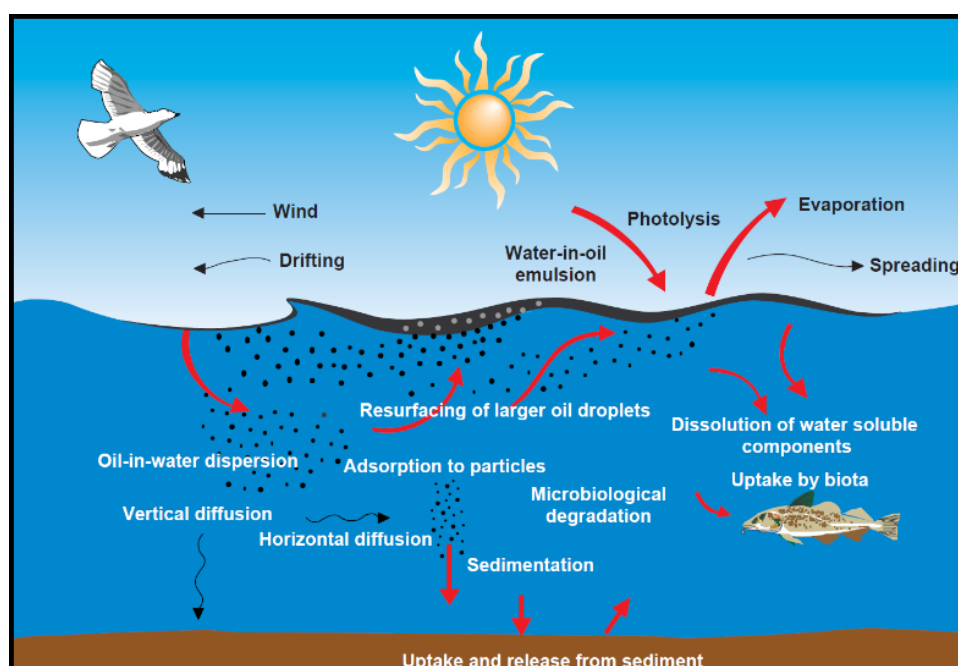# Report

## Visund Sør condensate and Visund crude oil– Weathering properties and behaviour at sea

In relation to oil spill response

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**SINTEF Ocean AS**

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# Report

## Visund Sør condensate and Visund crude oil– Weathering properties and behaviour at sea

**KEYWORDS:**
Weathering;
Oil Weathering Model;
Oil Spill Response;
Visund sør-and Visund

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**ABSTRACT**
A weathering study has been conducted on Visund Sør condensate and Visund crude oil. The weathering study is based on a small-scale laboratory testing at 13 °C. The SINTEF Oil Weathering Model (OWM was used to predict the weathering of Visund Sør and Visund if spilled on the sea surface. The weathering properties of the Visund Sør and Visund were discussed in relation to oil spill response.

MANAGEMENT SYSTEM CERTIFICATION

DNV·GL

ISO 9001 = ISO 14001
OHSAS 18001

| PREPARED BY | CHECKED BY | APPROVED BY |
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| Kristin R. Sørheim | Per S. Daling | Mimmi Throne-Holst |

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# Table of Contents

# 1 Executive summary

Spilled oils undergo changes when weathered on the sea surface. These changes affect oil behaviour and consequently oil spill countermeasures. Oil weathering varies over time and with different environmental conditions. Based on input from the experimental weathering data of the oil, the SINTEF Oil Weathering Model (OWM) is used to predict the properties of oil as it weathered over time. The lifetime of an oil spill at sea depends on the oil's composition, the release conditions (e.g. on the surface, underwater) and environmental conditions (temperature, wind, waves). Natural dispersion and evaporation are the main weathering processes that remove an oil spill from the sea surface. This summary gives a brief overview of the main changes predicted for Visund Sør condensate and Visund crude oil when weathered on the sea surface.

**Visund Sør condensate**

Visund Sør is a light paraffinic condensate with density of 0.742 g/mL. The condensate has low contents of asphaltenes (<0.01 wt. %) and wax (0.05 wt. %). The pour points are low for the fresh oil and the residues (-36 to -9°C). Similar, the condensate also exhibits very low viscosities (fresh oil and residues) ranging from 1 to 7 mPa.s measured at 13 °C (10 and 100s$^{-1}$). Visund Sør will neither form emulsions nor solidify if spilled at sea. The predicted mass balances show that the condensate has very short lifetime on the sea surface, particularly at high wind speeds, i.e. 0.5-1 hour, at 10 and 15 m/s due to high degree evaporative loss, and high degree of natural dispersion/entrainment of oil droplets into the water column. At lower wind speeds (2-5 m/s), the oil remains for a longer time (6-12 hours) on the surface.

If free gas is not associated with an oil release (e.g. surface release of stabilized oil at 1 atm.), the flash point of the oil is the most important parameter when evaluating the potential for fire /explosion hazard. Spilled oil on the sea surface assumes to reach the ambient water temperature within a short time. The fire hazard, based on the volatile components from the oil, may be high if the flash point of the oil is below the sea temperature. For Visund Sør, the flash point is predicted to exceed the sea temperature within the first 15 minutes at wind speeds (10-15 m/s), and in 1 hour at lower winds speeds (2-5 m/s). However, for larger release rates, the time for the flash point to exceed the sea temperature can be extended. Moreover, some storage tanks in vessels engaged in oil recovery operations may not be classified to carry liquids with flash points lower than 60 °C. Visund Sør reaches this limit (60 °C) in approx. 3-4 hours after a spill at calm wind speed (2 m/s) at summer and winter conditions respective, and more rapidly at higher wind speeds.

Mechanical recovery is assumed not to be an optimal response method due to very low viscosities (~10 mPa.s) that pronounce high risk for boom leakage for low viscous oils (lower than 1000 mPa.s). However, at low wind speeds low-viscous oils may be confined if the operational towing speed is low. In addition, mechanical recovery has in general low booming efficacy for thin oil films oil < 0.1-0.2 mm. But, in calm weather condition, after a surface (batch) release, mechanical recovery may have potential for Visund Sør blend in an early phase before the oil has spread on the surface producing thin films.

It was not performed dispersibility testing Visund Sør due to its negligible water uptake and low viscosity assuming high degree of natural dispersion. A simple test with and without application of dispersant by use of MNS (high energy test) verified that the condensate has a high degree of dispersion, and formed small oil droplets (< 70-100 µm) after dispersant application that remained in the water phase. The condensate is expected to have a rapid and vast spreading on the sea surface and produce thin oil films (≤50 µm) within short time at sea. Use of dispersants for film thicknesses < 0.1 mm are not considered to be optimal and efficient but may have a potential in the first hours in calm weather conditions, assuming film thicknesses > 0.1 mm, to enhance the natural dispersion.

Mechanical dispersion by use of high-capacity water flushing can be an option for thin oil films < 0.2-0.3 mm, in calm weather for very low viscous oils such as Visund Sør. A combination of mechanical dispersion and application of dispersants can be considered for film thicknesses lager than 0.3 mm.

Monitoring and remote sensing will in any case be important in an oil spill operation and can be evaluated as an acceptable and practical response option, particularly in increasing wind speeds (> 5m/s) for Visund Sør.

**Visund crude oil**

Visund is a light paraffinic crude oil with density of 0.794 g/mL. The crude oil has low contents of asphaltenes (0.03 wt. %) and wax (1.4 wt. %). The pour point is low for the fresh oil (- 33 °C) but increases significantly for the residues ranging from 0 to 24 °C. The viscosities (fresh oil and water-free residues) are ranging from 2 to 1508 mPa.s measured at 13 °C ($10s^{-1}$).

Visund forms water-in-oil (w/o) emulsions with a high-water uptake (~80 vol. %). The emulsions formed were stable but released water when adding different concentrations (500 and 2000 ppm by weight) of the emulsion breaker (Alcopol O 60 %). The highest concentration (2000 ppm) was shown to be slightly more effective to break the emulsions, i.e. 500 ppm should be sufficient for Visund. Emulsion breaker may effectively be used during an oil spill operation to remove or reduce water from the recovered oil/emulsion. Emulsion breakers are normally injected at the skimmer head prior to transferring the collected oil/water to storage tanks, which minimizes the storage volume.

The mass balances show that the Visund is broken up and removed from the sea surface within 1 day in high wind speeds (15 m/s) at winter (5 °C) and summer conditions (15 °C), due to evaporative loss and natural dispersion/entrainment. However, after 5 days in very calm weather conditions (2 m/s wind speed) as much as 40-45 % of the oil can still remain on the sea surface.

For Visund, the flash points are predicted to exceed the sea temperature within the first hour at all wind speeds. For larger release rates, the time for the flash point to exceed the sea temperature can be extended. In addition, the flash points of Visund reaches a temperature limit of 60 °C in 4-5 hours after a spill in very calm wind speed (2 m/s) at 15 °C and 9 hours at 5 °C, but more rapidly at higher wind speeds at both temperatures. However, this limit is not considered at relevant for oil recovery vessels with A-class certification for transport of liquids (Class I/II, flash point < 60 °C).

The risk for boom leakage in a mechanical recovery operation is more of a concern for low viscous oils (lower than 1000 mPa.s) compared to emulsions that are more viscous. Boom leakage is also influenced by other factors such as operational speed and weather conditions. Here we show that the emulsion viscosities of Visund e.g. surpassed 1000 mPa.s about 1-2 days at 5 m/s wind speed (5 and 15 °C), and about 9-12 hours at 10 m/s wind speed at 5 and 15 °C. Moreover, viscosities larger than 15-20 000 mPa.s are known to reduce the flowability of the oil/emulsion when using traditional weir skimmers. However, Visund has predicted emulsion viscosities lower than this limit within 5 days weathering at summer and winter conditions.

Visund is expected to have potential for chemical dispersion in both winter and summer conditions. The oil was found to be easily dispersible with the dispersant Dasic NS (DOR 1:25) for viscosities < 2000 mPa.s, and not dispersible >7000 mPa.s (estimated). In the field, if the viscosity of Visund is reduced dispersible, additional energy (e.g. thrusters, Fire Fighting (Fi-Fi) systems or MOB (Man overboard boats) or higher DOR and/or repeated dispersant application may increase dispersant effectiveness. It is expected that Visund, particularity in calm weather conditions, requires artificial energy and high DOR to enhance the dispersibility of the oil emulsions. With viscosities higher than 7000 mPa.s the efficacy of dispersant application is expected to be low. Increased weathering potentially increases the high pour points to the point of solidification (elastic properties) at the sea surface.

Solidification typically arises when the pour point of the oil is 5-15 °C above the seawater temperature. In such cases, if solidified (low emulsified /water free) lumps are observed on the sea surface, a lower dispersant effectiveness is likely.

# 2 Introduction

New oil types (from heavy crude oil to light crude oils and condensates) are continuously coming into production worldwide. Due to large variations in different crude oils' physical and chemical properties, their behaviour and fate may vary greatly if spilled at sea. For example, the "Braer" accident at the Shetlands (1993) and the "Sea Empress" accident in Wales (1996) have demonstrated how different the fate and behaviour of the crude oils can be when spilled on the sea surface. For that reason, obtaining comprehensive knowledge about the expected behaviour of spilled oil at sea is of great importance. Moreover, the "Deepwater Horizon" incident in the Gulf of Mexico (2010) clearly showed how the efficacy of the different response techniques changed as the oil weathered and emulsified on the sea surface over a long period. These past experiences shape the knowledge base and the subsequent refinement of future operative strategies in terms of where, when, and how the mitigation methods should operate during a response operation. Appendix A describes the general physical and chemical properties and weathering processes of crude oils spilled on the sea surface.

SINTEF Ocean has performed a weathering study (refers to Aktivitetsforskriften § 59) on Visund Sør condensate (hereinafter called Visund Sør) and Visund crude oil (hereinafter called Visund) based on a request from Equinor. The weathering study was conducted at 13 °C as agreed upon with Equinor. The obtained laboratory data were further used to predict the weathering properties of the oils by use of the SINTEF Oil Weathering Model (OWM). Information about the Visund field is given in Figure 2-1, below.



Visund is an oil and gas field in blocks 34/8 and 34/7, 22 kilometres north-east of the Gullfaks field in the Tampen area of the North Sea. The water depth is 335 metres.

On stream in the spring of 1999, this development embraces a floating production, drilling and quarters platform.

The subsea-completed wells on the field are tied back to the floater with flexible risers. Oil is piped to Gullfaks for storage and export. The Visund field began producing gas and exporting it to continental Europe on 7 October 2005.

Visund Sør is an oil and gas field consisting of the Pan and Pandora discoveries located 10 kilometres from both the Gullfaks C and Visund A-platforms. The field is developed by means of a subsea installation and is tied back to Gullfaks C for processing.

Visund Sør started producing in November 2012. Water depth 290 m.

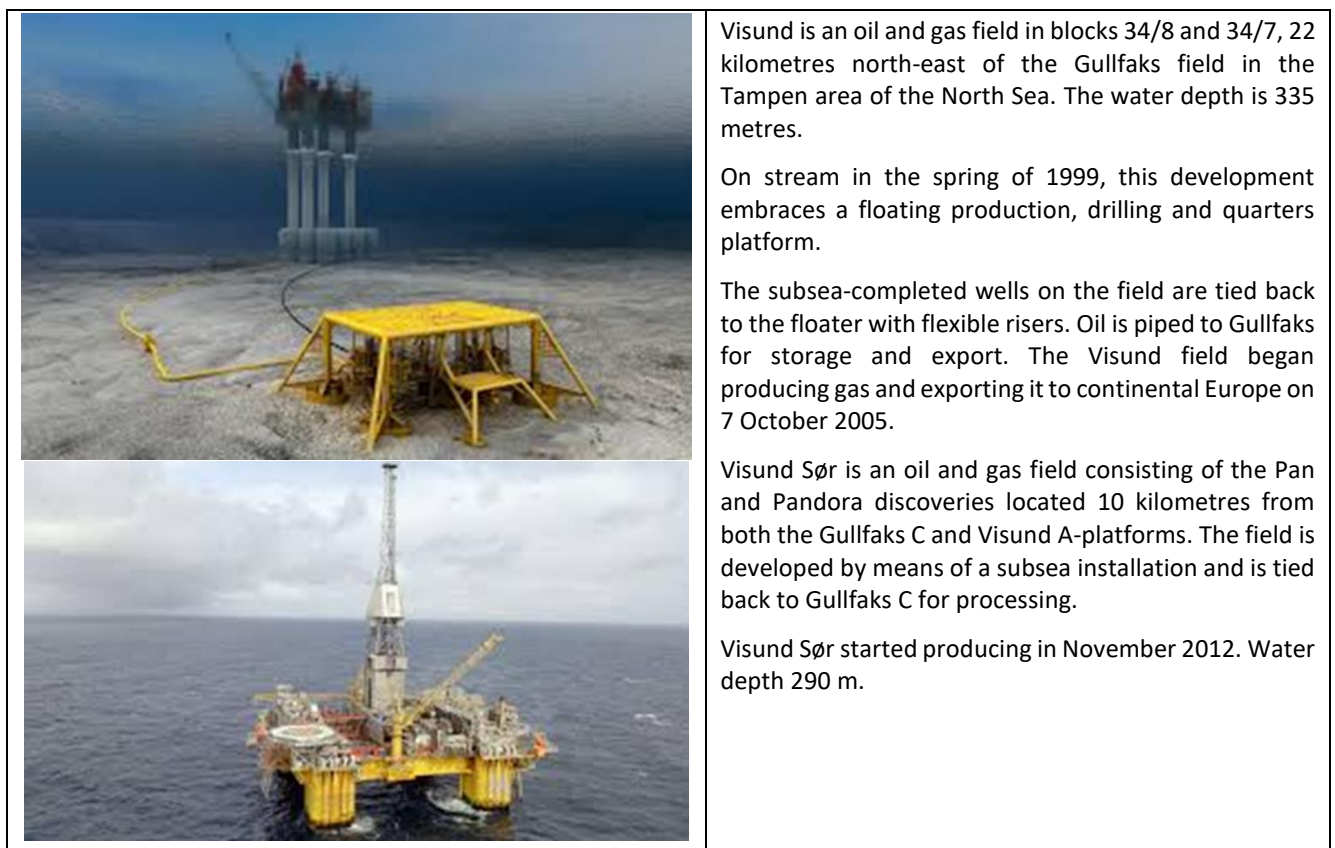*Figure 2-1*      https://www.equinor.com/en/what-we-do.html#fields-and-platforms

## 3 Small-scale laboratory testing results of Visund Sør and Visund

The methodology of small-scale weathering study is described in Appendix B. Physico-chemical parameters and weathering properties of Visund Sør and Visund were compared with similar data of other oils as listed in Table 3-1: Visund 1998, Visund 2009, Kvitebjørn 2019, and Kristin. The oils in comparison were selected in agreement with Equinor. Visund was preciously tested for its weathering properties in 1998 and 2009, in addition to previous limited studies (re-checks) reported in 1999 and 2002. The weathering data of Visund from 1998 and 2009 are included in the SINTEF Oil database for oil weathering predictions.

*Table 3-1        Oils compared with Visund Sør and Visund\**

| Oil name | SINTEF ID | Report no | Reference |
|---|---|---|---|
| Visund 1998 | 98-001 | A98162 | Resby el al, 1998 |
| Visund 2009 | 2008-0227 | F110361 | Sørheim, 2009 |
| Kvitebjørn 2019 | 2019-1059 | OC2019 A-097 | Sørheim and Hellstrøm, 2019 |
| Kristin | 2006-0256 | A06221 | Leirvik, 2006 |

*\*Visund Sør: SINTEF ID 2020-3891 and Visund: SINTEF ID: 2020-4737*

### 3.1 Gas chromatographic (GC-FID) characterization

The hydrocarbon profiles of Visund Sør and Visund were analysed by use of gas chromatography (GC) coupled with Flame Ionization detector (FID). Figure 3-1 and Figure 3-2 illustrate the GC-FID outputs (i.e. gas chromatograms) of the fresh oil of Visund Sør and Visund and their corresponding evaporated residues at three different degree of evaporative loss of volatiles at 150, 200 and 200°C+ (see Appendix B.2). The loss of low molecular weight (volatiles) compounds (shown towards the left of the chromatogram) at the three temperatures mimics that of natural weathering (evaporative loss at sea) and provides support for the artificial evaporation of the crude oil by use of distillation (topping) in the laboratory. The gas chromatograms show the $n$-alkanes as systematic narrow peaks. The first peaks in the chromatogram represent components with the lowest boiling points. Some of the more complex components, such as resins and naphthenes, are shown as a broad and poorly defined bump below the sharp peaks and are often described as the "Unresolved Complex Mixture" (UCM). Heavier compounds such as asphaltenes ($> n$C$_{40}$) are not possible to analyze with this technique.

