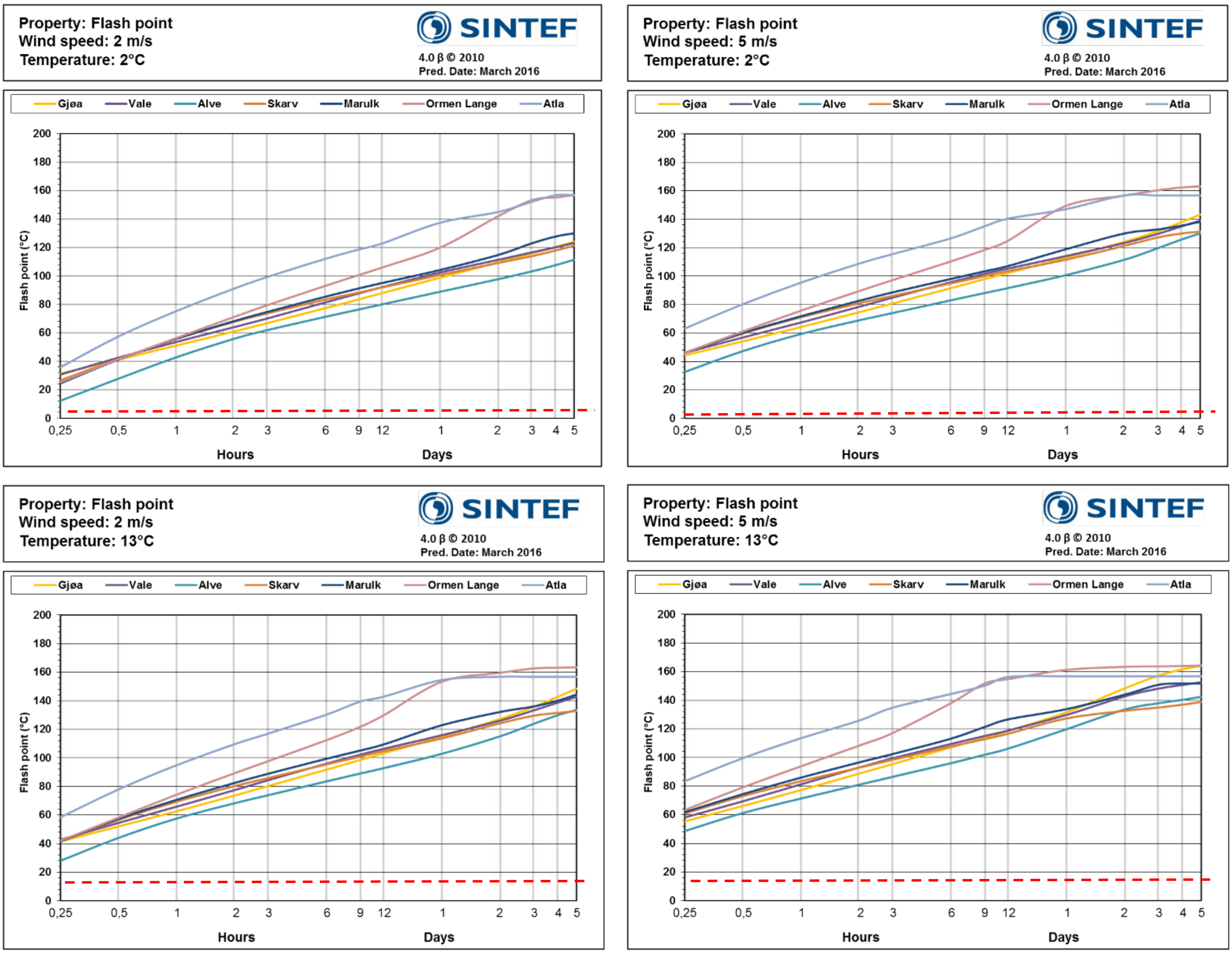


Figure 5.3 *Comparison of flash points for Gjøa and Vale (light crude oils), and the condensates Alve, Skarv, Marulk, Ormen Lange and Atla at 2 and 13°C with 2 and 5 m/s wind speeds. Release rate: 250 m^3 for 1 hour; GOR: 50; water depth: 300 m (Table 4.1).*

Red dashed line: seawater temperature. Predictions based on the "standard" subsea release:

Water uptake:

Only three of the oils studied in the TOF project (the reference oil Statfjord C blend included) are predicted to take up water and form w/o emulsions by the "standard" scenario. The predictions indicate the amount of water incorporated into the oil as a function of time on the sea surface, but do not include the stability of the w/o emulsion formed.

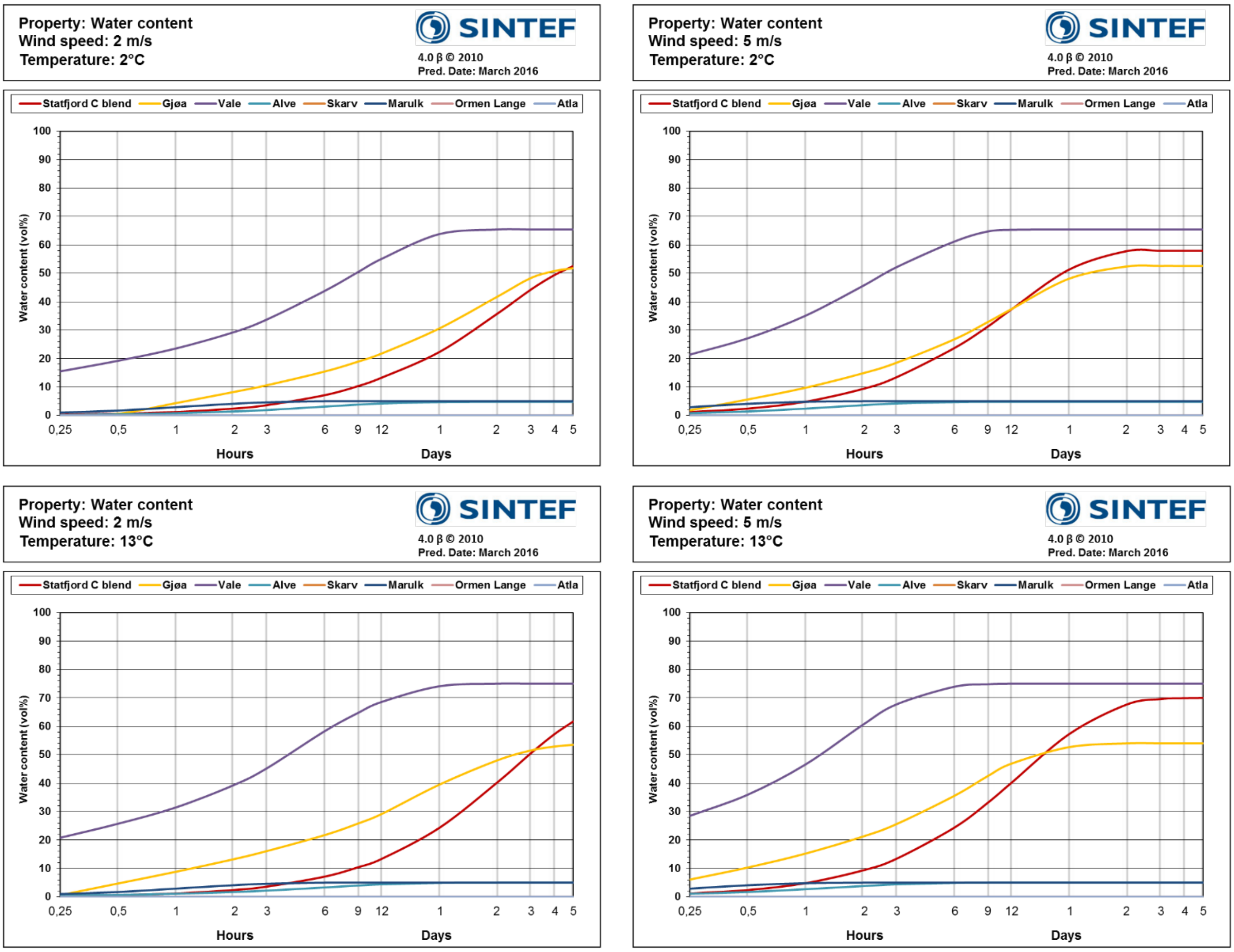


Figure 5.4 Comparison of water content for Statfjord C Blend (ref. oil), Gjøa and Vale (light crude oils) at 2 and 13°C with 2 and 5 m/s wind speeds. The condensates Alve, Skarv, Marulk, Ormen Lange and Atla will not take up water and emulsify. Predictions based on the "standard" subsea release: Release rate: 250 m^3 for 1 hour; GOR: 50; water depth: 300 m (Table 4.1).

Oil/emulsion viscosity:

The viscosity is an important parameter for all potential oil spill response options. For mechanical recovery, viscosity is important in order to evaluate the ability of a boom to retain the oil and avoid boom leakage. For use of dispersants, viscosity is used to define the "window of opportunity". This is oil specific and testing is normally performed as part of a weathering study for a specific oil. For mechanical dispersing by high capacity water flushing, an upper viscosity limit of 250 mPa.s is defined. This is based on laboratory and field testing in the TOF project.