Visund Sør is a light paraffinic condensate with high amounts of light $n$-alkanes in the range of $n$C$_5$-$n$C$_{15}$ and with a minor content of $n$-alkanes above C$_{15}$ (Figure 3-3) that reflects the very low content of wax. For comparison, the hydrocarbon profile of Visund Sør shows similarities with the condensate Kvitebjørn 2019 (Figure 3-3). Visund is classified as a light paraffinic crude oil that show similarities in the hydrocarbon profiles with previous batches of Visund 2009 and Visund 1998 and has also similarities with Kristin light oil (Figure 3-3). Overall, the crude oils in comparison have a main range of $n$-alkanes from $n$C$_5$ to $_n$C$_{36}$, where $n$-alkanes $>$ C$_{20}$ reflect a certain wax content.

Moreover, GC/FID is an important tool for oil characterization and for oil spill identification as an initial step. Common screening parameters used for identification, as well as for the degree of biodegradation, are the $n$C$_{17}$/Pristane and $n$C$_{18}$/Phytane ratios. Table 3-2 shows the ratios of Visund Sør and Visund in comparison with the other oils.

*Table 3-2        $n$C$_{17}$/Pristane and $n$C$_{18}$/Phytane ratios\**

| Oil name | $n$C$_{17}$/Pristane\* \* | $n$C$_{18}$/Phytane\*\* |
|---|---|---|
| Visund Sør | 1.5 | 2.9 |
| Visund | 1.5 | 2.2 |
| Visund 2009 | - | - |
| Visund 1998 | 2.0 | 3.1 |
| Kvitebjørn 2019 | 1.7 | 2.7 |
| Kristin | 1.9 | 2.6 |

*\*Ratios > 2 typical for high paraffinic oils, ratios < 1 typical for biodegraded /naphthenic oil. -: not calculated*
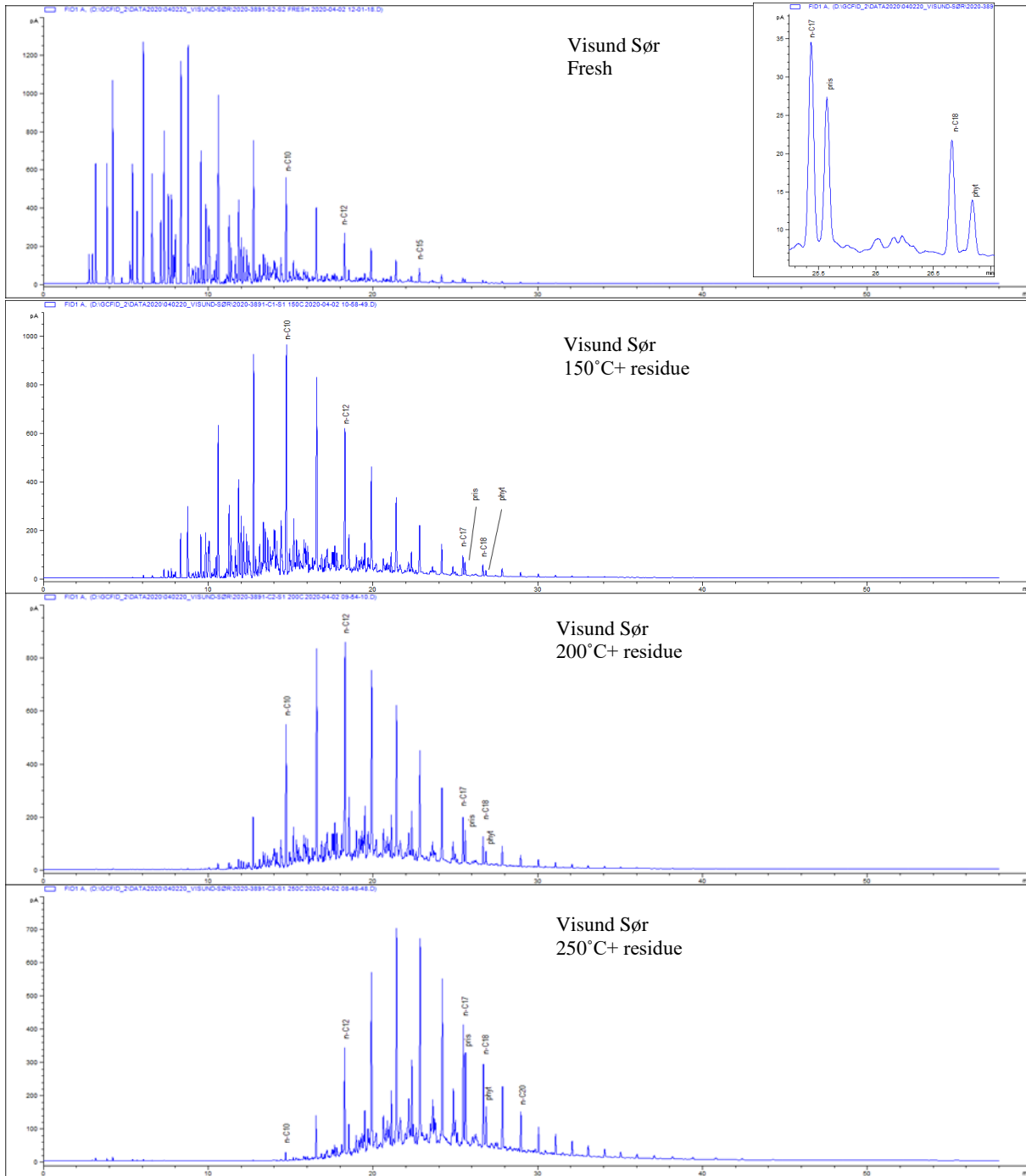
*Figure 3-1     GC-FID chromatograms of fresh sample and evaporated residues of Visund Sør*

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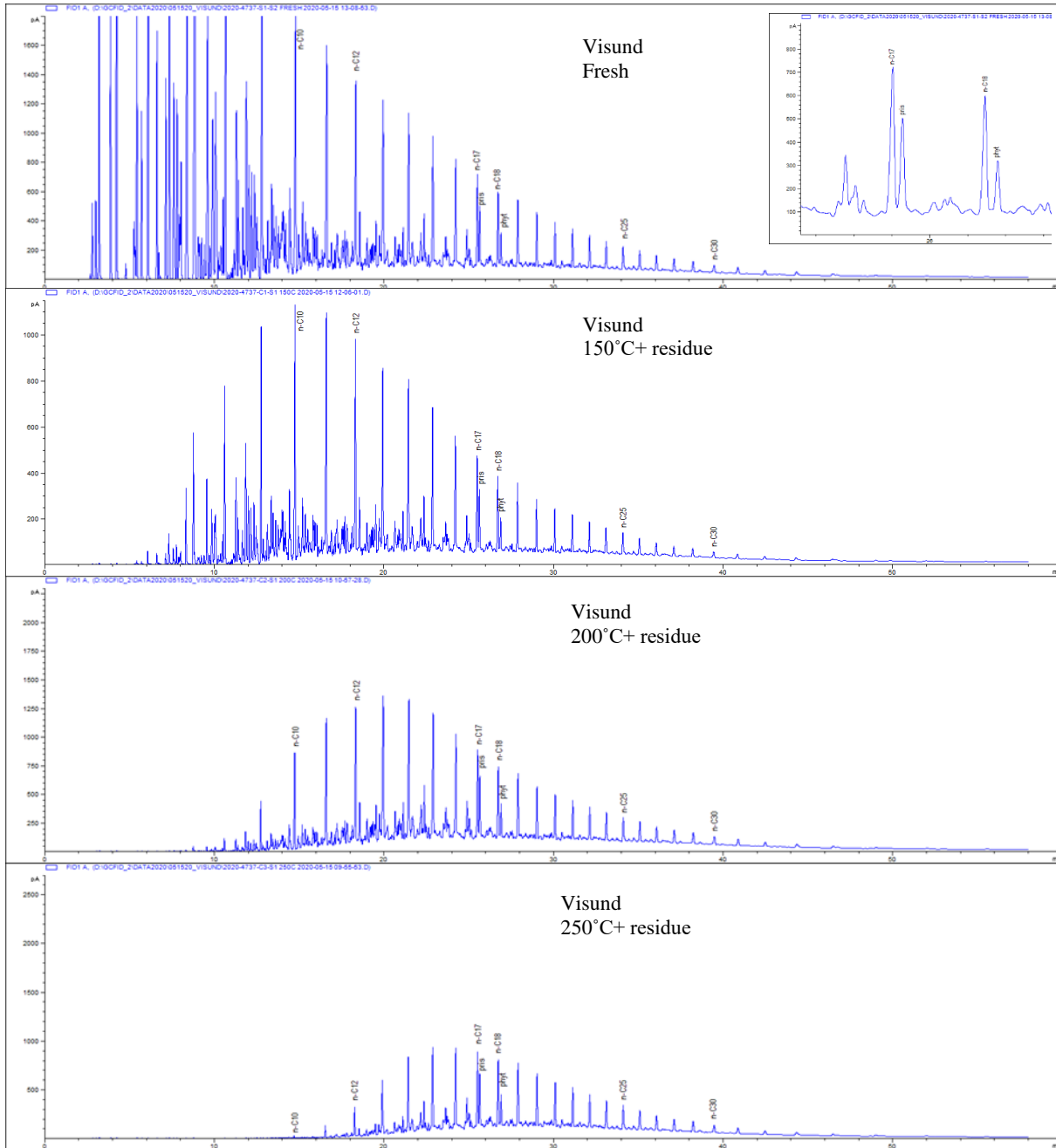
*Figure 3-2      GC-FID chromatograms of fresh sample and evaporated residues of Visund, normalised on nC20*

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Visund Sør- Fresh
(SINTEF ID: 2020-3891)

Visund - Fresh
(SINTEF ID: 2020-4737)

Visund 2009- Fresh
(SINTEF ID: 2008-0227)

Visund 1998 - Fresh
(SINTEF ID: 98-001)

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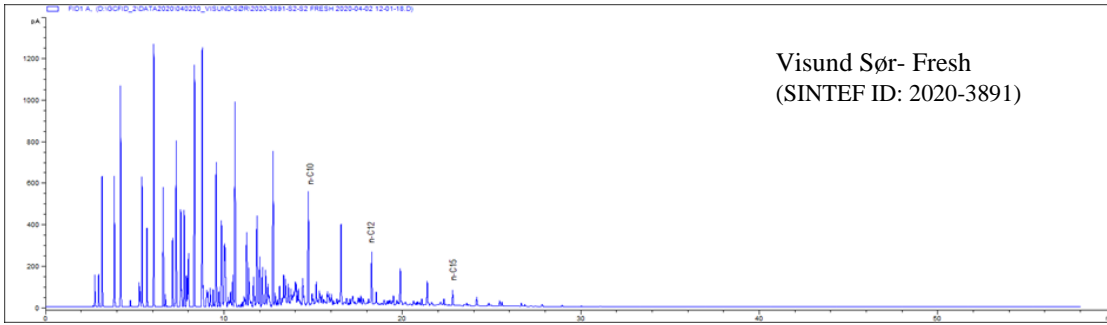
Figure 3-3    *GC-FID chromatograms for fresh oils of Visund Sør and Visund in comparison with Visund 2009, Visund 1998, Kvitebjørn 2019 and Kristin. The retention times differ between the chromatograms due to different temperature programs (relative comparison)*
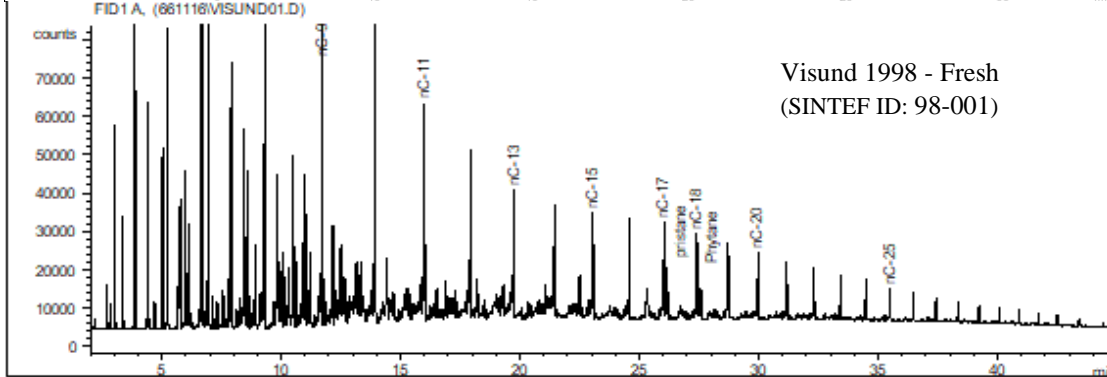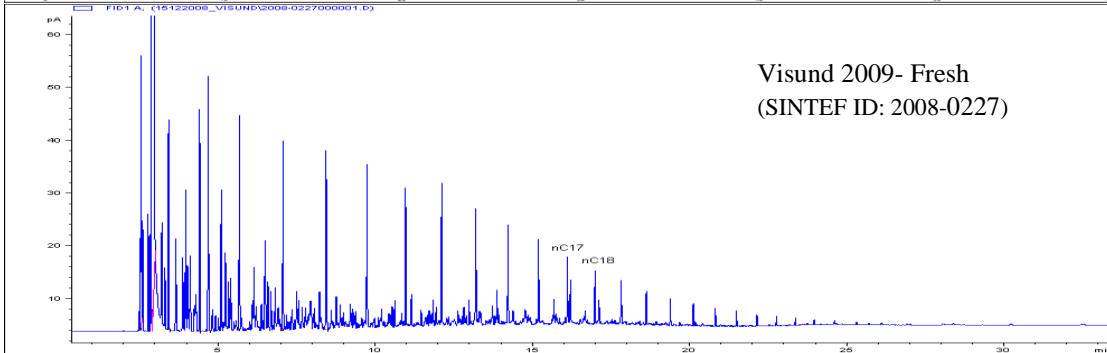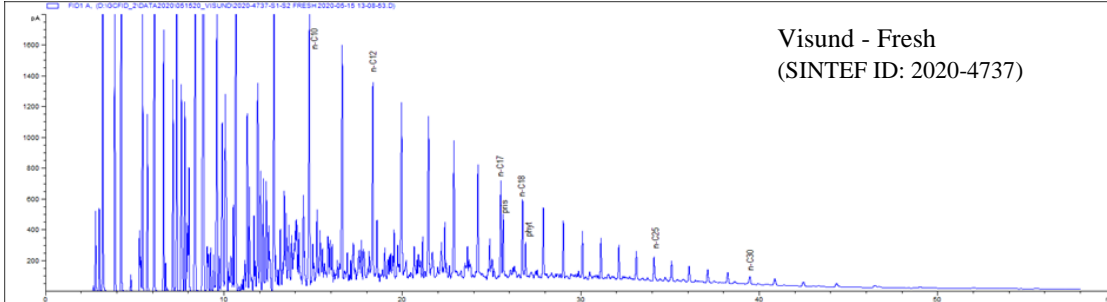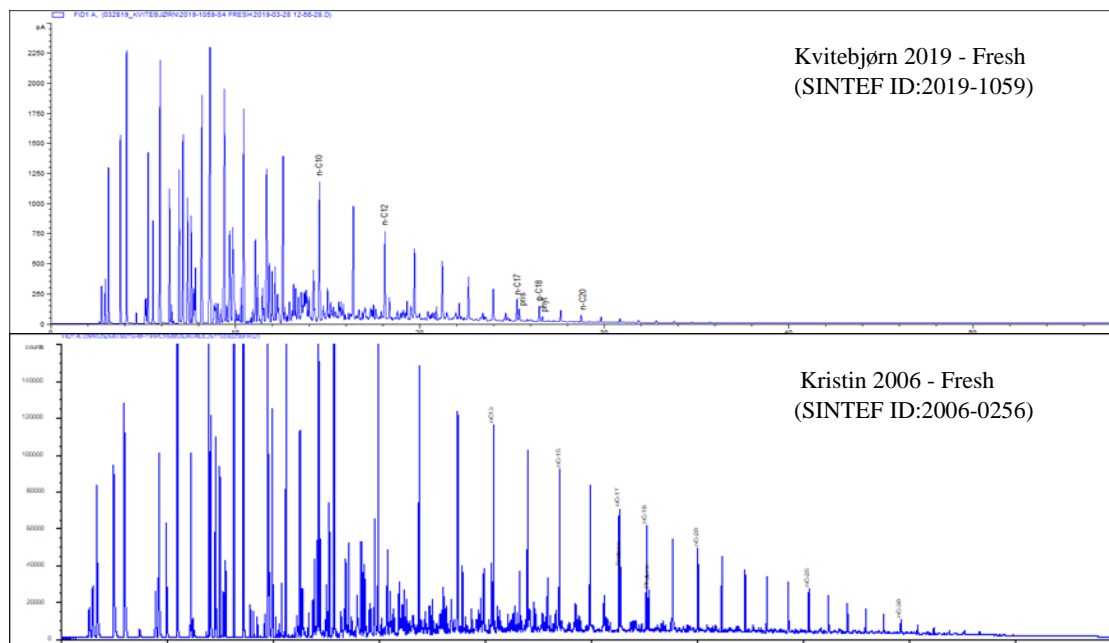
## 3.2  Chemical composition and physical properties

Figure 3-4 shows the fresh oil and the corresponding residues (150, 200 and 250°C+) of Visund Sør to visualize the change in the appearance /colour upon distillation. The fresh condensate is orange /yellow, whilst the residues have a much darker appearance. The 150, 200 and 250°C+ residues exhibit an orange/brownish colour, but are still translucent, compared to typical crude oils like Visund (not shown).



Figure 3-4    *Visund Sør from left to right: Fresh oil and residues (150, 200 and 250°C+)*

### *Asphaltenes and wax content of the fresh and weathered residues*

The contents of asphaltene and wax of Visund Sør and Visund in comparison with the other oils are given in Table 3-3. Visund Sør (fresh oil) has low contents of wax (0.05 wt.%) and asphaltenes (0.01 wt.%), and the condensate is comparable with Kvitebjørn 2019. Visund has similar low contents of asphaltenes (0.03 wt. %)

as the previous batch (Visund 2009), but the recent batch has a slightly reduced content of wax (1.4 vs. 2.0 wt.%, respectively). Visund 1998 and Kristin exhibit higher content of wax (6.4 and 6.8 wt. %, respective) compared with the other oils but have low asphaltenes like the other oils in comparison.

Table 3-3        Asphaltene ("hard") and wax content for different oils in comparison

| Oil type | Residue | Asph* (wt. %) | Wax (wt. %) |
|---|---|---|---|
| Visund Sør 2020 | Fresh | <0.01 | 0.05 |
| | 150°C+ | <0.01 | 0.14 |
| | 200°C+ | 0.01 | 0.31 |
| | 250°C+ | 0.01 | 0.92 |
| Visund 2020 | Fresh | 0.03 | 1.4 |
| | 150°C+ | 0.04 | 2.1 |
| | 200°C+ | 0.05 | 2.7 |
| | 250°C+ | 0.07 | 3.7 |
| Visund 2009 | Fresh | 0.02 | 2.0 |
| | 150°C+ | 0.03 | 2.8 |
| | 200°C+ | 0.04 | 3.8 |
| | 250°C+ | 0.05 | 5.3 |
| Visund 1998 | Fresh | 0.02 | 6.4 |
| | 150°C+ | 0.02 | 7.2 |
| | 200°C+ | 0.03 | 8.3 |
| | 250°C+ | 0.03 | 9.8 |
| Kvitebjørn 2019 | Fresh | <0.01 | 0.14 |
| | 150°C+ | 0.01 | 0.39 |
| | 200°C+ | 0.02 | 0.80 |
| | 250°C+ | 0.05 | 1.91 |
| Kristin 2006 | Fresh | 0.02 | 6.8 |
| | 150°C+ | 0.03 | 9.7 |
| | 200°C+ | 0.04 | 12.0 |
| | 250°C+ | 0.05 | 15.0 |

*n-heptane (nC$_7$) precipitation


### Physical properties for the fresh and weathered residues

The physical properties of Visund Sør and Visund in comparison with Visund 2009, Visund 1998, Kvitebjørn 2019, and Kristin are listed in Table 3-4.

The evaporative loss of Visund Sør  is high typically for light condensates and is comparable with Kvitebjørn 2019. The condensates express the highest evaporative loss among the oils in comparison.  Visund and Visund 2009 have similar degree of the evaporative loss, whilst Kristin has a slightly lower evaporation. Visund 1998 has, on the other hand, much lower evaporative loss compared with the other oils in comparison that reflects its higher density.

The density of Visund Sør (0.749 g/mL) is comparable with Kvitebjørn 2019 (0.752 g/mL), followed by Kristin (0.794 g/mL). Visund and Visund 2009 have comparable densities  (0.794 vs. 0.791 g/mL), whilst Visund 1998 exhibits the highest density of 0.834 g/mL among these oils.

The pour points of Visund Sør are very low and are in the range of <-36 to -9 °C. Low pour points are also measured on Kvitebjørn 2019, whilst Visund, Visund 2009, Visund 1998 and Kristin have higher pour points. High pour points also reflect higher wax of the crude oils compared with the condensates.

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The viscosities of Visund Sør are very low (1 to 7 mPa.s) measured at 13 °C ($10s^{-1}$) and are in the same range as Kvitebjørn 2019. The crude oils (Visund, Visund 2009, Visund 1998 and Kristin) show increasing viscosities of their residues by evaporation.

*Table 3-4        Physical properties of Visund Sør, Visund, Visund 2009, Visund 1998, Kvitebjørn 2019, and Kristin*

| Oil type | Residue | Evap. (vol. %) | Residue (wt. %) | Density (g/mL) | Flash point (°C) | Pour point (°C) | Visc. (mPa.s) 13°C (10 s⁻¹) |
|---|---|---|---|---|---|---|---|
| Visund Sør 2020 | Fresh | 0 | 100 | 0.742 | - | <-36 | 1 |
| | 150°C+ | 67 | 35 | 0.789 | 31 | <-36 | 1 |
| | 200°C+ | 86 | 16 | 0.813 | 68 | -30 | 3 |
| | 250°C+ | 95 | 5 | 0.839 | 83 | -9 | 7 |
| Visund 2020 | Fresh | 0 | 100 | 0.794 | - | -33 | 3 |
| | 150°C+ | 37 | 67 | 0.837 | 36 | 0 | 16 |
| | 200°C+ | 52 | 52 | 0.857 | 75 | 15 | 157 |
| | 250°C+ | 65 | 38 | 0.877 | 113 | 24 | 1508 |
| Visund 2009 | Fresh | 0 | 100 | 0.791 | -12 | -30 | 2 |
| | 150°C+ | 31 | 72 | 0.824 | 30 | -6 | 5 |
| | 200°C+ | 51 | 53 | 0.844 | 73 | 6 | 22 |
| | 250°C+ | 65 | 39 | 0.861 | 112 | 15 | 280 |
| Visund 1998 | Fresh | 0 | 100 | 0.834 | - | 6 | 15* |
| | 150°C+ | 12 | 89 | 0.851 | 32 | 15 | 55* |
| | 200°C+ | 26 | 77 | 0.866 | 75 | 21 | 241* |
| | 250°C+ | 37 | 65 | 0.879 | 113 | 27 | 621* |
| Kvitebjørn 2019 | Fresh | 0 | 100 | 0.752 | - | <-36 | 1 |
| | 150°C+ | 65 | 37 | 0.797 | 33 | -24 | 2 |
| | 200°C+ | 84 | 18 | 0.816 | 72 | -6 | 4 |
| | 250°C+ | 93 | 7.5 | 0.835 | 102 | 9 | 26 |
| Kristin 2006 | Fresh | 0 | 100 | 0.794 | - | -39 | 2 |
| | 150°C+ | 33 | 70 | 0.831 | 36 | 0 | 26 |
| | 200°C+ | 47 | 57 | 0.846 | 72 | 12 | 539 |
| | 250°C+ | 58 | 45 | 0.860 | 114 | 27 | 7730 |

*Measured at shear rate 100s⁻¹: No data*

The True Boiling Point curves (TBP) of Visund Sør, Visund, Visund 2009, Visund 1998, Kvitebjørn 2019, and Kristin are shown in Figure 3-5. The TBPs clearly show similarities of the condensates of Visund Sør and Kvitebjørn 2019, and similarities between the crude oils of Visund and Visund 2009, followed by Kristin. Visund 1998 has the lowest TBP among these oils for comparison.
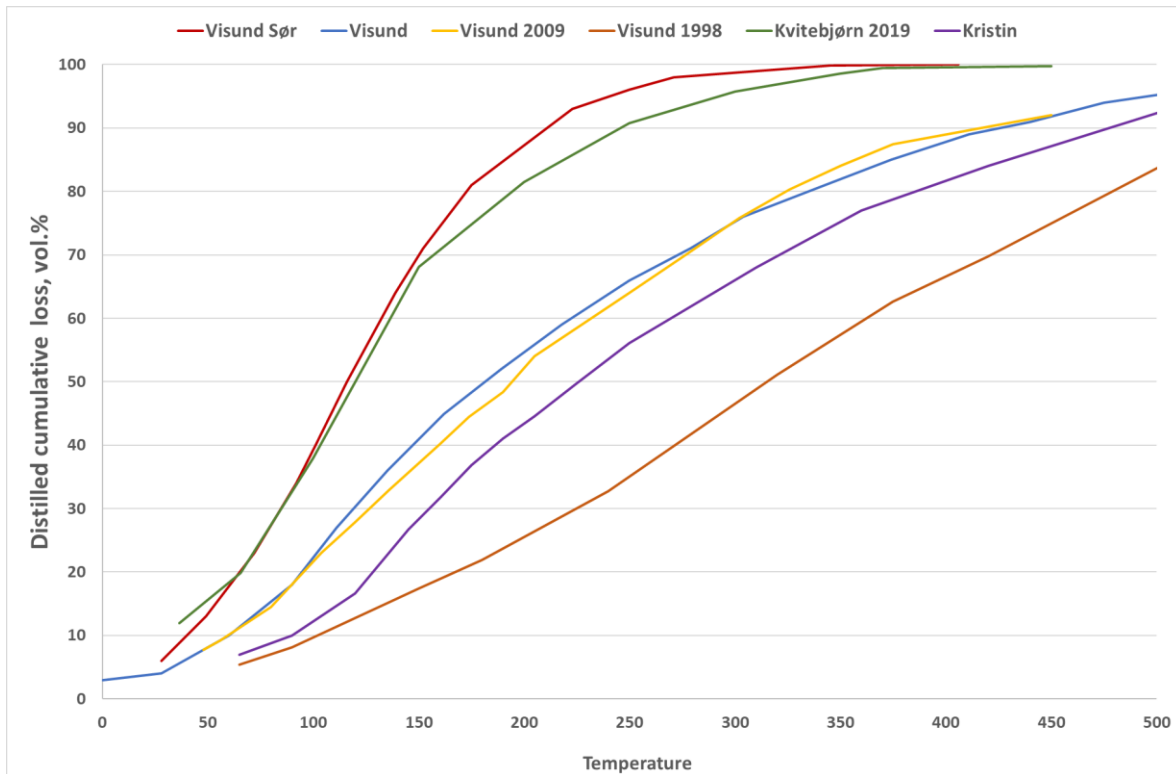
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*Figure 3-5*       *TBP of Visund Sør and Visund in comparison with other oils*

## 3.3  Viscosity of fresh oil and water-free residues

The viscosity describes the oils ability to resist gradual deformation by increasing shear, where viscosities of so-called *Newtonian* oils remains constant independent on the applied shear rate (s$^{-1}$) at a given temperature. The opposite when shear is applied on so-called *non-Newtonian* oils the viscosity of such oils decreases.

The dynamic viscosities (mPa.s) of Visund Sør and Visund fresh oils and their corresponding water-free residues are given in Table 3-5. The viscosities are given with increasing shear rates (10, 100 and 1000 s$^{-1}$) at 13 °C. Visund Sør (fresh oil and residues) exhibits *Newtonian* behaviour with very low viscosities. The fresh oil of Visund is *Newtonian*, but its  residues behave more like *non-Newtonian* oils due to the formation of wax structure upon evaporation.

*Table 3-5*       *Viscosities of fresh oil and residues of Visund Sør and Visund with increasing shear rates*

| Oil type | Residue | Visc. (mPa.s) 13°C (10 s$^{-1}$) | Visc. (mPa.s) 13°C (100 s$^{-1}$) | Visc. (mPa.s) 13°C (1000 s$^{-1}$) |
|---|---|---|---|---|
| Visund Sør | Fresh | 1 | 1 | 2 |
|  | 150°C+ | 1 | 1 | 3 |
|  | 200°C+ | 3 | 3 | 4 |
|  | 250°C+ | 7 | 7 | 7 |
| Visund | Fresh | 3 | 2 | 3 |
|  | 150°C+ | 16 | 13 | 11 |
|  | 200°C+ | 157 | 64 | 35 |
|  | 250°C+ | 1508 | 412 | 133 |

## 3.4 Emulsifying properties

In general, emulsification is the mixing of seawater droplets into spilled oil at the water's surface (water-in-oil emulsion), forming a weathered oil residue that often tends to be relatively resistant to other weathering processes such as evaporation, and increases the total volume of oil due to the uptake of water into the oil. The procedure for maximum water uptake is described in Hokstad et al., 1993 (Appendix B).

### 3.4.1 Visund Sør

Formation of emulsion is not likely for Visund Sør based upon the fact that the oil is a light condensate with negligible content of stabilizing components like the asphaltenes and very low content of wax. A simple emulsification test on the 250°C+ residue was conducted to very this assumption. No real emulsion was observed and expressed a low water uptake (28-29 vol. %), see Figure 3-6. Further testing of emulsifying properties was therefore not performed on Visund Sør.
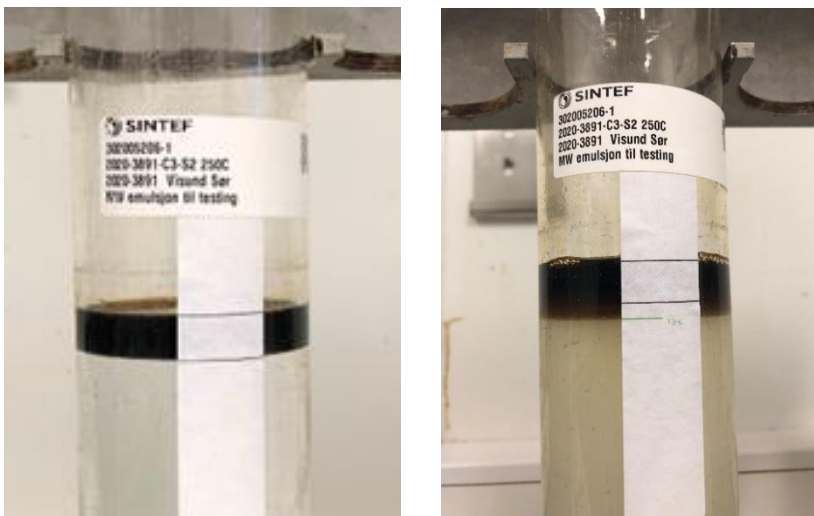


*Figure 3-6      Test of water uptake of Visund Sør 250°C+. Left: Water-free residue. Right: After rotation (no real emulsion)*

### 3.4.2 Visund

Emulsification properties of Visund were conducted on residues of 150°C+, 200°C+ and 250°C+ to produce data for stability, viscosity, maximum water uptake, kinetics, and the effectiveness of the emulsion breaker application. Emulsions of maximum water content after 24 hours rotation are shown in Figure 3-7, below. The figure shows from left to right four emulsions prepared from the residues of 150°C+, 200°C+ and 250°C+, respectively.



*Figure 3-7      Rotating cylinders of water-in-oil (w/o) emulsions of Visund crude oil after 24 hours at 13 °C*

### Water uptake and maximum water content

The rate of water uptake (kinetic) was also studied by use of the rotating cylinder method. The water content in the water-in-oil (w/o) emulsions as a function of time is tabulated in Table 3-6. The $t_{1/2}$ values are defined as the time (hours) it takes to incorporate <u>half</u> of the maximum water uptake (vol. %) in 24 hours (rotating time). Visund expressed high-water uptake for all the residues 150°C+, 200°C+ and 250°C+, which ranged from 72 to 91 vol. % (Table 3-5). Supersaturation of the maximum water uptake for the 200°C+ emulsion was observed. This means that all the water was totally emulsified into the oil. However, a maximum water of 91 vol. % is not likely on the sea surface.

Table 3-6        *Water uptake for the evaporated residues of Visund at 13 °C*

| Mixing time | 150°C+ * (vol. % water) | 200°C+ * (vol. % water) | 250°C+ * (vol. % water) |
|---|---|---|---|
| **Start** | 0 | 0 | 0 |
| **5 min** | 14 | 27 | 6 |
| **10 min** | 16 | 38 | 23 |
| **15 min** | 22 | 44 | 52 |
| **30 min** | 24 | 52 | 81 |
| **1 hour** | 27 | 63 | 83 |
| **2 hours** | 31 | 73 | 83 |
| **4 hours** | 39 | 91** | 84 |
| **6 hours** | 43 | 91** | 84 |
| **24 hours** | 72 | 91** | 85 |
| **t ½** | **2.80** | **0.35** | **0.22** |

*\* Depending on weather situation and release rate, the residues are corresponding to approximately 0.5-1-hour, 0.5-1 day and 0.5-1 week of weathering on the sea surface*
*\*\*Supersaturation, not likely to happen in a spill situation*

### Efficiency of emulsion breaker and stability of emulsion

In mechanical recovery operations, separating oil from water enables optimal use of available storage (i.e. facilities/tankers), and the efficiency of this separation can be enhanced by applying emulsion breakers. The effectiveness of the emulsion breaker Alcopol O 60% was evaluated on different residues of emulsified Visund.

The results show that the emulsified oil volume decreased after treatment with the emulsion breaker in all residues, as water was released from the emulsion (Table 3-6). The emulsions were  almost totally broken when adding the emulsion breaker (Alcopol O 60%). Adding 2000 ppm of the emulsion breaker, relative to the oil was shown to be slightly more efficient to break the emulsion compared with  a  lower concentration of 500 ppm.

The emulsion stability was studied by quantifying the amount of water released from the emulsion after 24 hours settling time. Visund formed stable w/o-emulsions of the 150, 200 and 250°C+ residues, as shown in the first main row of Table 3-7.

Table 3-7  *Stability of emulsion and the effectiveness of emulsion breaker at 13 °C of Visund*

| Residue | Emulsion breaker | Water-in-oil emulsion (vol. %) at 13 °C | | Stability ratio** |
|---------|------------------|-----------|------------|--------|
| | | Reference | 24 hours * | |
| 150ºC+ | None | 72 | 74 | 1.00 |
| 200ºC+ | None | 91 | 91 | 0.97 |
| 250ºC+ | None | 85 | 84 | 0.94 |
| 150ºC+ | Alc. O 60 % 500 ppm | 72 | 9 | 0.04 |
| 200ºC+ | Alc. O 60 % 500 ppm | 91 | 33 | 0.05 |
| 250ºC+ | Alc. O 60 % 500 ppm | 85 | 32 | 0.08 |
| 150ºC+ | Alc. O 60 % 2000 ppm | 72 | 0 | 0.00 |
| 200ºC+ | Alc. O 60 % 2000 ppm | 91 | 3 | 0.01 |
| 250ºC+ | Alc. O 60 % 2000 ppm | 85 | 12 | 0.02 |

ppm: parts per million
*: w/o-emulsion after 24 hours rotation and 24 hours settling
** Stability ratio of 0 implies a totally unstable emulsion after 24 hours settling; all the water is settled out for 24 hours settling. Stability ratio of 1 implies a totally stable emulsion


### Viscosities of water-free and emulsified residues

The viscosity describes the oils ability to resist gradual deformation by increasing shear, where viscosities of so-called *Newtonian* oils remains constant independent on the applied shear rate ($s^{-1}$) at a given temperature. When shear is applied on so-called *non-Newtonian* oils, the viscosity of such oils decreases with increasing shear rates. The viscosities of the water-free residues and emulsified residues of Visund are given in Table 3-8. The water-free residues and emulsions behave as *non-Newtonian* fluids due to the increasing degree of weathering (evaporation and water uptake), with higher viscosities at a lower shear rate ($10\ s^{-1}$) compared to the viscosities measured at higher shear rates ($100$ and $1000\ s^{-1}$).