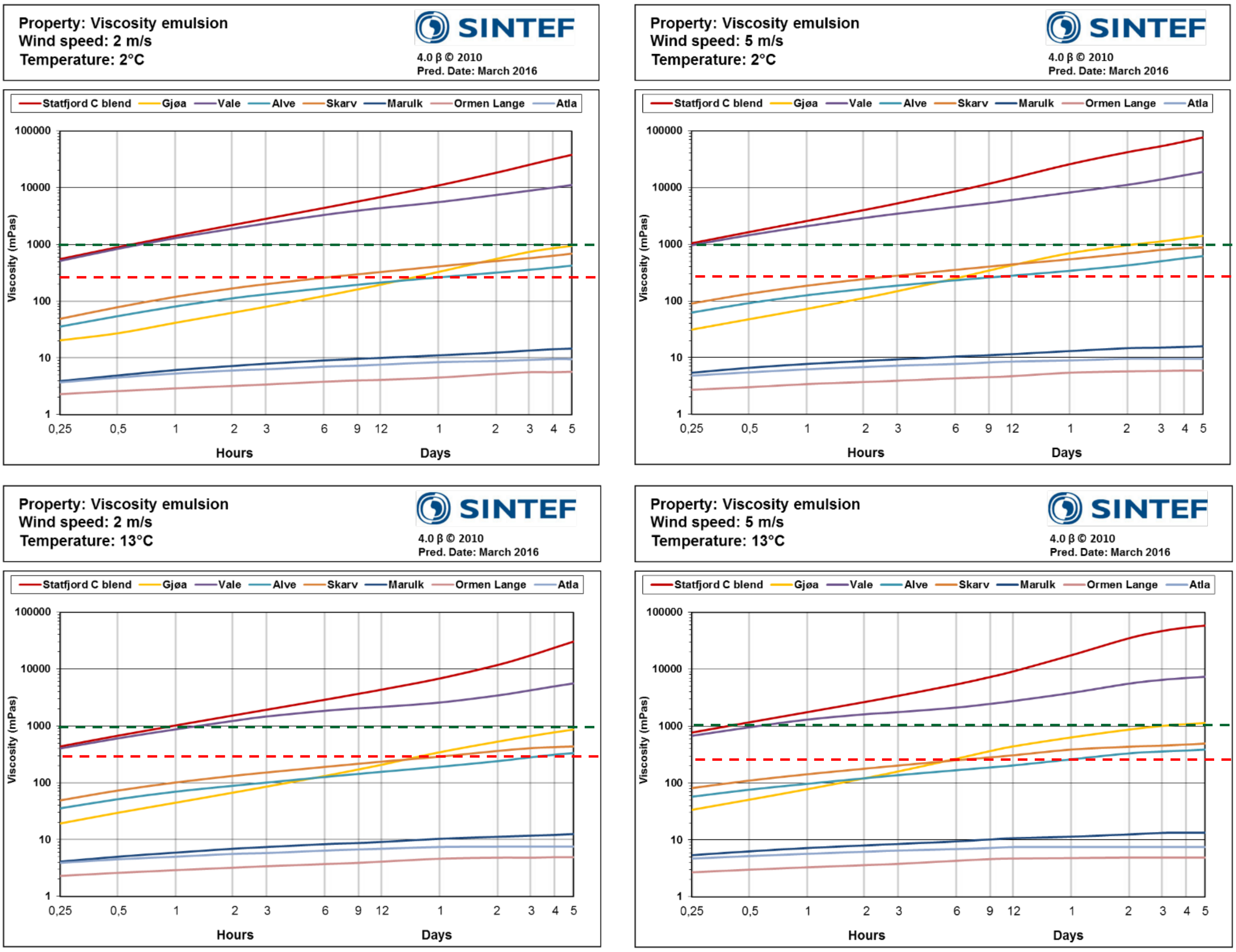


Figure 5.5 Comparison of oil/emulsion viscosity for Statfjord C Blend (ref. oil), Gjøa and Vale (light crude oils), and the condensates Alve, Skarv, Marulk, Ormen Lange and Atla at 2 and 13°C with 2 and 5 m/s wind speeds. Predictions based on the "standard" subsea release:
Release rate: 250 m^3 for 1 hour; GOR: 50; water depth: 300 m (Table 4.1).

Green dashed line: 1000 mPa.s used as a lower viscosity limit for efficient confinement of oil/emulsion in a boom. Red dashed line: a viscosity below 250 mPa.s is required for effective treatment by high-capacity water flushing (mechanical dispersion). 250 mPa.s has also been used as a lower viscosity limit for containment of thin oil films in a boom.

Pour Point:

The pour point is defined as the temperature where the oil/emulsion becomes semi-solid and starts to lose its flow characteristics. A high pour point is generally associated with a high wax content in the oil. It is an important parameter for potential solidification of an oil at the sea surface, and it plays an important role for the use of different oil spill response techniques.

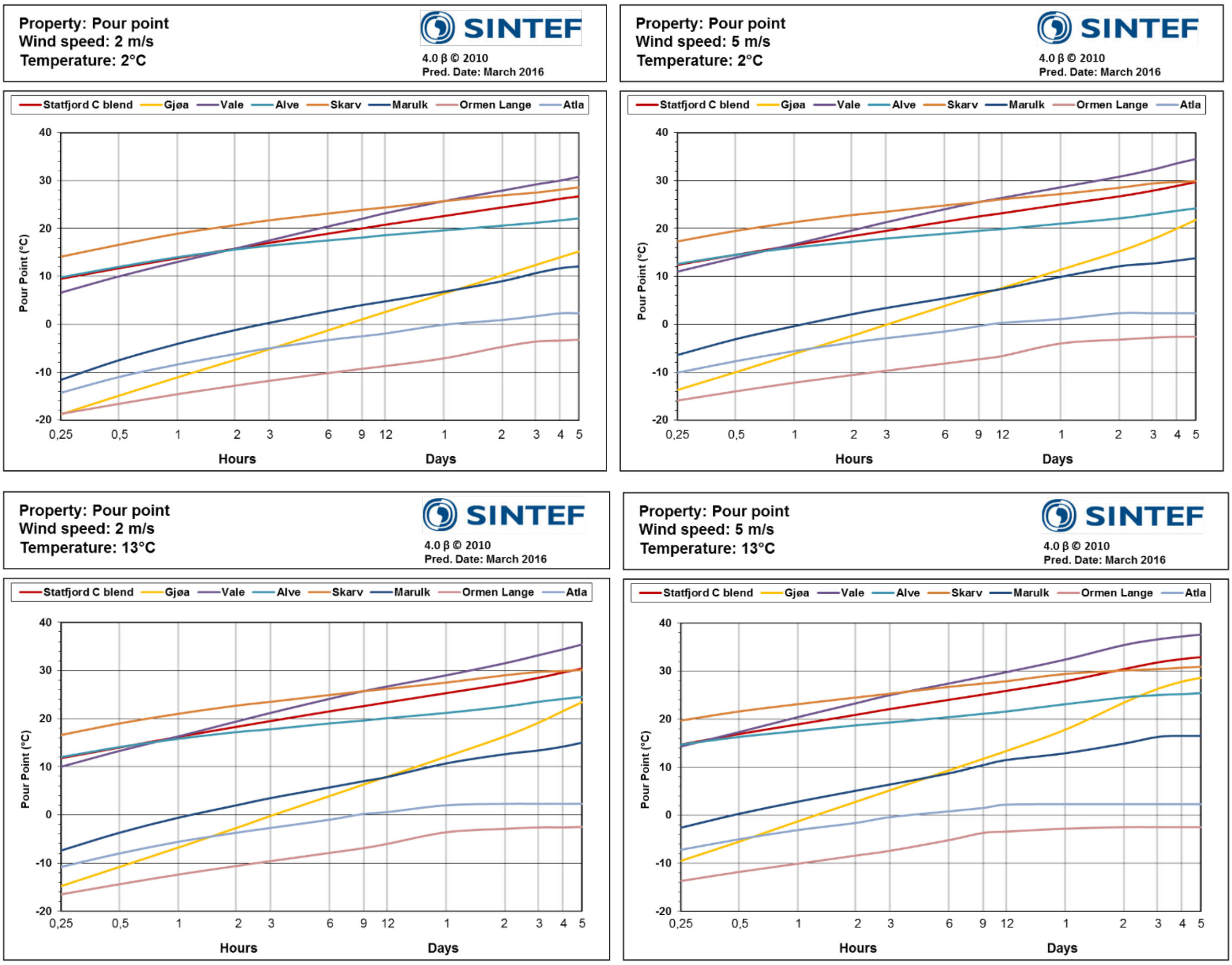


Figure 5.6 Comparison of pour point for Statfjord C Blend (ref. oil), Gjøa and Vale (light crude oils), and the condensates Alve, Skarv, Marulk, Ormen Lange and Atla at 2 and 13°C with 2 and 5 m/s wind speeds. Predictions based on the "standard" subsea release:
Release rate: 250 m^3 for 1 hour; GOR: 50; water depth: 300 m (Table 4.1).

Oil/emulsion film thickness:

The initial film thickness after an oil release to sea is dependent of several factors such as oil type, subsea or surface release, release amount, duration etc. If the oil solidifies or form w/o emulsions, the thickness increases. For oils that do not solidify or form w/o emulsions, the thickness decreases due to drift and spreading. Film thickness is an important parameter when evaluating the efficiency of different oil spill response techniques and strategies.