Table 3-8  *Viscosities of fresh oil, residues and emulsions of Visund at 13 °C*

| Residue | Water content (vol. %) | Viscosity (mPa.s), Visund 13 °C | | |
|---------|------------------------|----------|-----------|------------|
| | | $10\ s^{-1}$ | $100\ s^{-1}$ | $1000\ s^{-1}$ |
| Fresh | 0 | 3 | 2 | 3 |
| 150°C+ | 0 | 16 | 13 | 11 |
| 200°C+ | 0 | 157 | 64 | 35 |
| 250°C+ | 0 | 1508 | 412 | 133 |
| 150°C+ | 50 | 168 | 86 | n.a |
| 200°C+ | 50 | 792 | 284 | n.a |
| 250°C+ | 50 | 1981 | 731 | n.a |
| 150°C+ | 75 | 481 | 146 | n.a |
| 200°C+ | 75 | 2131 | 641 | n.a |
| 250°C+ | 75 | 4686 | 1344 | n.a |
| 150°C+ | 75 | 638 | 213 | n.a |
| 200°C+ | 91 | 1676 | 323 | n.a |
| 250°C+ | 84 | 4772 | 855 | n.a |

n.a: not applicable

## 3.5 Chemical dispersibility

### 3.5.1 Visund Sør

No standardized dispersibility testing was conducted on Visund Sør due to negligible emulsification. However, a simple dispersibility test was performed on the "emulsified" 250°C+ residue (see section 3.4.1) using the MNS test reflecting typically breaking waves conditions (> 5 m/s wind speed) (Mackay and Szeto, 1980). As shown in Figure 3-8 (Left), the "emulsion" was easily dispersed into the water column without adding dispersants. However, lager droplets will arise to the surface in calm sea states. The dispersant, Dasic NS, was also added to the oil and produced even smaller oil droplets (< 70-100 μm) that remained in the water phase, see Figure 3-8 (Right).
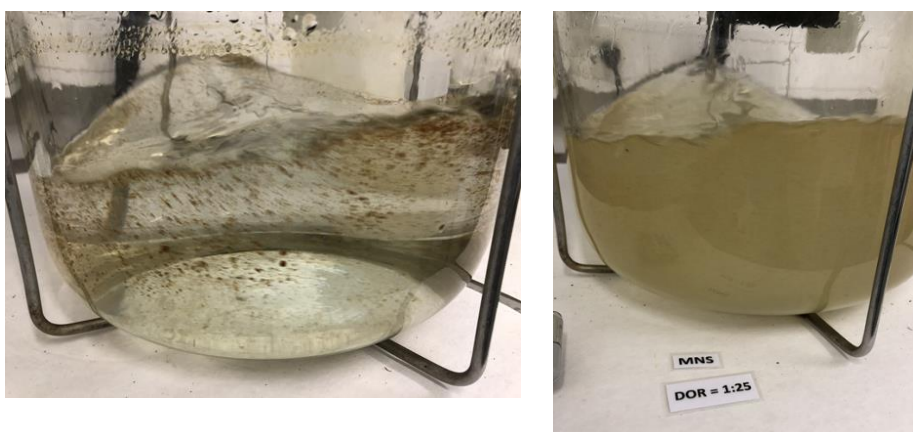


Figure 3-8    Left: Naturally dispersion of 250°C+ residue of Visund Sør.
Right: Dispersion after adding Dasic NS (dispersant to oil ratio (DOR) of 1:25)

### 3.5.2 Visund

Screening and dosage testing were not performed on Visund as in agreement with Equinor. Dasic NS was chosen to estimate the time-window for dispersant use at varying weathering degrees. A dispersant-to-oil ratio (DOR) of 1:25 (4 wt.%) is commonly used as the standard procedure to establish the time-window for dispersant application. Dasic NS is also the dispersant agent in NOFO's stockpile

Table 3-9 shows the results from the systematic dispersant testing as basis to establish the dispersibility limits (viscosities) expressed as a function of effectiveness. The dispersibility limits are further used as input to the SINTEF Oil Weathering Model (OWM) to predict the time-window for dispersant use.

Table 3-9    Effectiveness of Dasic NS on Visund  residues and emulsions at 13 °C

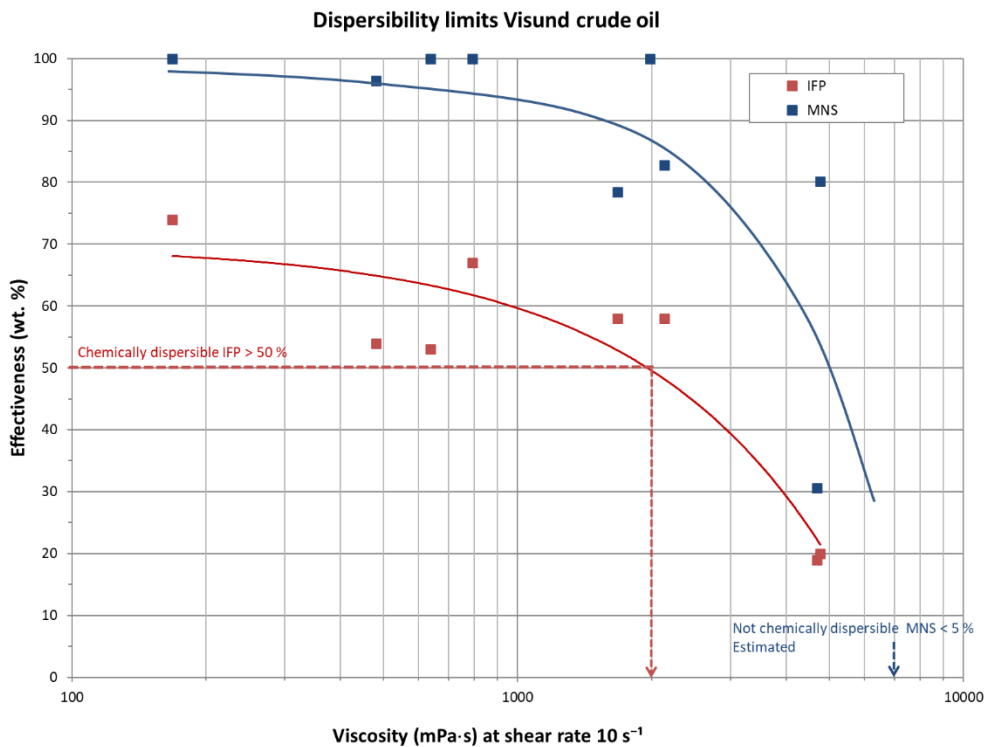| Residue | Water content (vol. %) | Viscosity (mPa.s) 10 s$^{-1}$ | Effectiveness (%) IFP | Effectiveness (%) MNS |
|---------|-----------------------|------------------------------|-----------------------|-----------------------|
| 150°C+ | 50 | 168 | 74 | 100 |
| 200°C+ | 50 | 792 | 67 | 100 |
| 250°C+ | 50 | 1981 | 20 | 100 |
| 150°C+ | 75 | 481 | 54 | 96 |
| 200°C+ | 75 | 2131 | 58 | 83 |
| 250°C+ | 75 | 4686 | 19 | 31 |
| 150°C+ | 75 | 638 | 53 | 100 |
| 200°C+ | 91 | 1676 | 58 | 78 |
| 250°C+ | 84 | 4772 | 20 | 80 |

*Figure 3-9        Dispersant effectiveness limits on Visund at 13 °C*

Visund was found to be dispersible for viscosities lower than 2000 mPa.s, reflecting > 50 % effectiveness by use of the IFP-test. The upper limit for then Visund is not chemically dispersible was not reach in the laboratory testing by using the MNS-test (reflecting < 5-10 % effectiveness) but was estimated to 7000 mPa.s. Reduced dispersibility is expected with viscosities between 2000 and 7000 mPa.s, and means that the oil is still dispersible but may require additional energy and/or higher dispersant dosage to enhance effective dispersion. The dispersibility limits are also summarised in Table 3-10.

*Table 3-10        Estimated viscosity limits for Visund for use of dispersant and definition of time window*

| Dispersibility | Criteria for effectiveness (wt. %) | Dispersibility limits based on emulsion viscosity (mPa.s) |
|---|---|---|
| Chemically dispersible | IFP > 50 % | 2000 |
| Not chemically dispersible | MNS < 5 % | 7000 |

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## 4 Predictions with SINTEF Oil Weathering Model (OWM)

### 4.1 Description of SINTEF OWM

A systematic stepwise laboratory procedure developed at SINTEF (Daling et al., 1990) was used to isolate and map the various weathering processes that take place when oil is spilled on the sea surface. Laboratory study of Visund Sør and Visund was conducted at 13 °C, and the analytical data were further used as input to the SINTEF Oil Weathering Model (OWM) (version 12.0.0). The experimental design for the study is described in Appendix B. The input data of Visund Sør and Visund to the SINTEF OWM are given in Appendix C.

The SINTEF OWM relates oil properties to a chosen set of conditions (oil/emulsion film thickness, wind speeds and sea temperature) and predicts the change rate of the oil's properties on the sea surface with time. The SINTEF OWM is schematically shown in Figure 4-1. The predictions obtained from the SINTEF OWM are useful tools in the oil spill contingency planning related to the expected behaviour of oil on the sea surface, and to evaluate the time window for operational response strategies in a spill operation. In this report, the presented predictions span a period from 15 minutes to 5 days after an oil spill has occurred. The SINTEF OWM is described in more detail in Johansen (1991), and in the user's guide for the model.
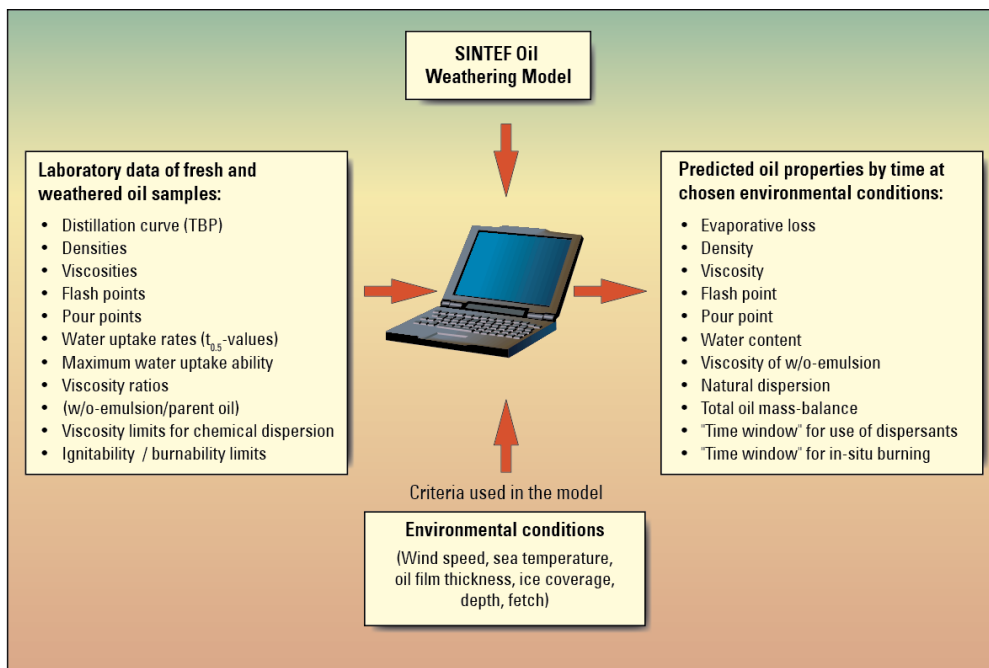


*Figure 4-1        Schematic input data to the SINTEF OWM and the predicted output oil properties*

#### Spill scenario

A standard surface release was used as a spill scenario (see section 4.2). The scenario chosen is not oil field specific but selected to give predictions of the expected weathering properties of the oil based on the experimental data and specified terminal oil film thickness. A standardized scenario will also more easily compare results of weathering properties with other oils.

#### Oil film thickness

Oils are categorized as condensate, emulsifying crude, low emulsifying crude, heavy bunker fuel or refined distillate. The categorization is also based on the experimental results obtained in the laboratory. The terminal film thicknesses vary among these categories based on experimental (field) experience. Visund Sør is categorized as a condensate with a terminal oil film thicknesses of 0.05 mm, whilst Visund is categorized as a crude oil with a terminal oil film thickness of 1 mm.

*Seawater temperature*

The prevailing weather conditions greatly influence the weathering rate of oil on the sea surface. Due to the location of the oil field, the prediction seawater temperatures chosen for Visund Sør and Visund was 5 and 15 °C, reflecting typically winter and summer conditions.

*Wind speed*

The relationship between the wind speed and significant wave heights used in the prediction charts obtained from the SINTEF OWM are shown in Table 4-1.

*Table 4-1        Relationship between wind speed and significant wave height used in the SINTEF OWM*

| Wind speed [m/s] | Beaufort wind | Wind type | Wave height [m] |
|---|---|---|---|
| 2 | 2 | Light breeze | 0.1 - 0.3 |
| 5 | 3 | Gentle to moderate breeze | 0.5 - 0.8 |
| 10 | 5 | Fresh breeze | 1.5 - 2.5 |
| 15 | 6 – 7 | Strong breeze | 3 - 4 |

## 4.2  Predictions of Visund Sør and Visund

*Input to the OWM*

| | |
|---|---|
| Oil types: | Condensate and crude oil |
| Geographical area: | North Sea |
| Terminal oil film thickness: | 0.05 (condensate) and 1 mm (crude oil) |
| Release rate: | 1.33 metric tonnes /15 min, a total of 20 metric tonnes (80 m$^3$/hour) |
| Seawater temperature: | 5 and 15 °C |
| Wind speed: | 2 m/s, 5 m/s, 10 m/s and 15 m/s |

*Predicted properties*

- Evaporative loss
- Viscosity
- Flash point
- Pour point
- Mass balance

The predictions are based on 5 days weathering independently if there is not predicted any remining oil within shorter time. The predictions are shown to indicate the weathering properties in cases there are patches or oil left on the surface up to 5 days.

*How to use the prediction charts: an example*

If the oil has drifted on the sea surface, the following prediction charts could be used to determine the weathering properties of the oil/emulsion. Table 4-2 and Table 4-3 give examples of  predicted weathering properties for Visund Sør and Visund.

*Table 4-2      Example of weathering properties for Visund Sør obtained from the OWM predictions after 2 hours of weathering at 2, 5 and 10 m/s wind speed*

| Weathering property | 2 hours 15 ˚C 2 m/s | 2 hours 15 ˚C 5 m/s | 2 hours 15 ˚C 10 m/s |
|---|---|---|---|
| Evaporation, wt. % | 75 | 89 | 97 |
| Flash point, ℃ | 48 | 75 | 89 |
| Pour Point, ℃ | -25 | -22 | -21 |
| Viscosity, mPa.s * | 3 | 6 | 10 |
| Mass balance / Oil on surface wt.% | 25 | 7 | 0 |

*\*mPa.s = cP (mPa.s: SI-standard / cP: Industrial denotation)*

*Table 4-3      Example of weathering properties for Visund  obtained from the OWM predictions after 2 hours of weathering at 2, 5 and 10 m/s wind speed*

| Weathering property | 2 hours 15 ˚C 2 m/s | 2 hours 15 ˚C 5 m/s | 2 hours 15 ˚C 10 m/s |
|---|---|---|---|
| Evaporation, wt. % | 36 | 43 | 51 |
| Flash point, ℃ | 44 | 62 | 81 |
| Pour Point, ℃ | 1 | 8 | 15 |
| Viscosity, mPa.s * | 40 | 85 | 230 |
| Mass balance / Oil on surface wt.% | 64 | 56 | 39 |

*\*mPa.s = cP (mPa.s: SI-standard / cP: Industrial denotation)*

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## 4.2.1 Visund Sør



Figure 4-2    *Evaporative loss of Visund Sør predicted at sea temperatures of 5 and 15 °C*

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Property: **VISCOSITY OF EMULSION**
Oil Type: **VISUND SØR 2020**
Description:
Data Source: **Sintef Ocean (2020), Weathering data used**