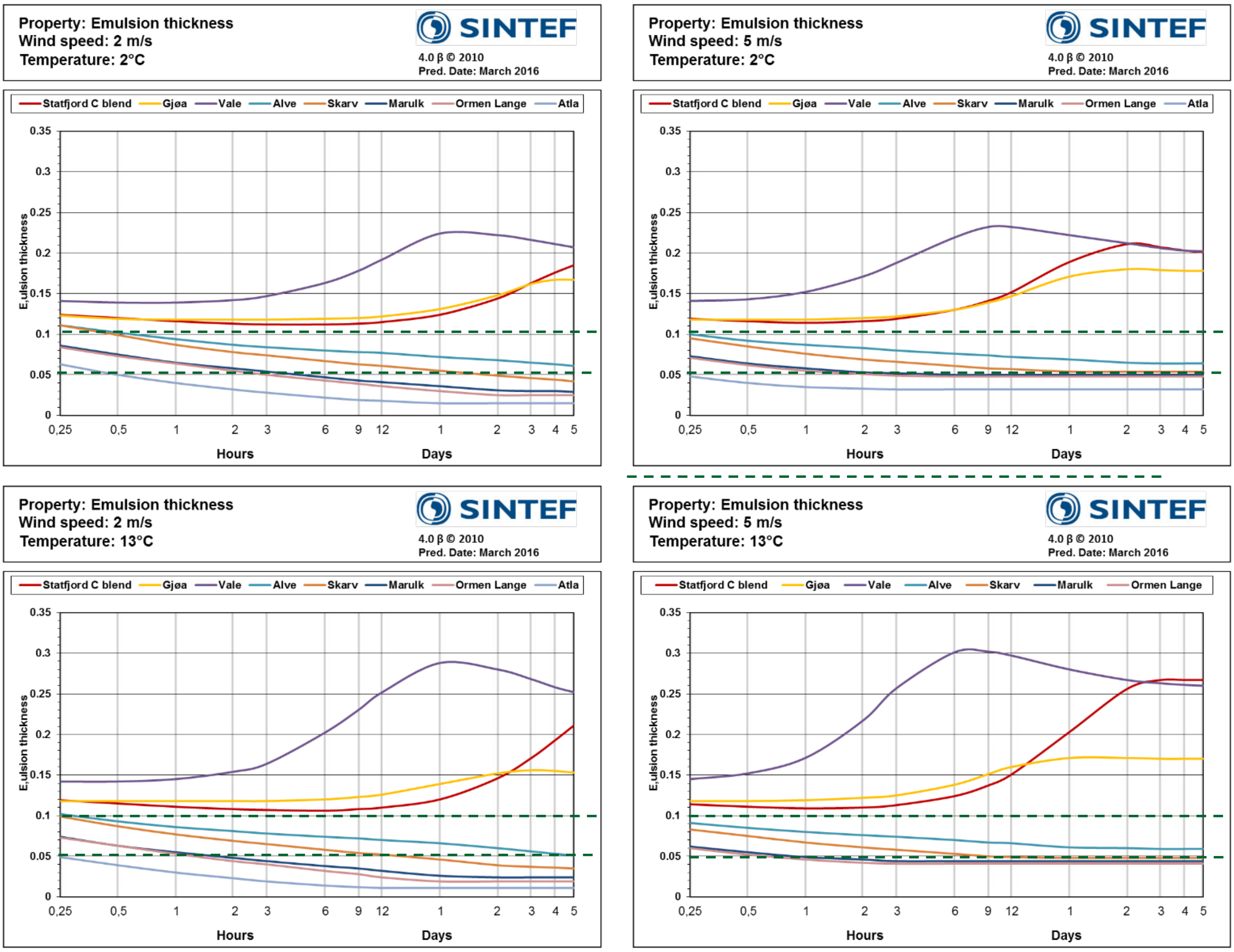


Figure 5.7 Comparison of oil/emulsion film thickness for Statfjord C Blend (ref. oil), Gjøa and Vale (light crude oils), and the condensates Alve, Skarv, Marulk, Ormen Lange and Atla at 2 and 13°C with 2 and 5 m/s wind speeds. Predictions based on the "standard" subsea release:
Release rate: 250 m^3 for 1 hour; GOR: 50; water depth: 300 m (Table 4.1).

Green dashed line: a film thickness of 0.1 mm is regarded as minimum for confinement in a boom, while 0.05 – 0.1 mm is regarded as a minimum for use of chemical dispersants from a low dosage spraying arm.

6 Project Recommendations

6.1 Oil spill response options for condensates and light crude oils

Oil slicks from condensates and light crude oils are thought to form thin oil films (typically less than 0.1-0.2 mm in thickness), which is on the limit for recovery by "traditional" response methods (mechanical recovery and use of dispersants). These thin oil films are thought to have a short lifespan on the sea surface due to evaporation and natural dispersion into the water by wave activity. Hence, it has been accepted that aerial monitoring of surface oil and subsea monitoring of oil naturally dispersed into the water column, was a sufficient "oil spill response option" for oil spills creating thin oil films on the sea surface.

However, the picture is nuanced as some condensates and light crude oils contain large amounts of waxes that may precipitate and contribute to solidification of residues on the sea surface. If the oil residue contains sufficient amounts of emulsifying components (e.g. asphaltenes), w/o emulsions may form; however, emulsions are often unstable and easily broken.

The oil film thickness expected after a spill of a condensate or light crude oil is not only dependent on the physicochemical and weathering properties of the oil. Release scenarios and weather conditions play an important role in the initial oil film thickness. A surface release may typically give a higher oil film thickness than a subsea release, at least in the early phase of a spill. For a subsea blowout, water depth, release rate and GOR are important for the initial oil film thickness. Typically, a high GOR may give decreasing initial oil film thickness compared to a low GOR. Increased release rates or increased release depth can contribute to increased oil film thickness on the surface. However, these parameters interact with each other and it is difficult to estimate the initial film thickness without prior modelling work based on a relevant DFU.

Thin oil film in this context has been defined as oil films having an initial film thickness ranging from 5 µm to 200 – 300 µm. In the Bonn Agreement Oil Appearance Correlation (BAOAC), oil films with a thickness ranged from 5 – 50 µm, which is at the lower end of the definition of thin oil films in this project, are referred to as "metallic". It is assumed that if a thin oil film is observed as "metallic" (5 – 50 µm), the oil properties are considered not to have any influence on the rheology of the modelled film. However, over time if the "metallic" film becomes redistributed into bands/stripes of thicker oil (> 50 µm) due to oceanographic conditions (e.g. swell and current), the rheology in such bands will be different and the oil can solidify due to high pour point.

6.2 Examples of oil spill response for different classes of condensates and light crude oils

The condensates and light crude oils studied in the TOF project vary in their physicochemical and weathering properties. Physicochemical properties for these oils have been used in establishing the four classes of oils. By use of the subsea release scenario described in section 4.1, the SINTEF OWM has been used to prepare predictions of weathering data for these oils. By combining the weathering predictions with the criteria for efficiency of the different response options, potential oil spill response options for each class have been developed for one specific release scenario. This selected release scenario demonstrates the different response options and tentative "time-windows" for the different classes of condensates and light crude oils, as an example for future use of this methodology.

If the release scenario (DFU) for a specific oil is different from the one used in section 4.1, the oil is still classified in the same class based on physicochemical data, but the response strategy will be different from what is suggested under the specific example given herein. The proposed approach is summarized as follows:

- The approach is only valid for condensates and light crude oils that form thin oil films on the sea surface and is restricted to calm sea conditions (typically 5 m/s wind speed or less).
- A condensate or a light crude oil is classified into one of the four classes described according to its physicochemical properties (regardless of variation in release scenarios).
- Recommended response options are evaluated based on predicted weathering properties for oil specific release scenarios (DFU's).

- If the release scenario for a specific condensate of light crude oil is different from the subsea release used as an example in this project, new analyses should be performed based on the relevant release scenario. This may give different response options and "time-windows" than what is exemplified under each class in this report.
- For new oils coming into production this could be part of a weathering study and for oils already in production it might be necessary to evaluate whether separate analyses are necessary.

The response options evaluated are: "traditional" mechanical recovery, application of dispersants and high capacity water flushing. Aerial monitoring of surface oil and subsea monitoring of dispersed oil is always performed as part of any oil spill response operation and can, in selected situations, also be a sufficient "oil spill response option" provided very short lifetime of thin oil slicks on the sea surface or under rougher weather conditions than predicted here (> 5 m/s wind speed).

6.2.1 Class 1: Non-emulsifying and non-solidifying oils

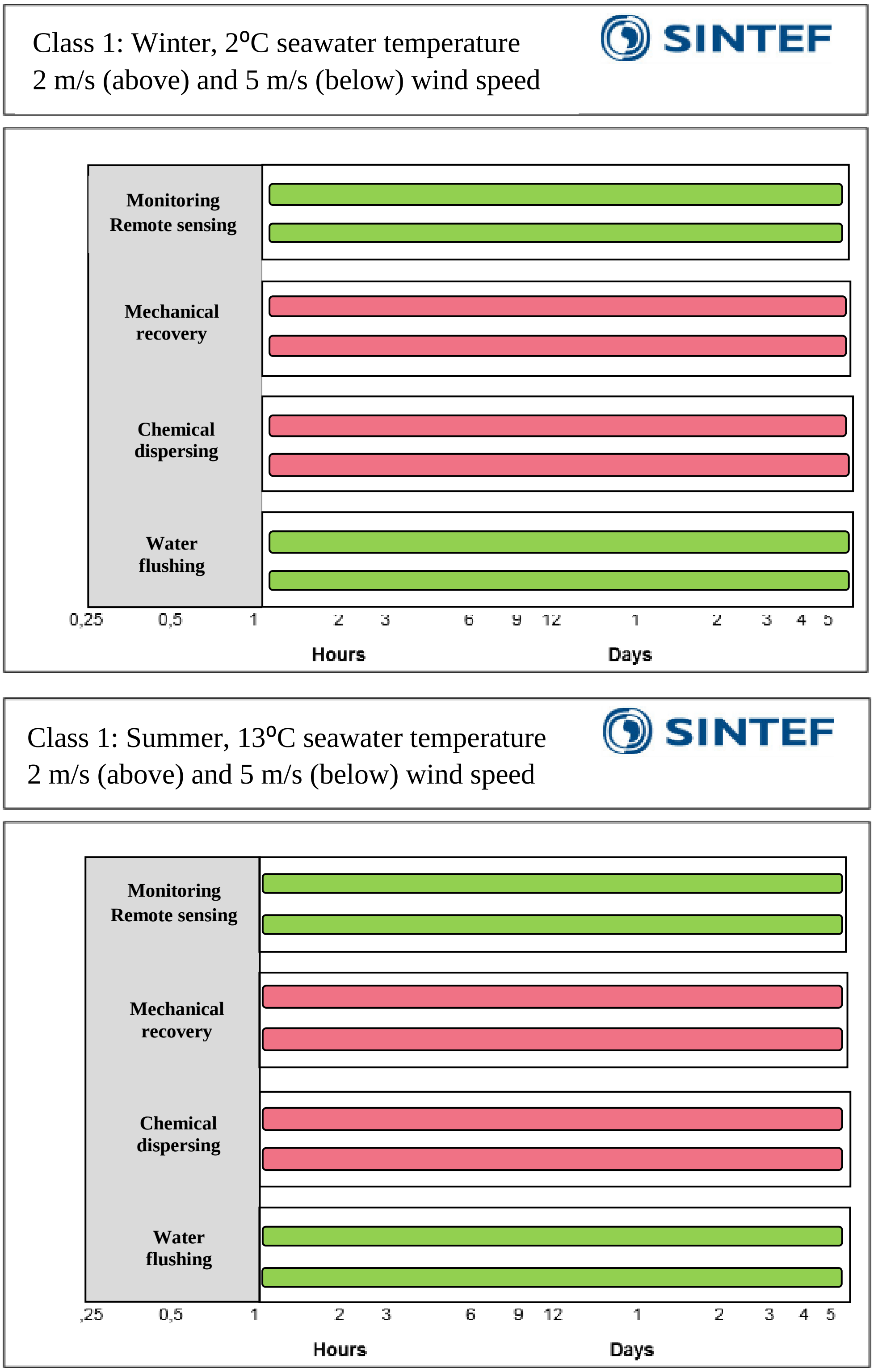


Figure 6.1 *Example of oil spill response strategy provided initial thin oil film and low wind conditions (< 5 m/s) by use of weathering data predicted by the SINTEF OWM, based on the "standard" release scenario in 4.1. The response criteria and color coding are explained in 4.3.5. Under each response option the upper bar represents 2 m/s wind speed and the lower 5 m/s.*

Justification:

Class 1 represents light condensates with physicochemical parameters as indicated in Table 4.2.

Prediction of weathering properties and oil film thickness by use of the "standard" subsea release scenario defined in section 4.1 indicate that oils falling into this class neither tend to form w/o emulsions nor solidify when spilled on the sea surface. Based on these predictions, potential response strategies for this selected release scenario is given below. If the release scenario or wind conditions are different from that described in 4.1, the recommended response strategy (illustrated with the brown box in Figure 6.2) will likely be different.

Response technology	Response strategy
Mechanical recovery	• The initial oil film thickness for these oils is below 0.1 mm (100 µm) for a subsea release and decreases with time. This is below the minimum thickness for confinement in a boom. • The viscosity is low and is predicted to be below 20 mPa.s even after some days on the sea surface. This is too low for confinement in an active booming operation. • Mechanical recovery is judged to have very low efficiency for the residues of oils falling into this class.
Use of chemical dispersants	• The predicted oil film thickness is judged to be too low for effective dispersant treatment by use of the low dosage spraying boom. For surface releases, dispersants may possibly be used in an early phase (a few hours) after a spill, as the initial thickness is expected to be higher.
High-capacity water flushing	• The predicted thickness is optimal for use of high-capacity water flushing. • The predicted viscosity is well below 250 mPa.s, an upper limit for treatment by water flushing, even after days on the sea surface. • Water flushing is judged to be the recommended response method, and has no "time-window" limitations as long as a thin oil film is still observed on the sea surface.
Monitoring and remote sensing	• Due to the expected short lifetime on the sea surface, particularly with increasing wind speed (> 5m/s), monitoring and remote sensing can be evaluated as a sufficient practical "response" option.

Summary of exemplified response evaluation:

Figure 6.2 illustrates the potential response options as summarized in section 4.3.5, based on an evaluation of oil film thickness and viscosity. The solid line for each response method represents the area where the method is judged applicable, while the dotted line represents the area where the method is judged feasible but with reduced efficiency. Both mechanical recovery and chemical dispersants can be used at higher film thicknesses and viscosities than illustrated on the axes. It is also important to note that mechanical dispersing can be used at lower film thicknesses than 0.01 mm.

Based on the example from the previous page with weathering predictions prepared by the "standard" subsea release scenario, the possible response strategy is illustrated as a brown box in the lower left corner of the figure. Given other release scenarios (DFU's), the response strategy will be different and should be evaluated for each specific oil by using the methodology described in this report.

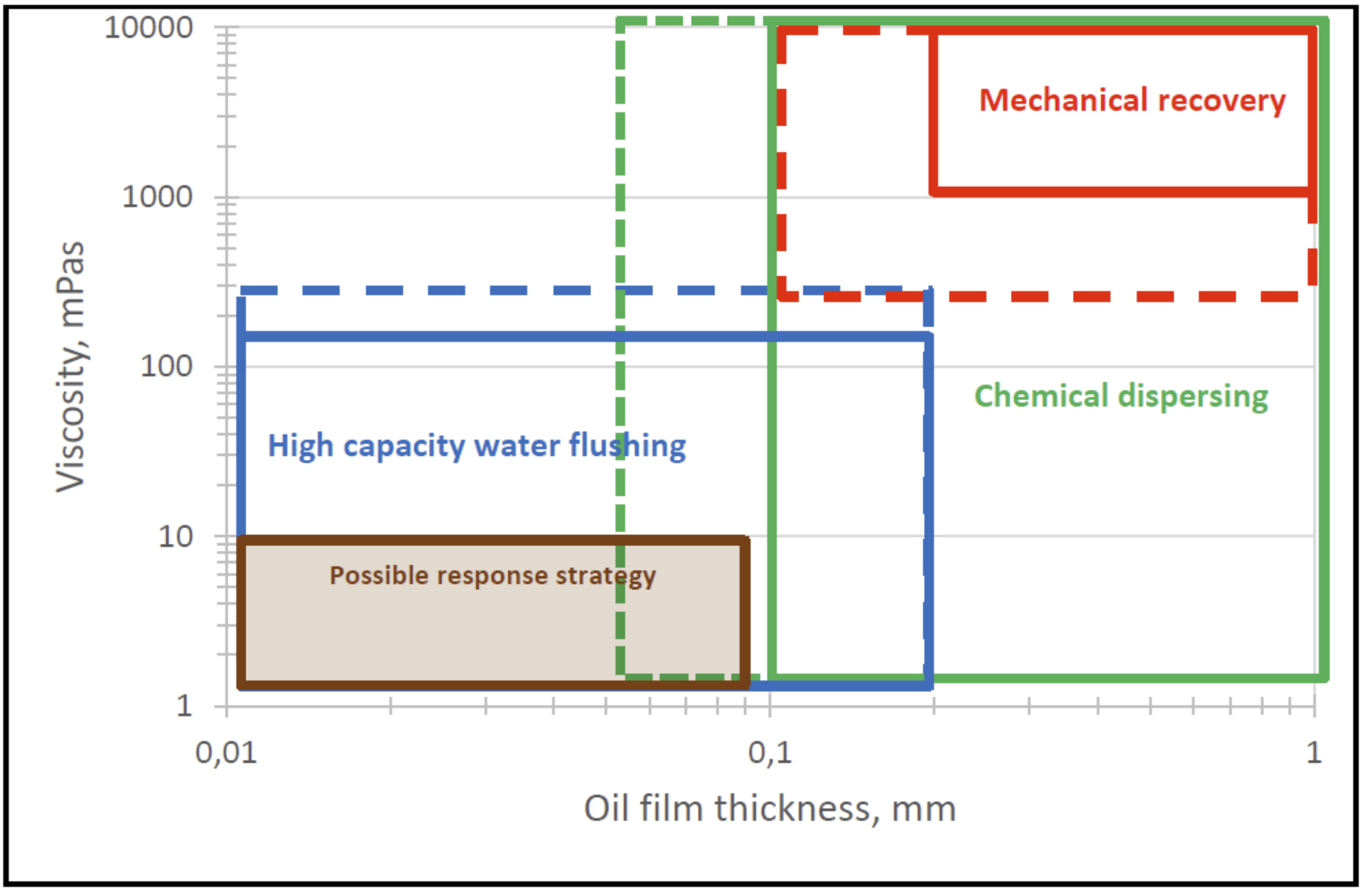
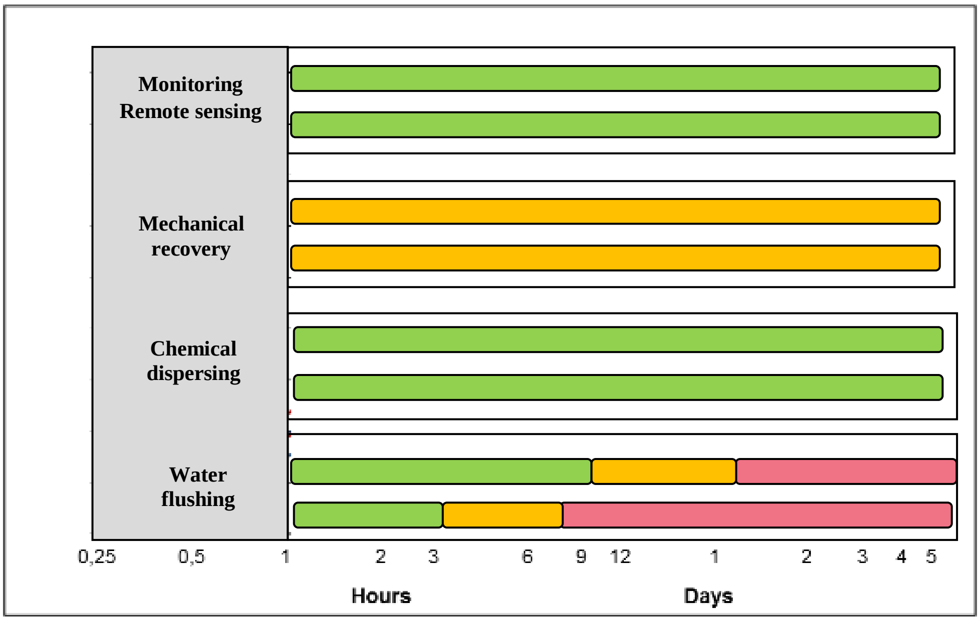