SINTEF

OWModel© 12.0

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

2.0
Pred. date: Aug. 21, 2020

——— Wind Speed (m/s): 15
— — — Wind Speed (m/s): 10
- - - - Wind Speed (m/s): 5
· · · · · · Wind Speed (m/s): 2
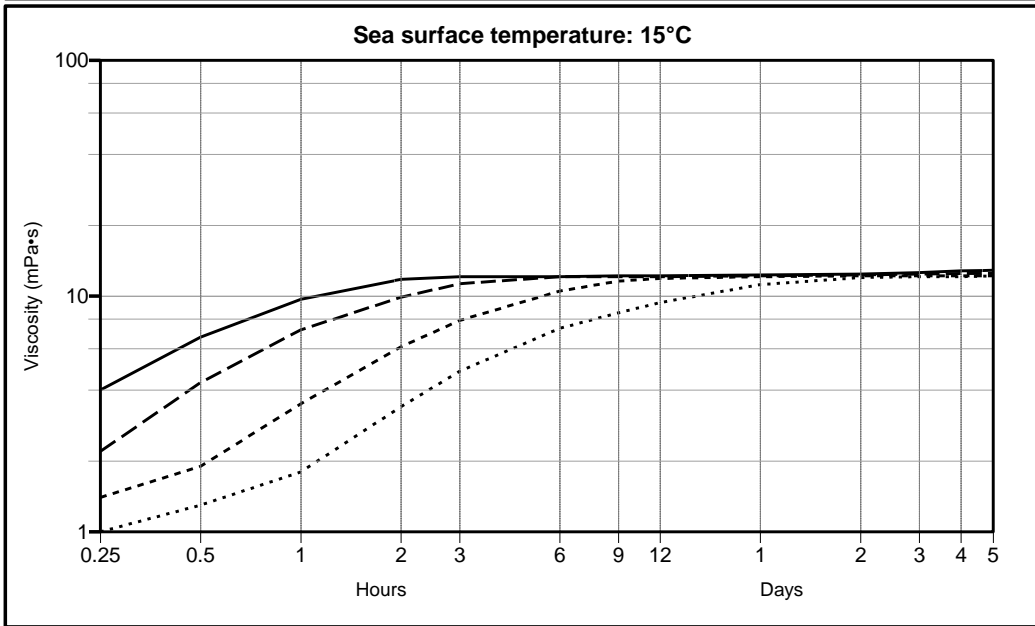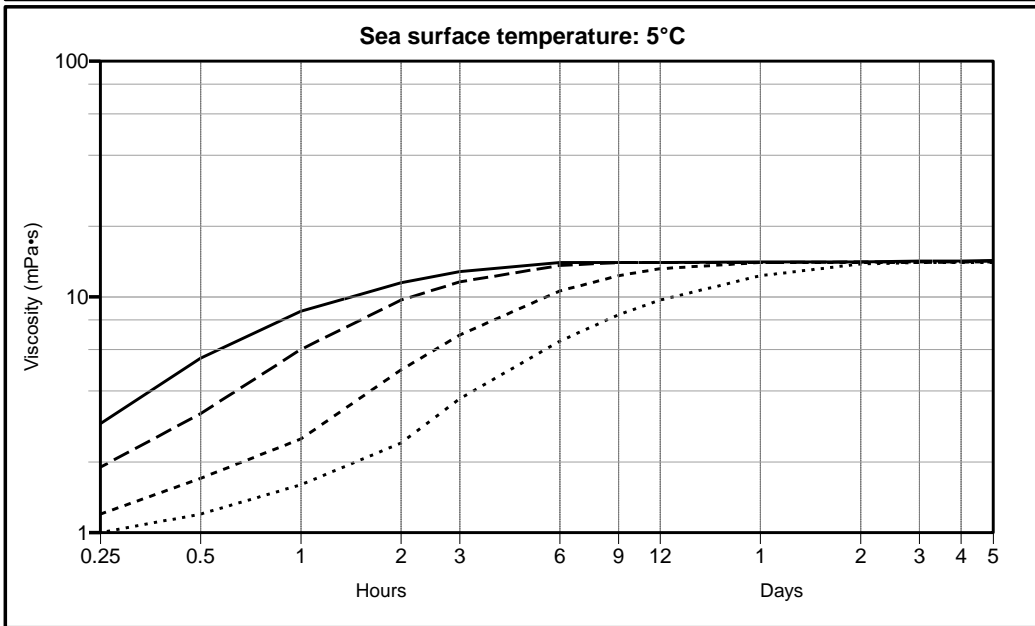
*Figure 4-3     Viscosity of Visund Sør predicted at sea temperatures of 5 and 15 °C,  shear rate 10 $s^{-1}$*

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| Property: WATER CONTENT | ⊙ SINTEF |
|---|---|
| Oil Type: VISUND SØR 2020 | |
| Description: | |
| Data Source: Sintef Ocean (2020), Weathering data used | OWModel© 12.0 |

| Surface release | 2.0 |
|---|---|
| Release rate/duration: 1.33 metric tons/minute for 15 minute(s) | Pred. date: Aug. 21, 2020 |

—— Wind Speed (m/s): 15
– – – Wind Speed (m/s): 10
- - - - Wind Speed (m/s): 5
· · · · · Wind Speed (m/s): 2
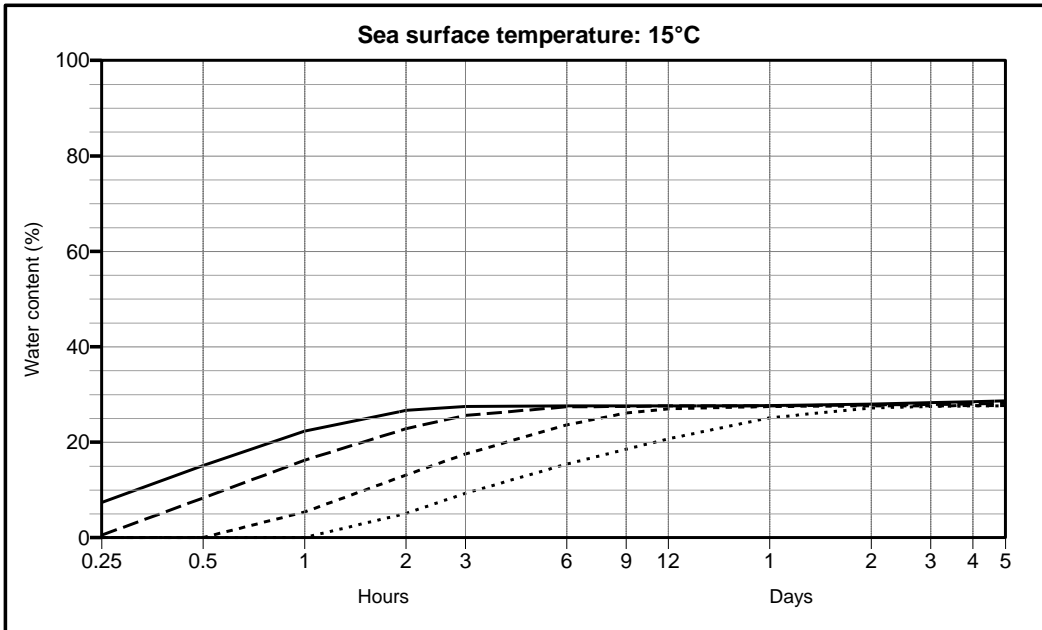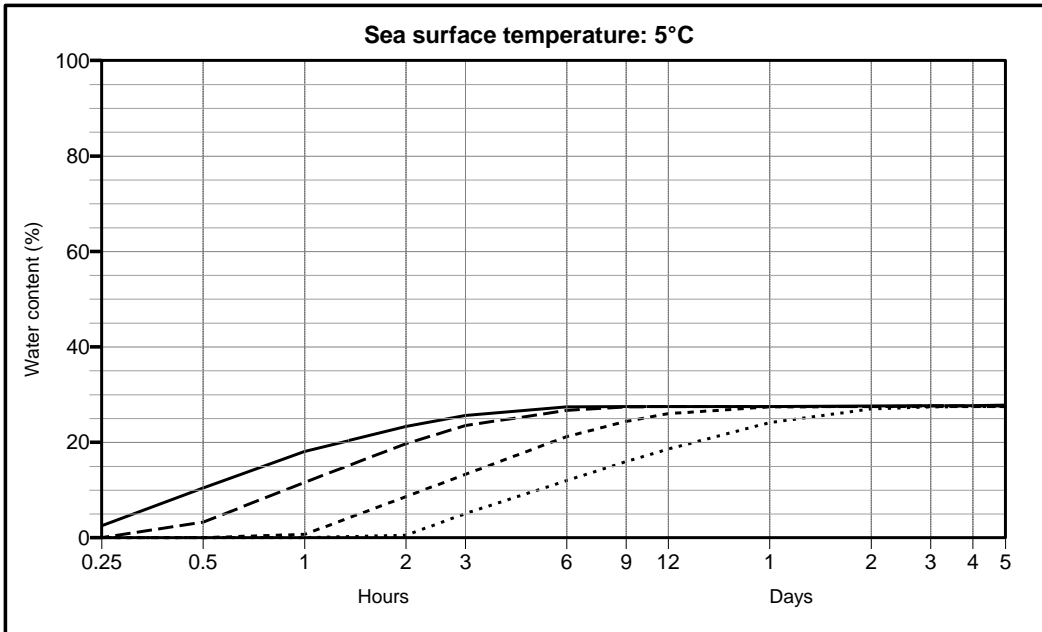


Figure 4-4    Water uptake Visund Sør predicted at sea temperatures of 5 and 15 °C,  shear rate 10 s$^{-1}$

**Property: FLASH POINT FOR WATER-FREE OIL**
**Oil Type: VISUND SØR 2020**
**Description:**
**Data Source: Sintef Ocean (2020), Weathering data used**

SINTEF

OWModel© 12.0

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

2.0
Pred. date: Aug. 21, 2020

Wind Speed (m/s): 15 — No fire hazard
Wind Speed (m/s): 10 — Fire hazard in tankage (<60 °C)
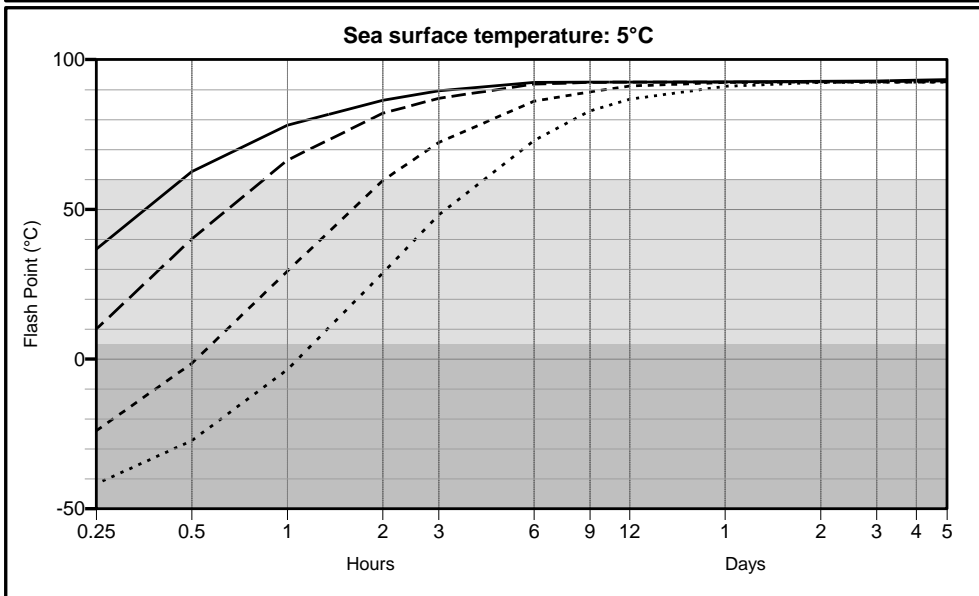Wind Speed (m/s): 5 — Fire hazard at sea surface (below sea temperature)
Wind Speed (m/s): 2

*Figure 4-5*      *Flash point of Visund Sør predicted at sea temperatures of 5 and 15 °C*

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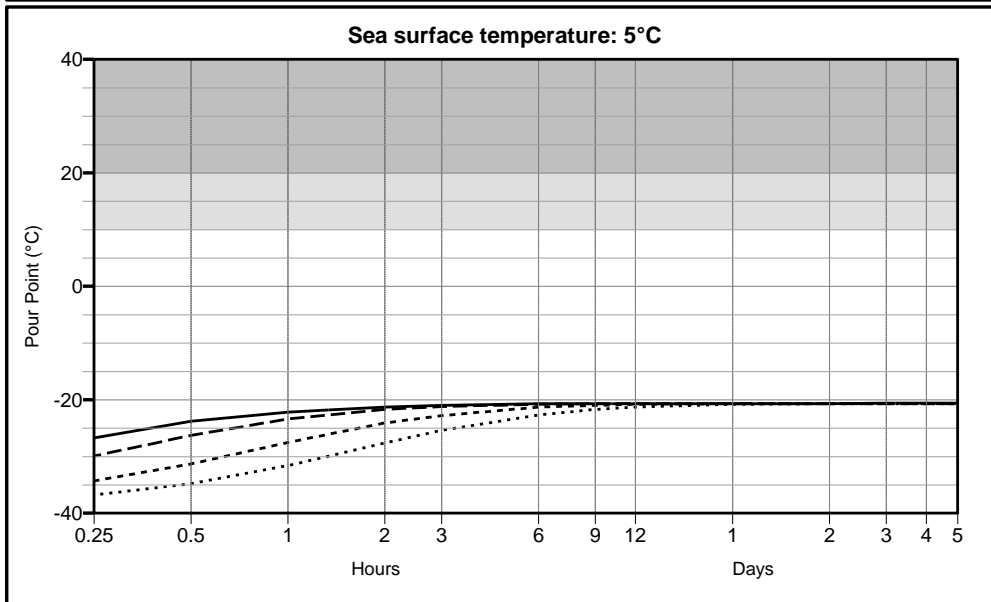REPORT NO.
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*Figure 4-6      Pour point of Visund Sør  predicted at sea temperatures of 5 and 15 °C*

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**Property: MASS BALANCE**
**Oil Type: VISUND SØR 2020**
**Description:**
**Data Source: Sintef Ocean (2020), Weathering data used**

**SINTEF**

OWModel® 12.0

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

Pred. date: Aug. 21, 2020

/// Evaporated
XXXX Surface
\\\ Naturally dispersed



*Figure 4-7        Predicted mass balance of Visund Sør predicted 5 °C, wind speeds of 2 and 5 m/s*

**Property: MASS BALANCE**
**Oil Type: VISUND SØR 2020**
**Description:**
**Data Source: Sintef Ocean (2020), Weathering data used**

SINTEF

OWModel® 12.0

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

Pred. date: Aug. 21, 2020
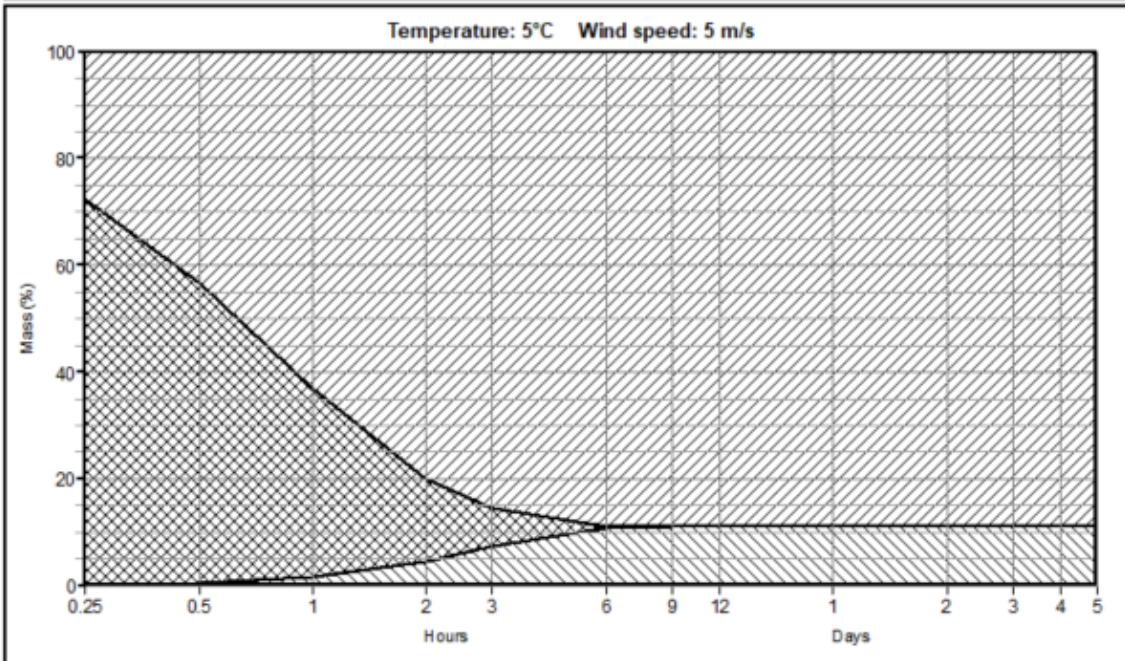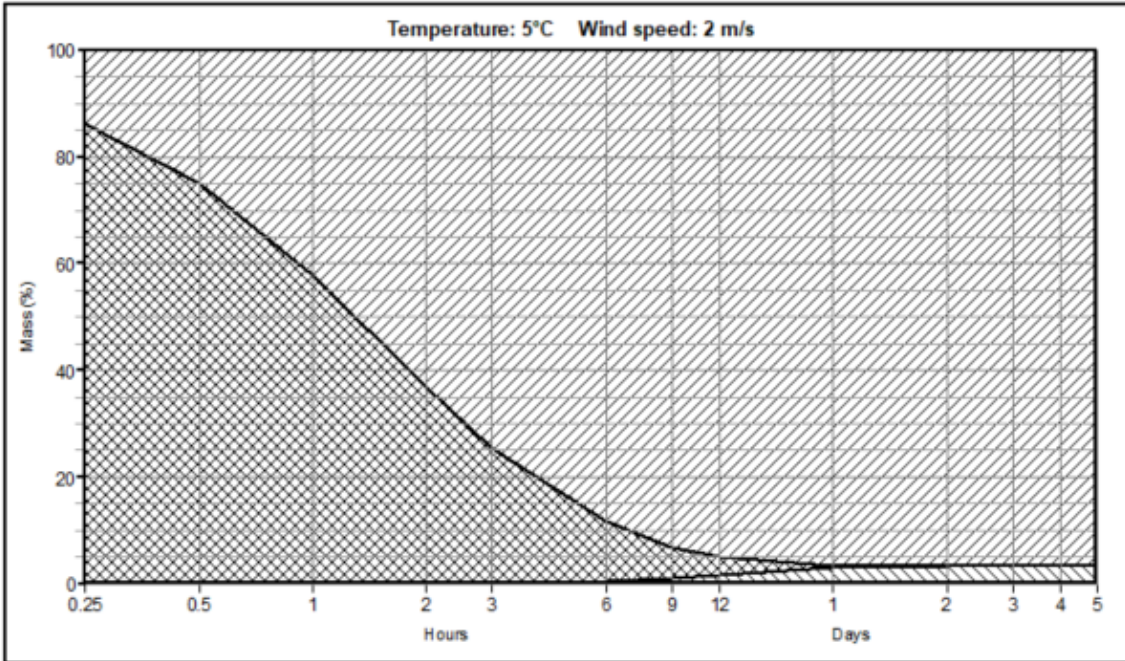
///. Evaporated
XXXX Surface
\\\\ Naturally dispersed



*Figure 4-8      Predicted mass balance of Visund Sør predicted 5 °C, wind speeds of 10 and 15 m/s*

**Property: MASS BALANCE**
**Oil Type: VISUND SØR 2020**
**Description:**
**Data Source: Sintef Ocean (2020), Weathering data used**