Figure 6.2 *Possible oil spill response strategy (shown in brown) for class 1 oils based on predicted viscosity and oil film thickness using the "standard" oil release scenario presented in section 4.1.*

6.3 Class 2: Low-emulsifying oils

Class 2: Winter, 2°C seawater temperature
2 m/s (above) and 5 m/s (below) wind speed



Class 2: Summer, 13°C seawater temperature
2 m/s (above) and 5 m/s (below) wind speed

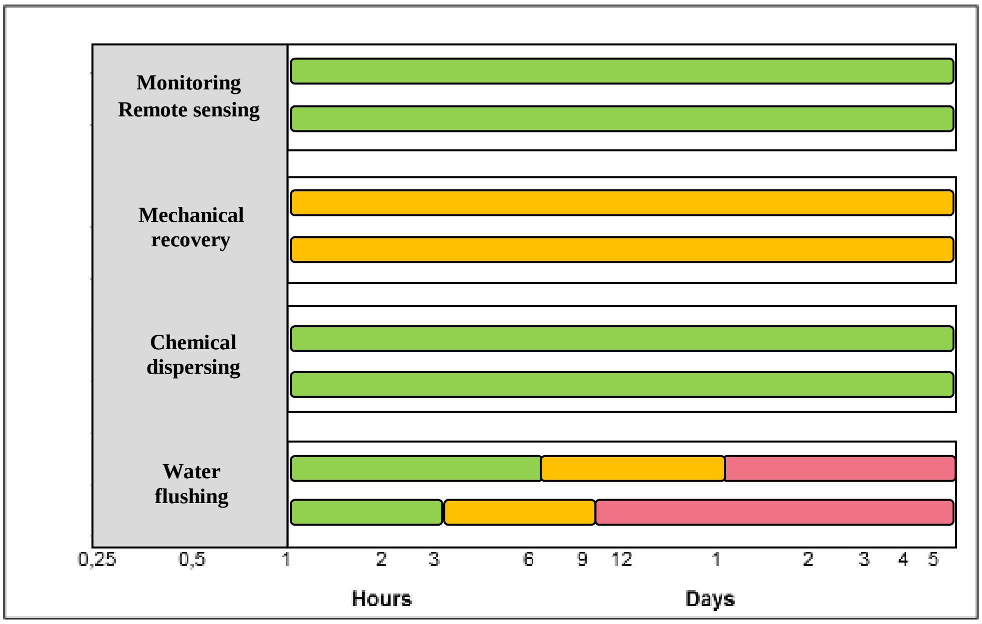


Figure 6.3 *Example of oil spill response strategy provided initial thin oil film and low wind conditions (< 5 m/s) by use of weathering data predicted by the SINTEF OWM, based on the "standard" release scenario in 4.1. The response criteria and color coding are explained in 4.3.5. Under each response option the upper bar represents 2 m/s wind speed and the lower 5 m/s.*

Justification:

Class 2 represents condensates and light crude oils with physicochemical parameters as indicated in Table 4.2.

Prediction of weathering properties and oil film thickness by use of the "standard" subsea release scenario defined in section 4.1 indicate that oils falling into this class tend to form unstable and low viscous w/o emulsions when spilled on the sea surface, provided that the initial oil film thickness is above 0.1 mm. Based on these predictions, potential response strategies for this selected release scenario is given below. If the release scenario or wind conditions are different from that described in 4.1, the recommended response strategy (illustrated with the brown in Figure 6.4) will likely be different.

Response technology	Response strategy
Mechanical recovery	• The initial oil film thickness is predicted to be above 0.1 mm (100 µm) from a subsea release. The thickness increases as the oil forms unstable w/o emulsion, but will likely not reach a thickness of 0.2 mm within the prediction period of 5 days. Confinement of oil in a boom should be feasible for such low (but increasing) thicknesses provided low wave action and reduced speed on the towing vessels. Reduced efficiency should be expected. • A thin oil film from a spill of oils in this class is not expected to reach a viscosity of 1000 mPa.s within the first 1-2 days. In low winds (< 5 m/s) and reduced recovery speed, mechanical recovery can commence, but reduced recovery efficiency should be expected. • Mechanical recovery may be a potential response option at low wind speeds (up to 5 m/s). For thin oil films (0.1 – 0.2 mm) recovery with booms should be performed at low vessel speed. "Bands" of thicker oil, if formed, may offer a possibility for mechanical recovery.
Use of chemical dispersants	• The low-dosage spraying boom is predicted to be highly effective on these predicted oil films. • The oils in this class will normally have a long "time-window" for use of dispersants. The oils will not form stable and high viscous w/o emulsions and are not expected to solidify. • At low wind speeds (< 5 m/s), artificial turbulence may be considered (e.g. high-capacity water flushing 0.5-1 hour after treatment).
High-capacity water flushing	• The predicted thickness from a subsea release is between 0.1 and 0.2 mm, and found to be optimal for high-capacity water flushing. • The predicted viscosity is below 150 mPa.s, for some hours, before it may increase due to w/o emulsification and evaporation. Water flushing is judged applicable up to a viscosity of 150 mPa.s and feasible before the viscosity raises above 250 mPa.s. • Water flushing is judged to be an efficient response method in an early phase after a release. There will be differences in the time-window between different oils based on the parameters above.
Monitoring and remote sensing	• Monitoring and remote sensing should be used as a support in a response operation and may be evaluated as the only practical action at higher wind speeds (>10 m/s).

Summary of exemplified response evaluation:

Figure 6.4 illustrates the different response options as summarized in section 4.3.5, based on an evaluation of oil film thickness and viscosity. The solid line for each response method represents the area where the method is judged applicable, while the dotted line represents the area where the method is judged feasible but with reduced efficiency. Both mechanical recovery and chemical dispersants can be used at higher film thicknesses and viscosities than illustrated on the axes. At the same time, mechanical dispersing can be used at lower film thicknesses than 0.01 mm.

Based on the example from the previous page with weathering predictions prepared by the "standard" subsea release scenario described, the possible response strategy is illustrated as a brown box in the middle of the figure. Both chemical dispersing and high-capacity flushing are shown to have potential for this release scenario. Given other release scenarios (DFU's), the response strategy will be different and should be evaluated for each specific oil by using the methodology described in this report.

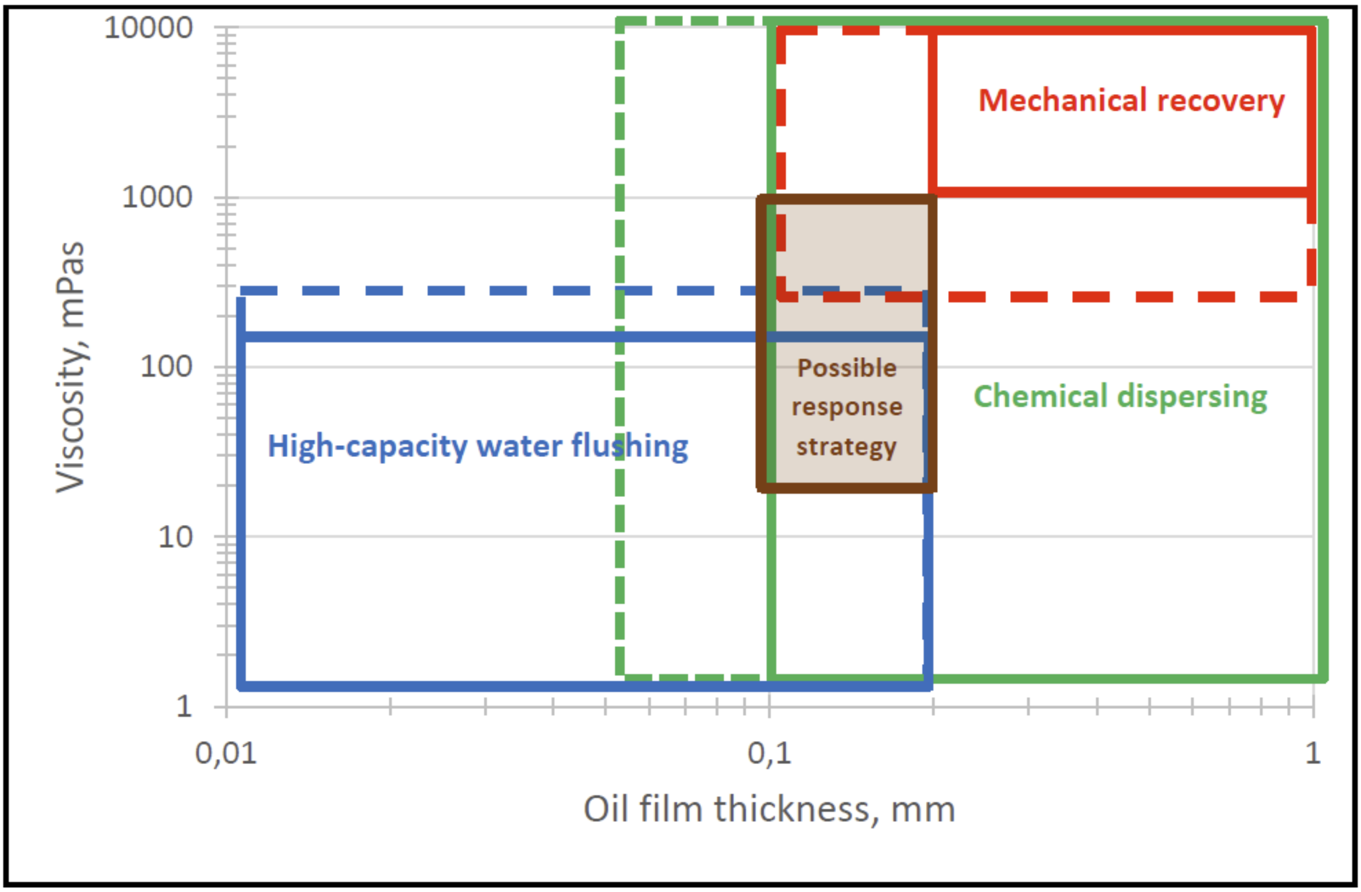
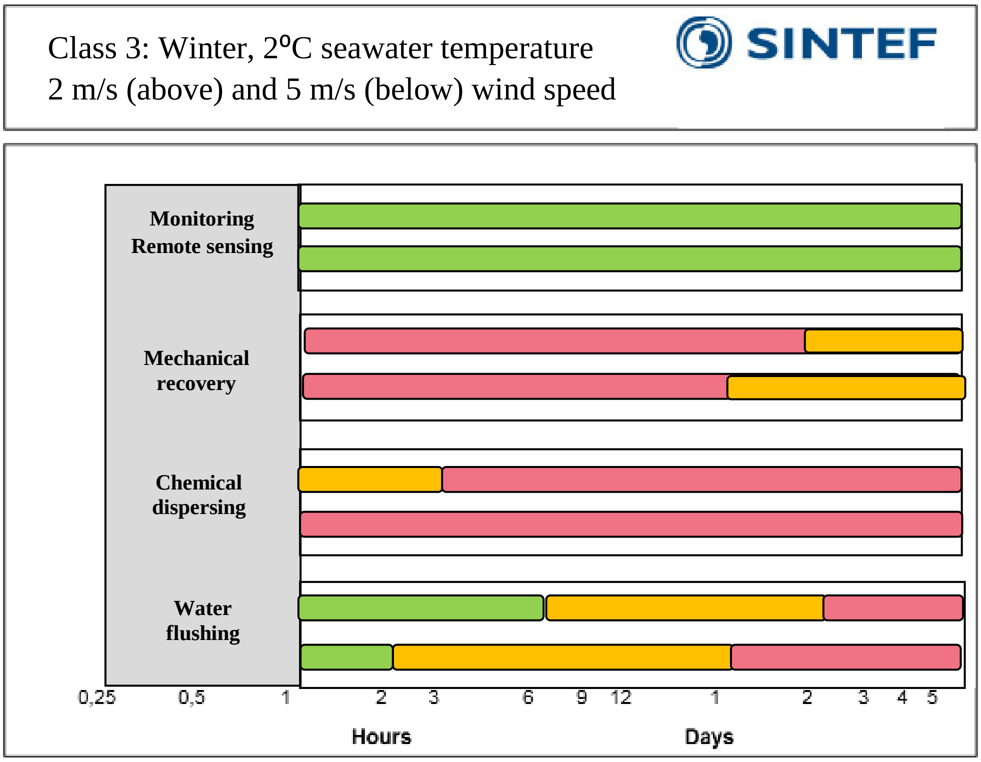


Figure 6.4 *Possible oil spill response strategy (shown in brown) for class 2 oils based on predicted viscosity and oil film thickness using of the "standard" oil release scenario presented in section 4.1.*

6.4 Class 3: Solidifying oils



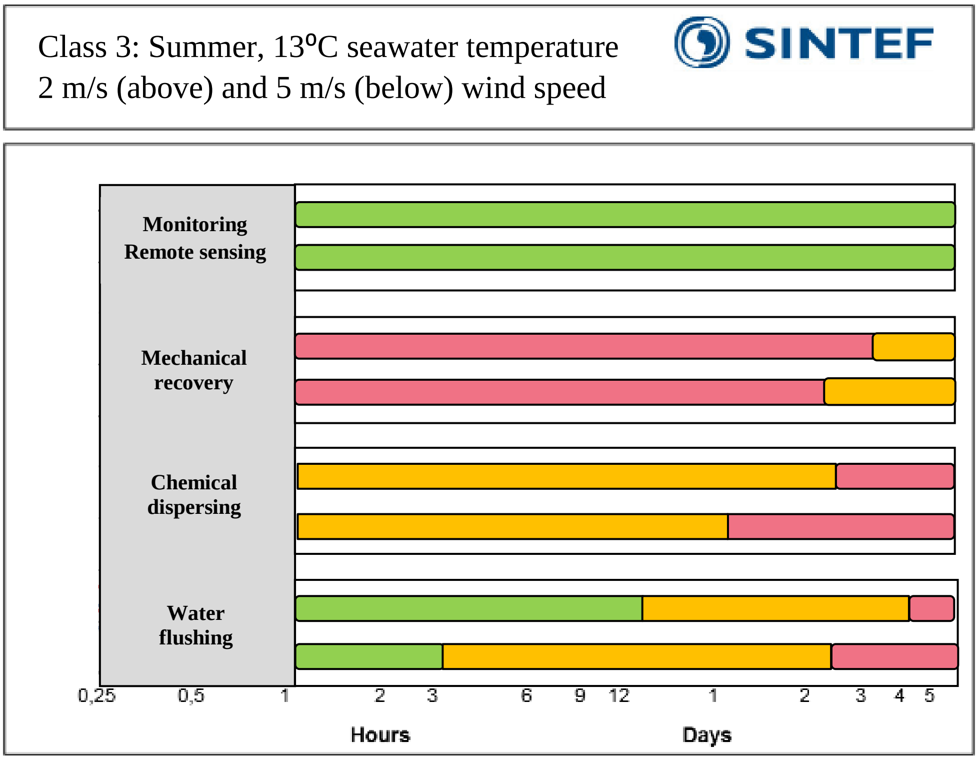


Figure 6.5 *Example of oil spill response strategy provided initial thin oil film and low wind conditions (< 5 m/s) by use of weathering data predicted by the SINTEF OWM, based on the "standard" release scenario in 4.1. The response criteria and color coding are explained in 4.3.5. Under each response option the upper bar represents 2 m/s wind speed and the lower 5 m/s.*

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Justification:

Class 3 represents condensates and light crude oils with physicochemical parameters as indicated in Table 4.2.

Predictions of weathering properties and oil film thickness by use of the "standard" subsea release scenario defined in section 4.1 indicates that oils falling into this class tend to solidify on the sea surface due to high pour points. Based on these predictions, an example of possible response strategy for this selected release scenario is given below. If the release scenario or wind conditions are different from that described in 4.1, the recommended response strategy (brown box in Figure 6.3) will likely be different.

Response technology	Response strategy
Mechanical recovery	• The initial oil film thickness is predicted to be around 0.1 mm (100 µm) as predicted by the subsea release scenario. The thickness decreases initially due to evaporation, spreading and relatively low-water uptake. However, provided that the initial film thickness is above 0.05 mm, the high wax content will cause the residue to solidify after a few hours, which would inhibit further spreading, and may cause "bands" of increased thickness to form (e.g. as observed in the NOFO OOW, 2016 with the Åsgard Blend). This may open a "window of opportunity" for confinement of such "bands" by booms and increase recovery. If the residue breaks up into individual lumps /flakes and spread over large areas, mechanical recovery will be very challenging. • A residue from a spill of oils will likely not surpass a viscosity of 1000 mPa.s. A possible mechanical recovery operation at low speed may have a potential for such oils, but reduced recovery efficiency should be expected.
Use of chemical dispersants	• The predicted initial oil film thickness indicates a potential for low-dosage dispersant application, but with a reduce efficacy in an early phase after release. • The oils falling into this class are described by their rapid increase in pour points with a tendency to solidify within the first one to two days. Dispersants do not normally work very well on solidified oils; however, before the oil solidifies or in an early phase after solidification, use of dispersants followed by high-capacity water flushing may have a potential. • Use of chemical dispersants is judged to be feasible, under summer conditions, but with reduced efficiency. The main reason being high pour point and potential formation of solidified oil lumps. This phenomenon is most pronounced at low seawater temperatures in winter conditions. • At low wind speeds (< 5 m/s) consider artificial turbulence, for instance by use of water flushing, 0.5-1 hr. after treatment.
High-capacity water flushing	• The predicted oil film thickness is found to be optimal for high-capacity water flushing. • Initially, the predicted viscosity is below 150 mPa.s, but increases within a few hours on the sea surface. • Mechanical dispersing by use of water flushing is judged to be applicable in an early phase after a release, with reduced efficiency when the viscosity increases.
Monitoring and remote sensing	• Monitoring and remote sensing should be used as a support in a response operation.