OWModel® 12.0

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

Pred. date: Aug. 21, 2020

////, Evaporated
XXX Surface
\\\\ Naturally dispersed



*Figure 4-9        Predicted mass balance of Visund Sør predicted 15 °C, wind speeds of 2 and 5 m/s*
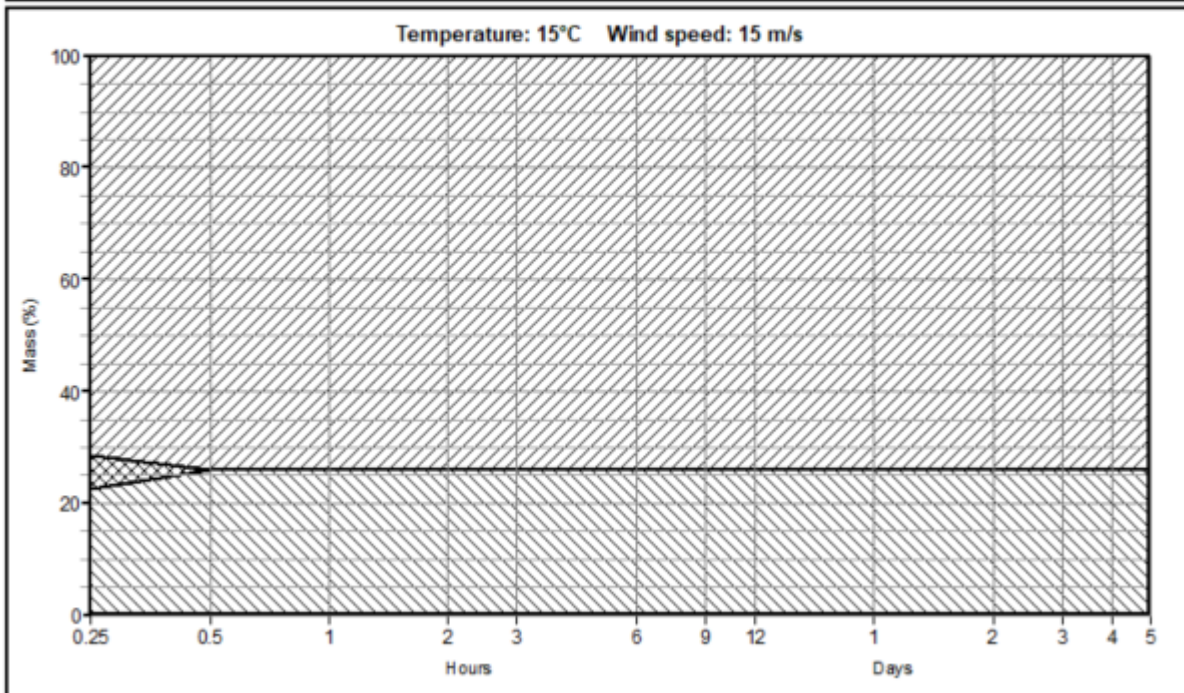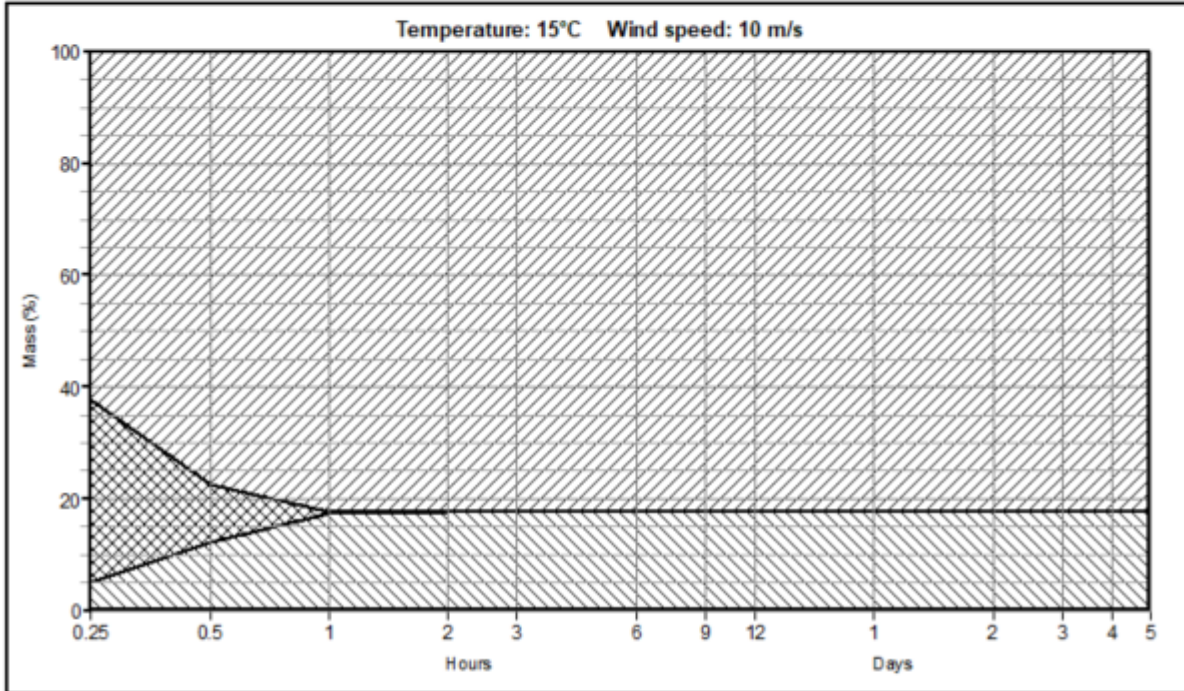
Figure 4-10       *Predicted mass balance of Visund Sør predicted 15 °C, wind speeds of 10 and 15 m/s*

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## 4.2.2 Visund



| Property: EVAPORATIVE LOSS | | ⊙ SINTEF |
|---|---|---|
| Oil Type: VISUND 2020 | | |
| Description: | | |
| Data Source: Sintef Ocean (2020), Weathering data used | | OWModel© 12.0 |
| Surface release | | 2.0 |
| Release rate/duration: 1.33 metric tons/minute for 15 minute(s) | | Pred. date: Aug. 21, 2020 |

Wind Speed (m/s): 15
Wind Speed (m/s): 10
Wind Speed (m/s): 5
Wind Speed (m/s): 2

**Sea surface temperature: 5°C**

**Sea surface temperature: 15°C**
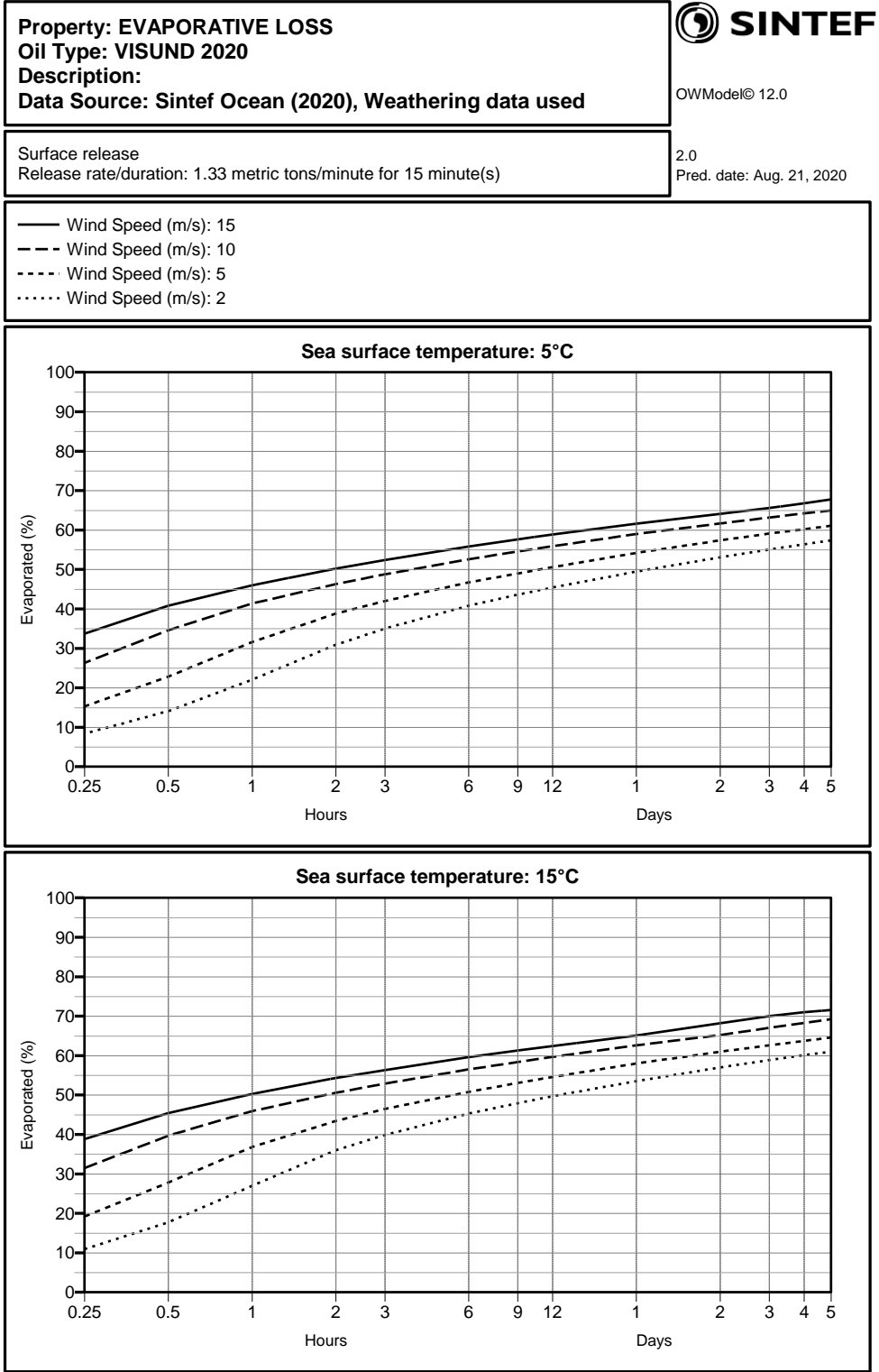
*Figure 4-11        Evaporative loss of Visund predicted at sea temperatures of 5 and 15 °C*

**Property: VISCOSITY OF EMULSION**
**Oil Type: VISUND 2020**
**Description:**
**Data Source: Sintef Ocean (2020), Weathering data used**

⊙ **SINTEF**

OWModel© 12.0

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

2.0
Pred. date: Aug. 21, 2020

—— Wind Speed (m/s): 15
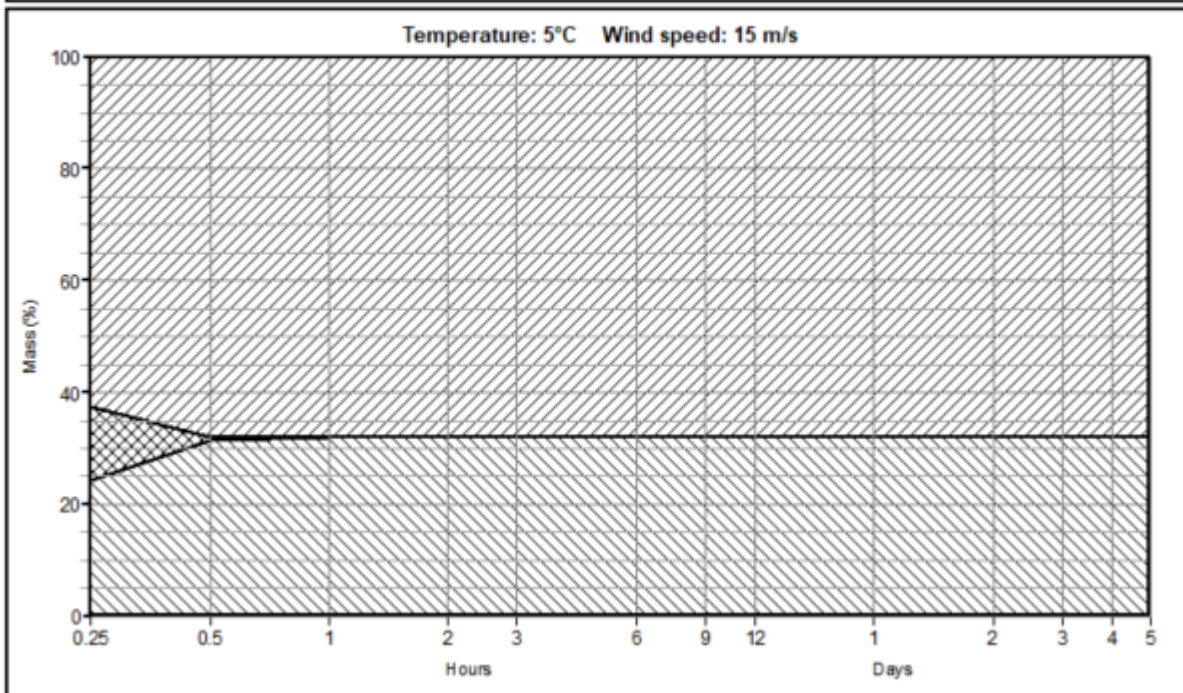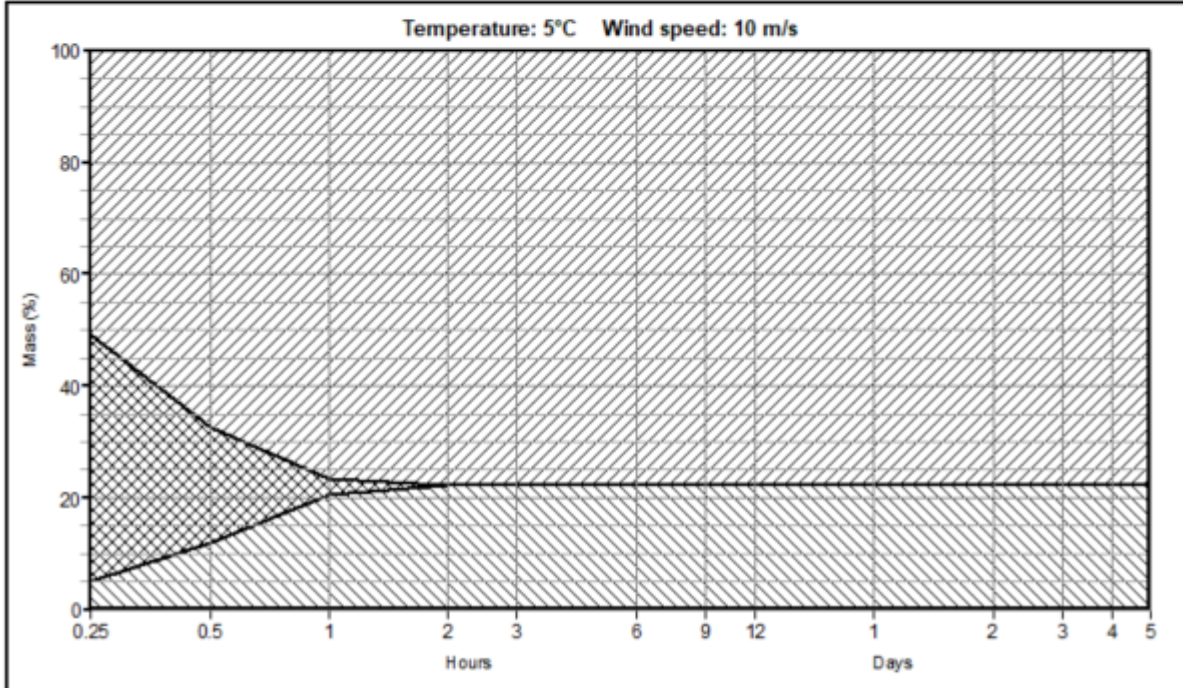– – Wind Speed (m/s): 10
- - - Wind Speed (m/s): 5
······ Wind Speed (m/s): 2

☐ Chemically dispersible (<2,000 mPa•s)
▨ Reduced chemical dispersibility
▨ Poorly / slowly chemically dispersible (>7,000 mPa•s)

**Sea surface temperature: 5°C**

**Sea surface temperature: 15°C**
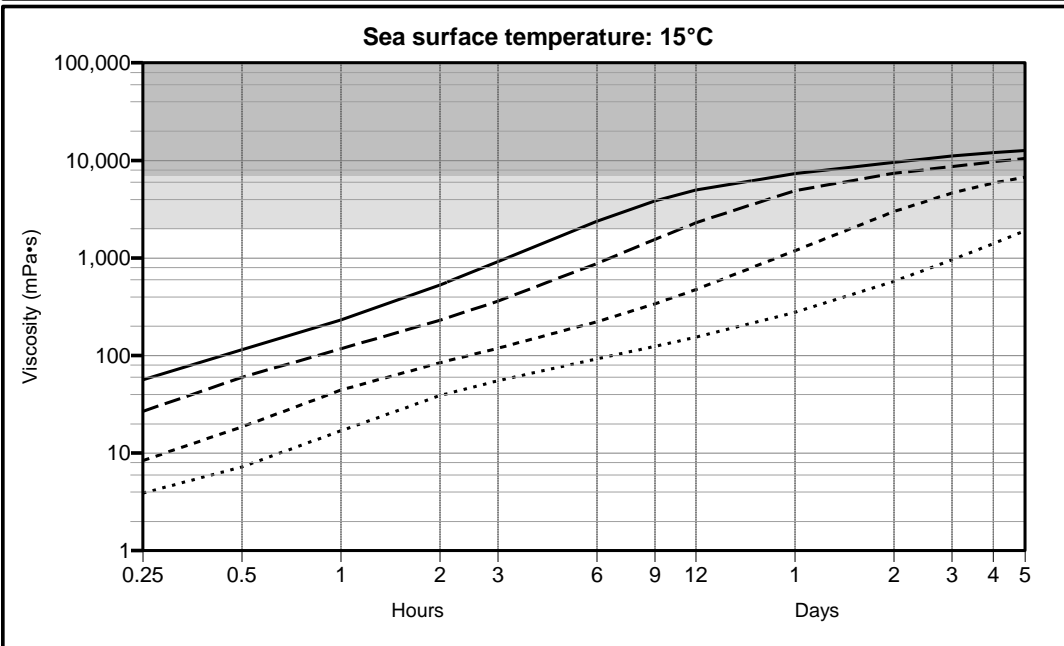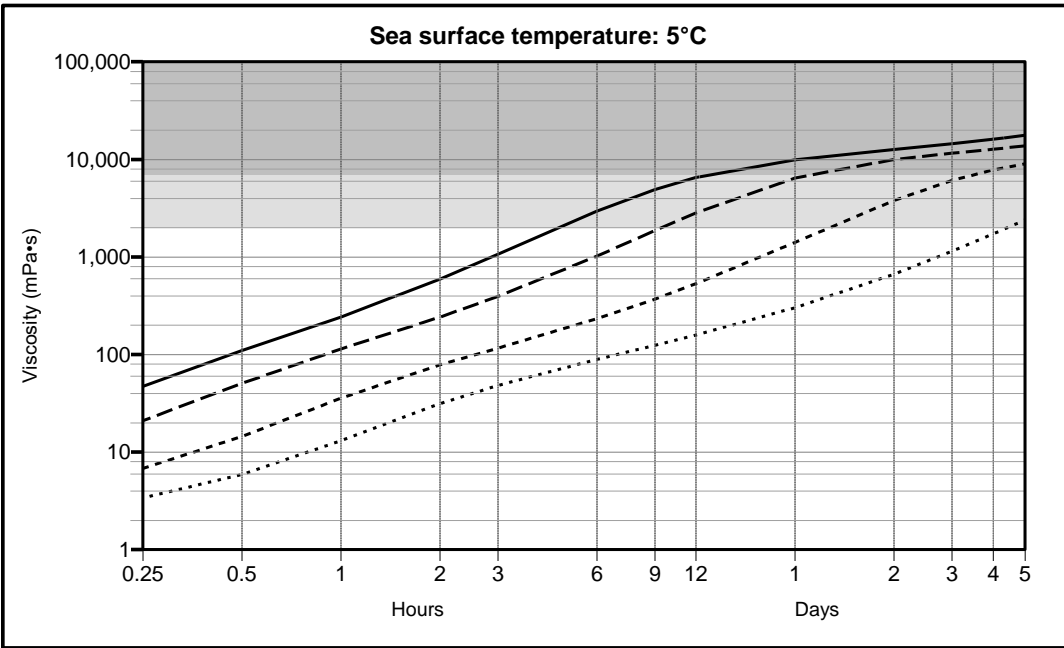
*Figure 4-12    Viscosity of Visund predicted at sea temperatures of 5 and 15 °C,  shear rate 10 s-1*

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**Property: WATER CONTENT**
**Oil Type: VISUND 2020**
**Description:**
**Data Source: Sintef Ocean (2020), Weathering data used**

OWModel© 12.0

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

2.0
Pred. date: Aug. 21, 2020

Wind Speed (m/s): 15
Wind Speed (m/s): 10
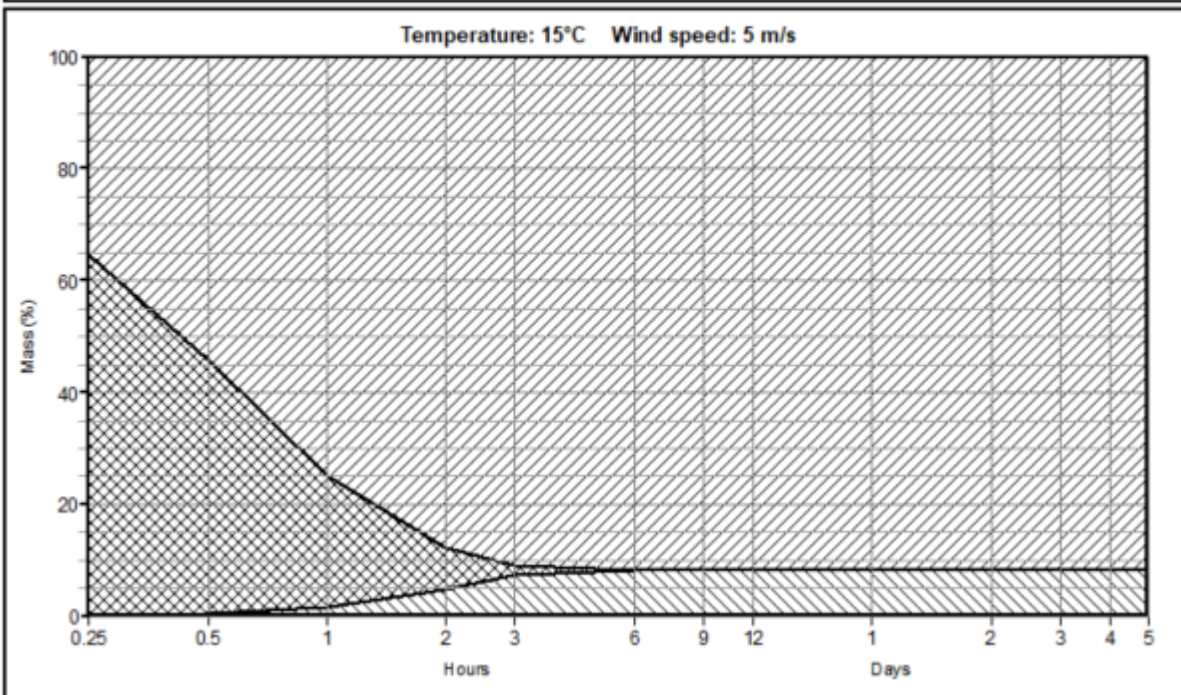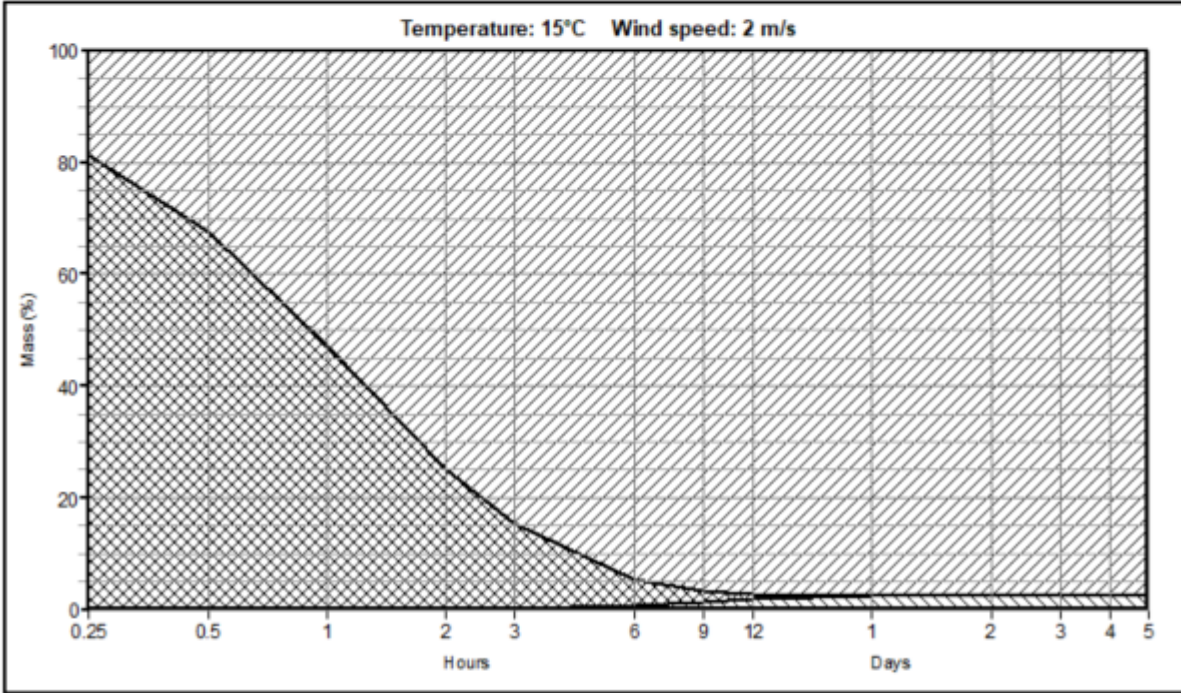Wind Speed (m/s): 5
Wind Speed (m/s): 2
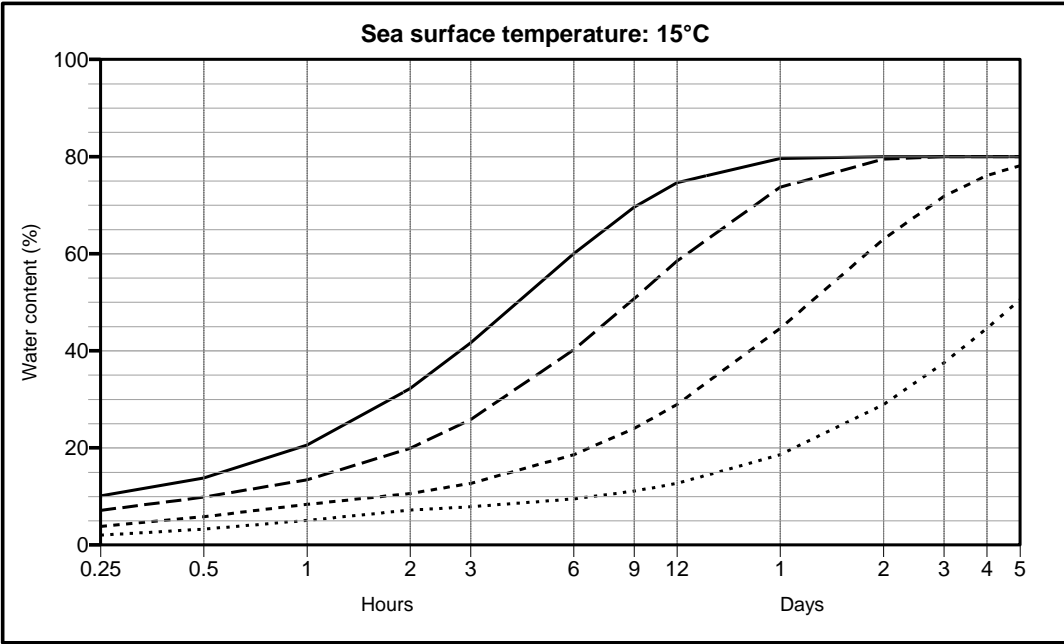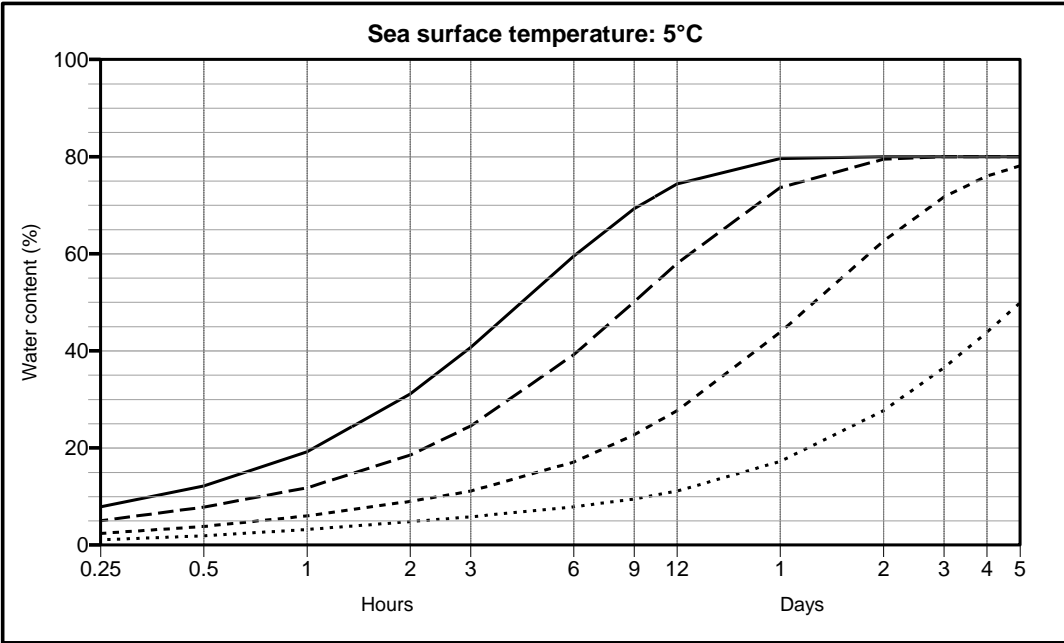
*Figure 4-13     Water uptake of Visund predicted at sea temperatures of 5 and 15 °C*

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**Property: FLASH POINT FOR WATER-FREE OIL**
**Oil Type: VISUND 2020**
**Description:**
**Data Source: Sintef Ocean (2020), Weathering data used**

SINTEF

OWModel© 12.0

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

2.0
Pred. date: Aug. 21, 2020

| | |
|---|---|
| Wind Speed (m/s): 15 | No fire hazard |
| Wind Speed (m/s): 10 | Fire hazard in tankage (<60 °C) |
| Wind Speed (m/s): 5 | Fire hazard at sea surface (below sea temperature) |
| Wind Speed (m/s): 2 | |

**Sea surface temperature: 5°C**

**Sea surface temperature: 15°C**
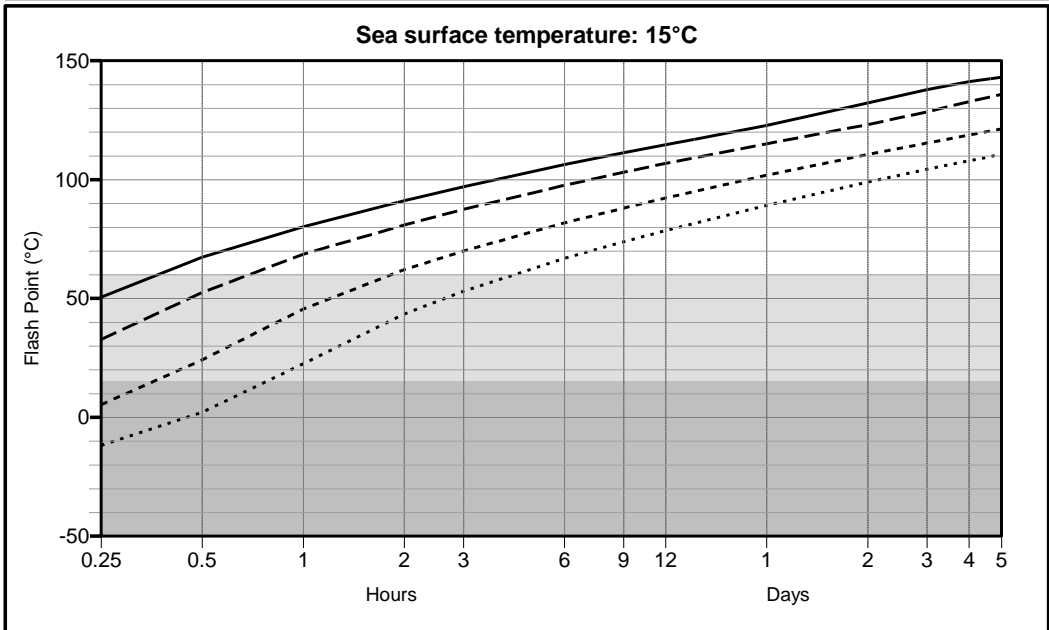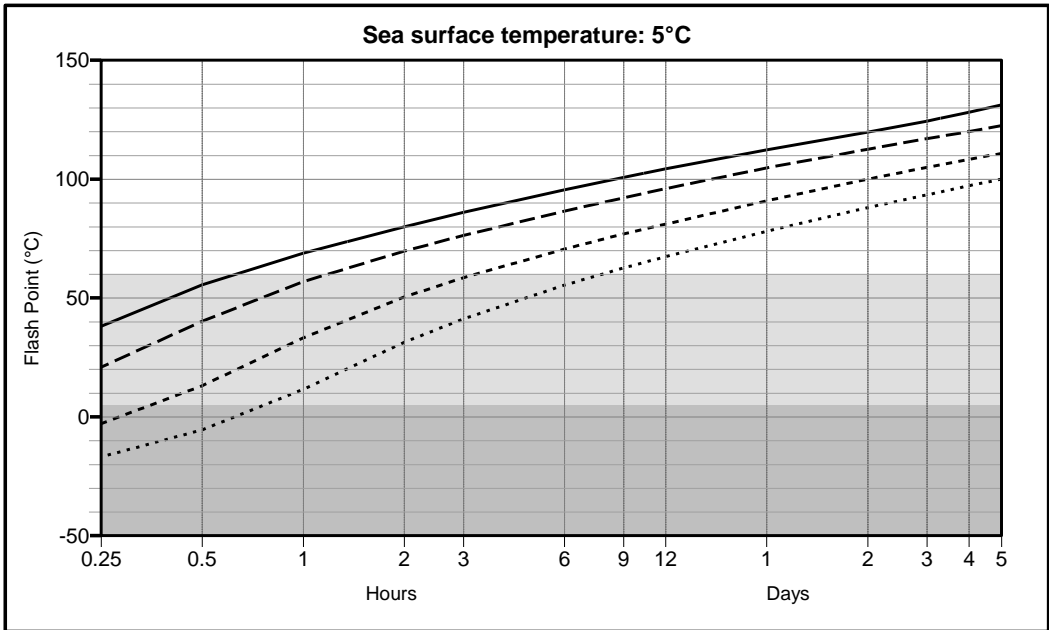
*Figure 4-14      Flash point of Visund predicted at sea temperatures of 5 and 15 °C*

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Property: **POUR POINT FOR WATER-FREE OIL**
Oil Type: **VISUND 2020**
Description:
Data Source: **Sintef Ocean (2020), Weathering data used**

OWModel© 12.0

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

2.0
Pred. date: Aug. 21, 2020

— Wind Speed (m/s): 15    ☐ Chemically dispersible
– – Wind Speed (m/s): 10    ☐ Reduced chemical dispersibility
· · · Wind Speed (m/s): 5    ☐ Poorly / slowly chemically dispersible
· · · · Wind Speed (m/s): 2