Summary of exemplified response evaluation:

Figure 6.6 illustrates the potential response options as summarized in section 4.3.5, based on an evaluation of oil film thickness and viscosity. The solid line for each response method represents the area where the method is judged applicable, while the dotted line represents the area where the method is judged feasible, but with reduced efficiency. Both mechanical recovery and chemical dispersants can be used at higher film thicknesses and viscosities than illustrated on the axes. It is also important to note that mechanical dispersing can be used at lower film thicknesses than 0.01 mm.

Based on the example from the previous page with weathering predictions prepared by the "standard" subsea release scenario, the possible response strategy is illustrated as a brown box in the middle of the figure. Due to high pour points and the potential for solidification, oil spill response to thin oil films from such oils may prove challenging. Dispersants and high-capacity water flushing may be efficient in an early phase before solidification, with a slightly longer "time-window" under summer conditions. If the oil solidifies and forms "bands" of thicker oil, mechanical recovery can be used, but will likely result in reduced efficiency due to scattered areas of thicker solidified oil. Given other release scenarios (DFU's), the response strategy will be different and should be evaluated for each specific oil by using the methodology described in this report.

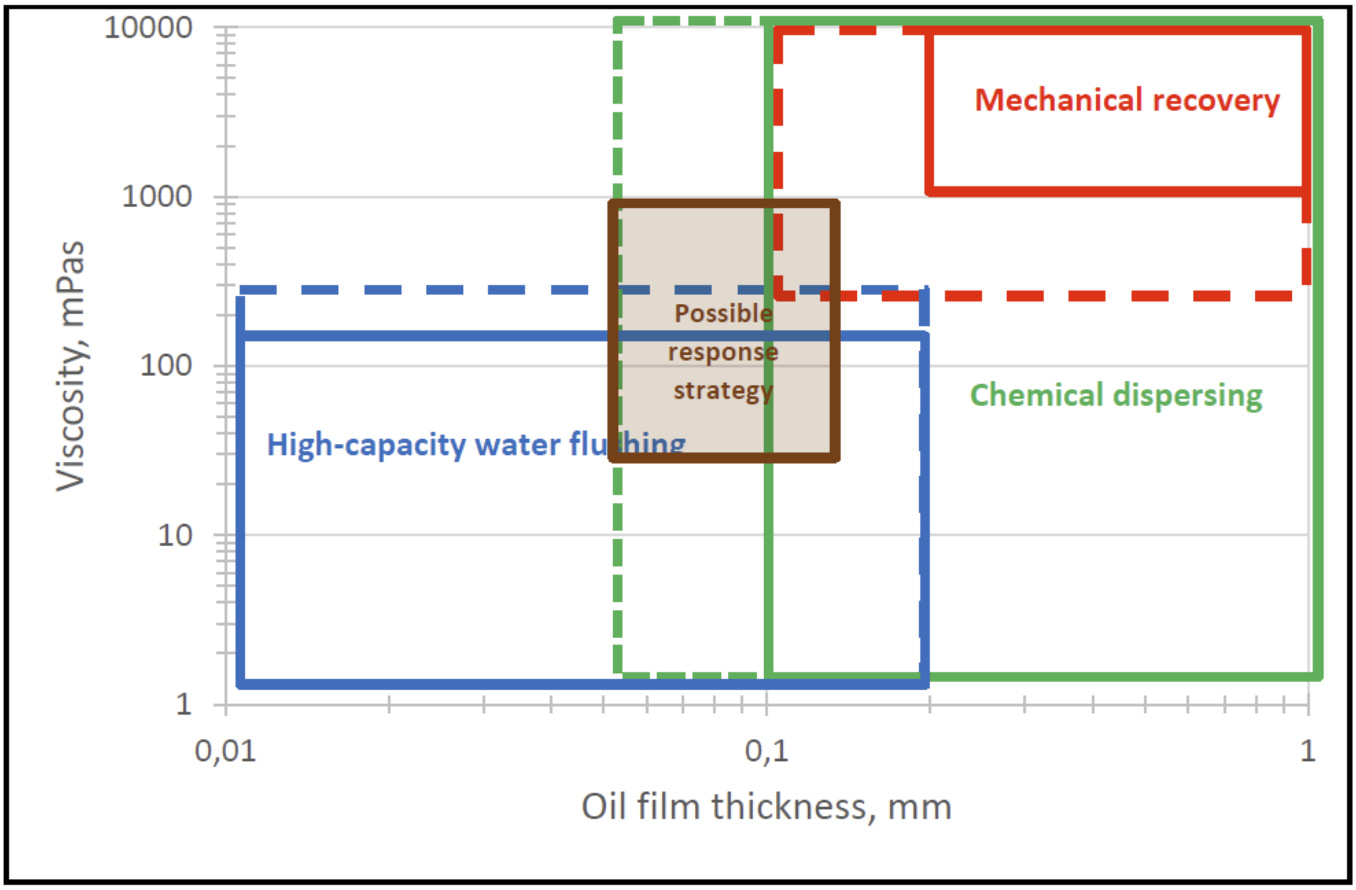
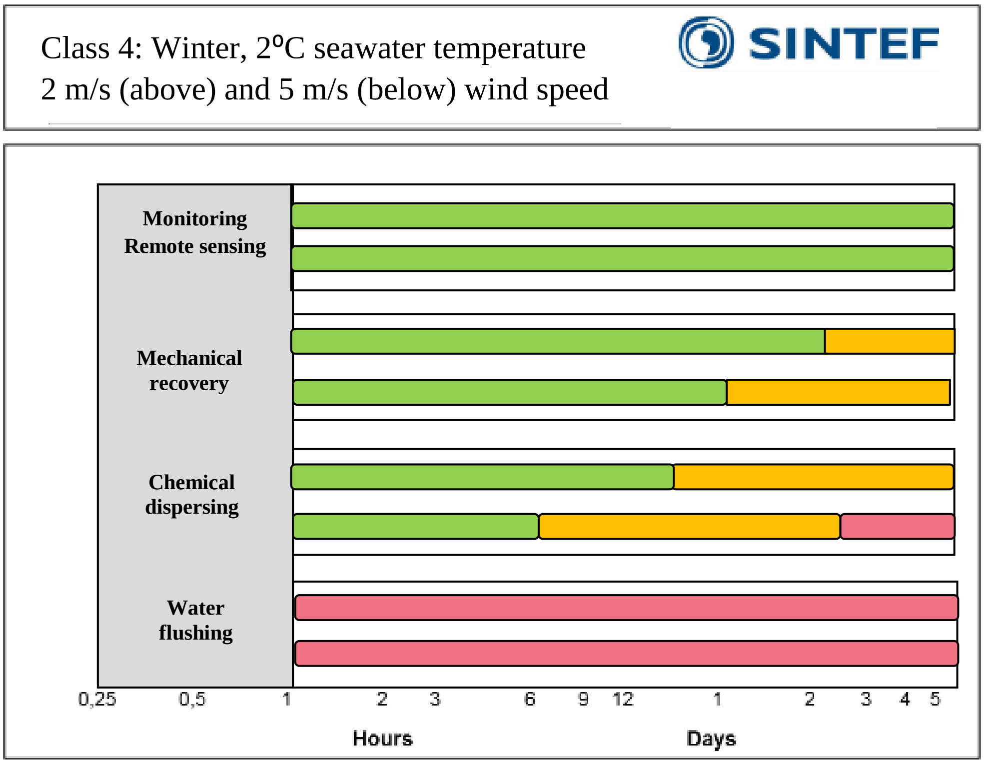


Figure 6.6 Possible oil spill response strategy (shown in brown) for class 3 oils based on predicted viscosity and oil film thickness using the "standard" oil release scenario presented in section 4.1.

6.5 Class 4: Emulsifying paraffinic crude oils



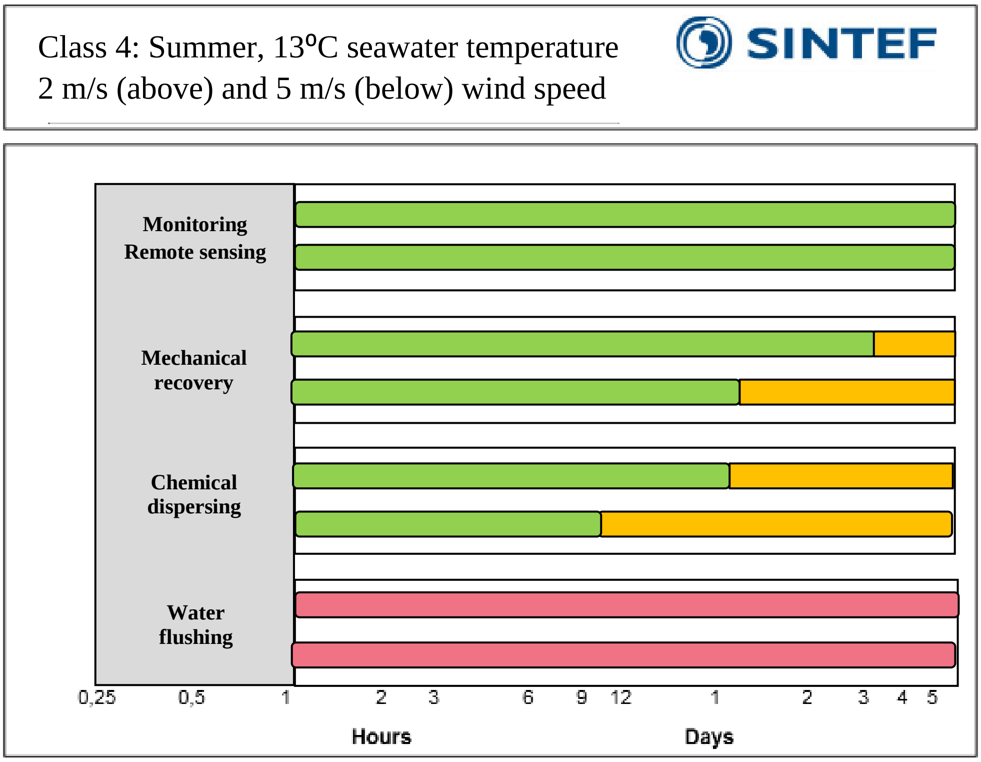


Figure 6.7 *Example of oil spill response strategy provided initial thin oil film and low wind conditions (< 5 m/s) by use of weathering data predicted by the SINTEF OWM, based on the "standard" release scenario in 4.1. The response criteria and color coding are explained in 4.3.5. Under each response option the upper bar represents 2 m/s wind speed and the lower 5 m/s.*

Justification:

Class 4 represents light to medium light crude oils with physicochemical parameters as indicated in Table 4.2.

Prediction of weathering properties and oil film thickness by use of the "standard" subsea release scenario defined in section 4.1 indicate that oils falling into this class form w/o emulsions with medium to higher stability and can reach viscosities above 1000 mPa.s after an oil spill to sea. Based on these predictions, potential response strategies for this selected release scenario is given below. If the release scenario or wind conditions are different from that described in 4.1, the recommended response strategy (illustrated with the brown in Figure 6.4) will likely be different.

Response technology	Response strategy
Mechanical recovery	• During a sub-sea release, the initial oil film thickness is predicted to be above 0.1 mm (100 µm), and will likely increase with w/o emulsification. • The viscosity starts at several hundred mPa.s and increases to several thousand by weathering on the sea surface. • Mechanical recovery is judged to have a large potential both under summer and winter conditions. After several days of weathering, a high-viscosity skimmer may be necessary.
Use of chemical dispersants	• During a sub-sea release, the initial oil film thickness is predicted to be above 0.1 mm (100 µm), and will likely increase by w/o emulsification. • The "time-window" for use of dispersants is relatively long, but reduced chemical dispersibility of the oil should be expected after several hours to a few days on the sea surface. The time-window will decrease with increasing wind speed and is somewhat longer under summer conditions compared to winter conditions. The time-window can be predicted based on dispersibility testing, normally part of standardized weathering studies. • Use of chemical dispersants is judged to have a large potential. At low wind speeds (< 5 m/s) artificial turbulence may be required, for instance by use of water flushing.
Water flushing (mechanical dispersing)	• High-capacity water flushing may be considered in the early phase after a spill, but the oil may rapidly start to emulsify and produce thicknesses above what is regarded as optimal for this technology. • The viscosity of the oil/emulsion will soon reach 250 mPa.s regarded as an upper limit for efficient water flushing. • Mechanical dispersing by use of water flushing is not judged to be an efficient response method in this scenario.
Monitoring and remote sensing	• Monitoring and remote sensing should be used as a support in a response operation.

Summary of exemplified response evaluation:

Figure 6.8 shows the different response options as summarized in section 4.3.5, based on an evaluation of oil film thickness and viscosity. The solid line for each response method represents the area where the method is judged applicable, while the dotted line represents the area where the method is judged feasible but with reduced efficiency. Both mechanical recovery and chemical dispersants can be used at higher film thicknesses and viscosities than illustrated on the axes. It is also important to note that mechanical dispersing can be used at lower film thicknesses than 0.01 mm.

Based on the example from the previous page with weathering predictions prepared by the "standard" subsea release scenario described, the possible response strategy is illustrated as a brown box in upper right corner of the figure. Both mechanical recovery and use of dispersants can have a large "time-window". High-capacity water flushing is not judged to be applicable in this scenario. Given other release scenarios (DFU's), the response strategy will be different and should be evaluated for each specific oil by using the methodology described in this report.

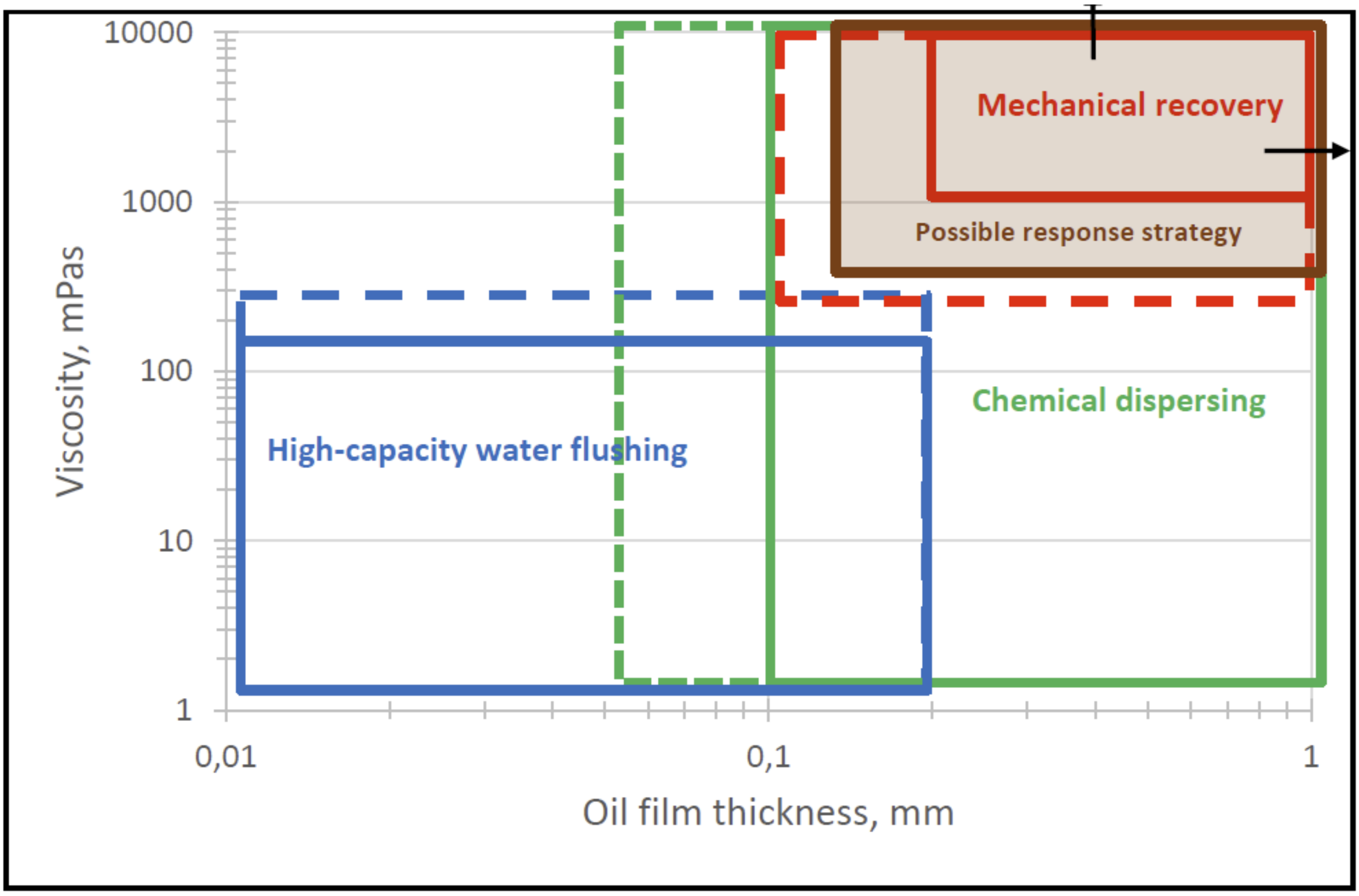


Figure 6.8 Possible oil spill response strategy (shown in brown) for class 4 oils based on predicted viscosity and oil film thickness using the "standard" oil release scenario presented in section 4.1.

7 Potential for further improvement

This section summarizes a few points for further improvement that have been identified through the TOF project.

- A set of criteria for defining "border" values for oil spill response efficiency have been defined (section 4.3). These are typically based on laboratory experiments and documentation from field trials, often with only one oil type involved. To increase the robustness, further field documentation is recommended for a wider range of different condensates, light crude oils and oil products.
- 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 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.
- The Recommendations given in this report are based on the 7 condensates and light crude oils included in the TOF project. The methodology for evaluating different response options is closely related to the 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 include three scenarios for analysis and prediction, as a basis for recommendation of response strategy:
    - A standard surface release (a common parameter for a weathering study today)
    - The "standard" subsea release scenario described in this report
    - A relevant subsea release based on DHA (DFU) for the oil in question
- Based on previous laboratory and field studies it is assumed that an oil may solidify at sea, having a pour point 5 - 15°C higher than the seawater temperature. At low wind speeds (< 5 m/s), oils may solidify at the lower end of that range. Solidification will influence the response options and is addressed in these Recommendations.
- 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. This is based on testing with only one oil type (Åsgard Blend) and should be further documented with other oil types.

Further refining of the water flushing technology could be obtained by (Daling *et al*., 2017):

- Laboratory experiments
    - Extend the test matrix for water-flushing with the test method designed during the Oljevern 2015. Testing a larger range of oils and weathering degrees with a wider variation in viscosity would establish 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 in close cooperation with remote sensing aircraft.
    - The promising demonstration of the of these response concepts during the 2016 NOFO OOW field trial should be extended at the future NOFO OOW trials planned for 2018. It is recommended that similar experiments be conducted, but using less persistent condensates or a surrogate such as a marine gas oil.

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