Sea surface temperature: 5°C

Sea surface temperature: 15°C
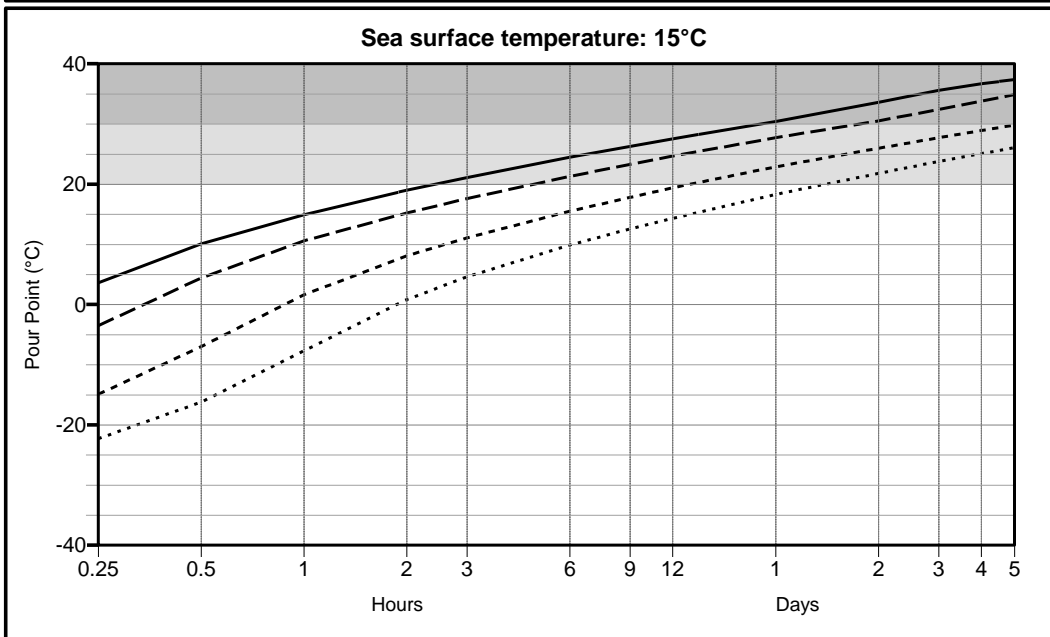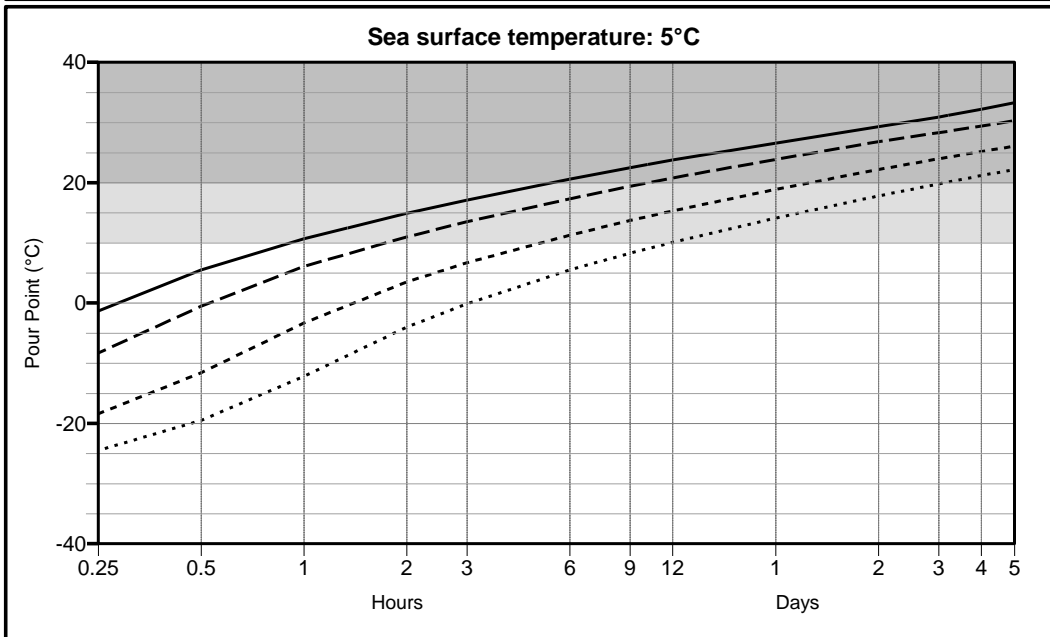
*Figure 4-15    Pour point of Visund  predicted at sea temperatures of 5 and 15 °C*

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| Property: MASS BALANCE | |
| --- | --- |
| Oil Type: VISUND 2020 | |
| Description: | |
| Data Source: Sintef Ocean (2020), Weathering data used | OWModel© 12.0 |

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

Pred. date: Aug. 21, 2020

Evaporated
Surface
Naturally dispersed

**Temperature: 5°C    Wind speed: 2 m/s**

**Temperature: 5°C    Wind speed: 5 m/s**
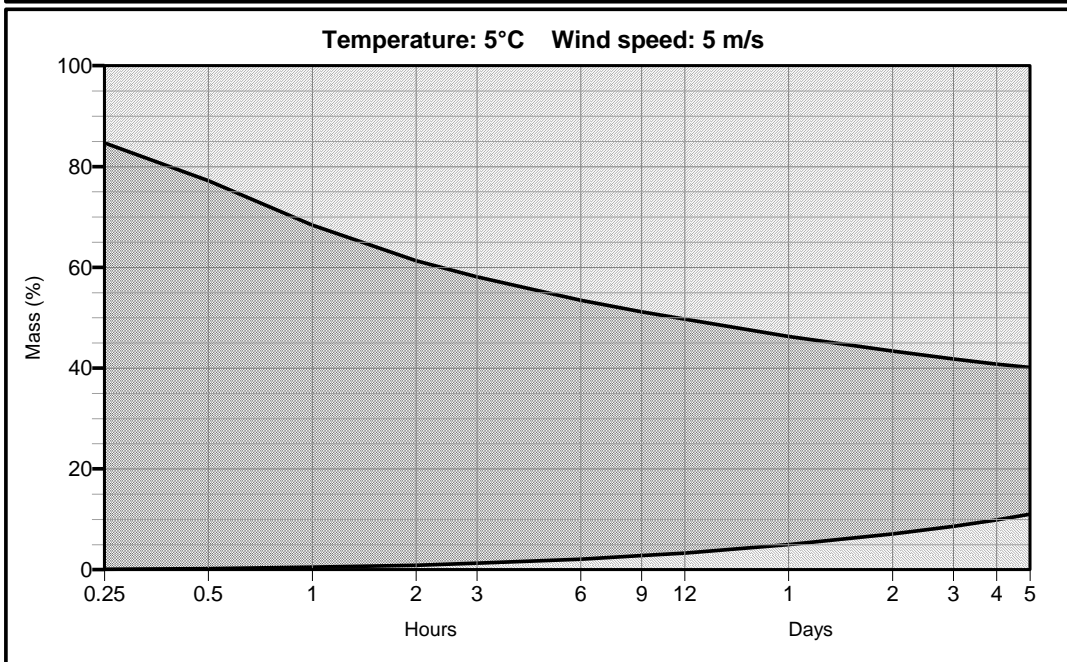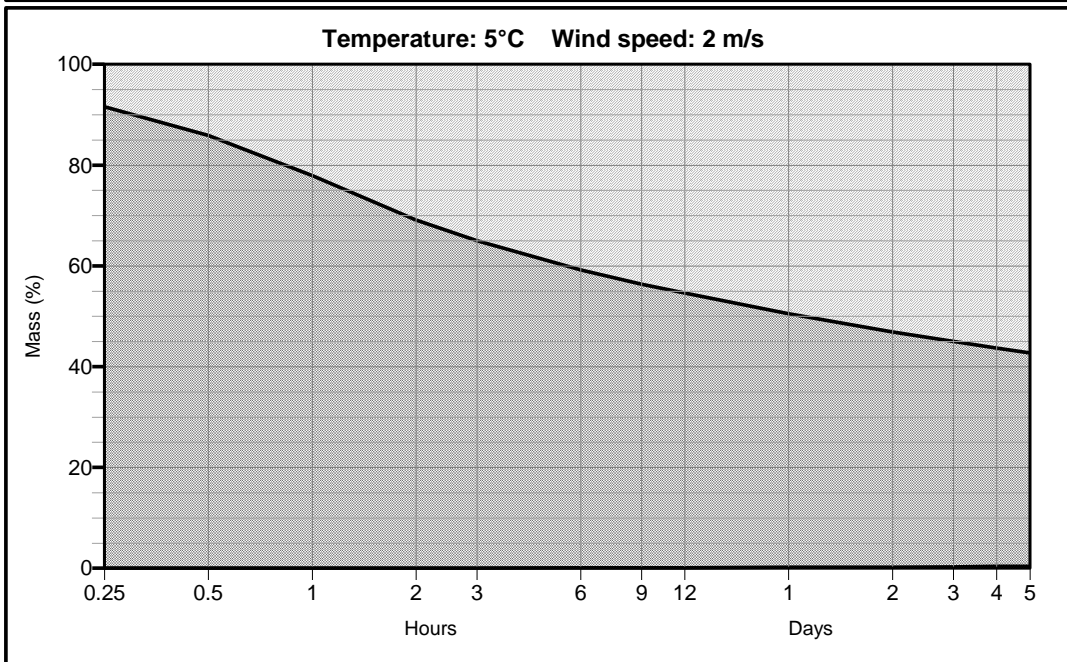
*Figure 4-16      Predicted mass balance of Visund predicted 5 °C, wind speeds of 2 and 5 m/s*

Property: **MASS BALANCE**
Oil Type: **VISUND 2020**
Description:
Data Source: **Sintef Ocean (2020), Weathering data used**

**SINTEF**

OWModel© 12.0

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

Pred. date: Aug. 21, 2020

Evaporated
Surface
Naturally dispersed



*Figure 4-17    Predicted mass balance of Visund predicted 5 °C, wind speeds of 10 and 15 m/s*

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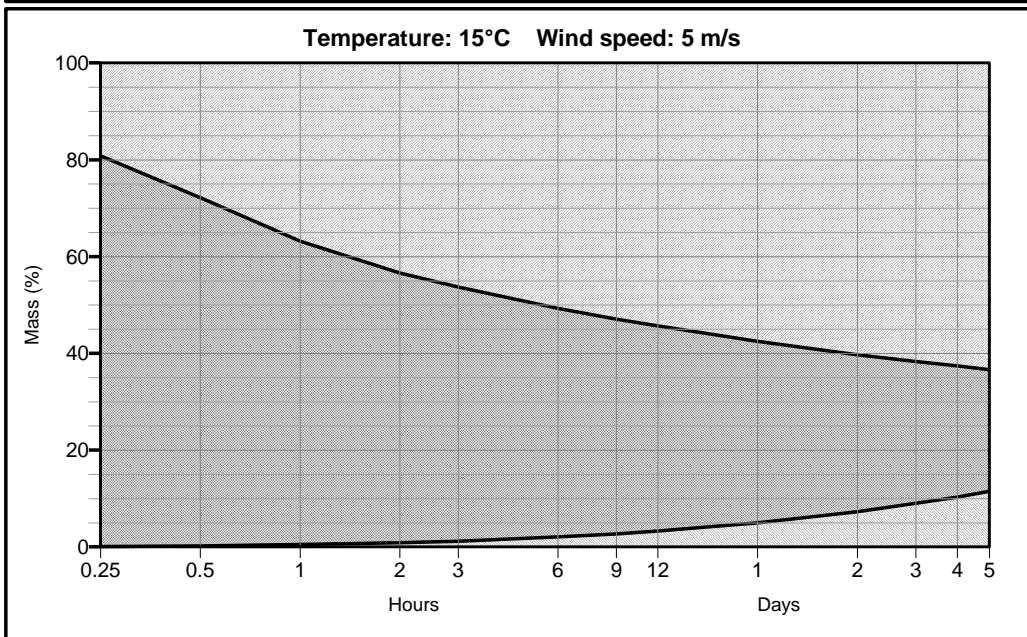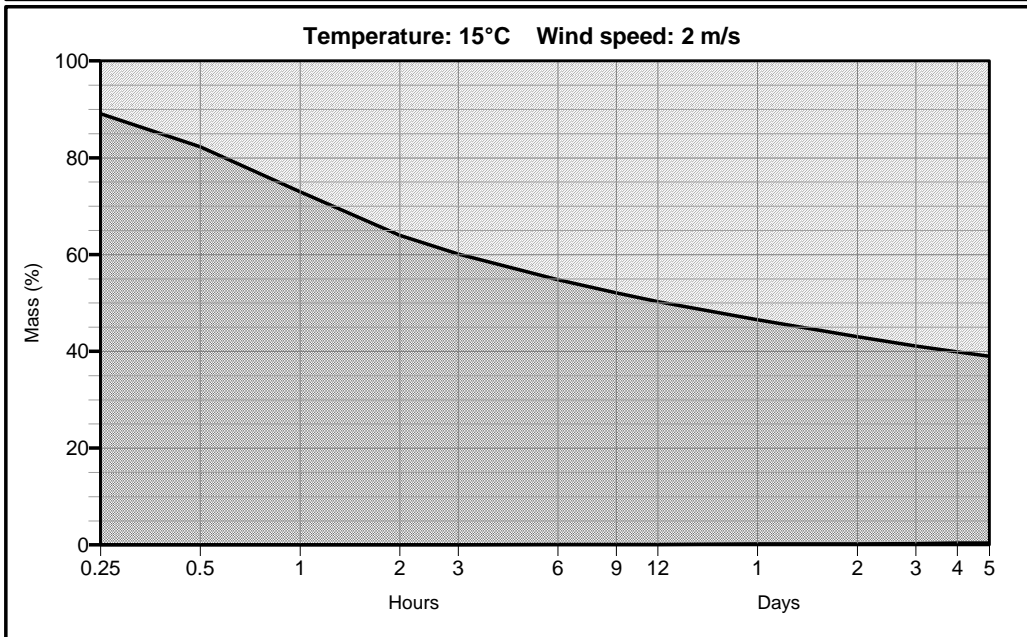
*Figure 4-18       Predicted mass balance of Visund predicted 15 °C, wind speeds of 10 and 15 m/s*

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**Property: MASS BALANCE**
**Oil Type: VISUND 2020**
**Description:**
**Data Source: Sintef Ocean (2020), Weathering data used**

⊚ SINTEF

OWModel© 12.0

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

Pred. date: Aug. 21, 2020

Evaporated
Surface
Naturally dispersed

**Temperature: 15°C    Wind speed: 10 m/s**

Mass (%)

Hours          Days

**Temperature: 15°C    Wind speed: 15 m/s**

Mass (%)

Hours          Days

*Figure 4-19       Predicted mass balance of Visund predicted 15 °C, wind speeds of 10 and 15 m/s*

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## 4.3 Find model oil

The "Find model oil" module in SINTEF OWM correlates Crude Assay (CA) variables for the fresh oil to weathering behaviour to search for a surrogate or a model oil in the SINTEF oil database. The approach for comparing fresh oil properties identifying a model oil is based on calculating a parameter describing the *fit factor* (Table 4-4) (Brandvik et al., 2015) between the new oil and the characterised oil present in the oil database.

The concept uses the CA variables: viscosity, asphaltene and wax content, density, pour point and the evaporation slope to search in the oil the oil database to find the closest match among the oils with existing weathering data. The evaporation slope (volume% evaporated / °C) is calculated based on the true boiling point curve (TBP) close to the 50 – 250 °C range (corresponds typically up to 5 days of weathering).

*Table 4-4        Fit factors for Find model oil*

| Fit factor | Description | Colour code |
|---|---|---|
| <0.25 | Good fit | Green |
| 0.26 -0.35 | Reasonable fit | Yellow |
| >0.40 | Unsatisfactory fit | Red |

The CA variables (viscosity, pour point, asphaltene, wax, density and evaporation slope) of Visund Sør and Visund were used as input in "Find model oil". The calculated fit to all the oils in the SINTEF oil database given as the 10 oils with the closest fit is shown in Figure 4-20 (Visund Sør) and Figure 4-21 (Visund). Visund Sør shows good fit with Kvitebjørn 2019, and reasonable fit with Aasta Hansteen Blend. Visund shows good fit with the previous Visund 2009, and reasonable fit with Kristin.
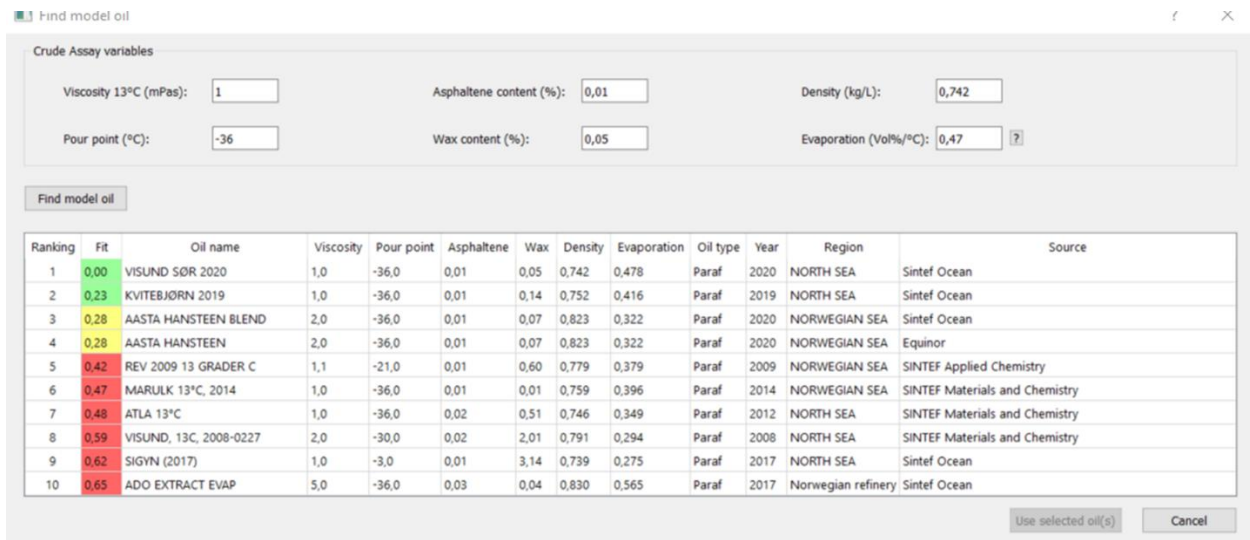


*Figure 4-20        The output crude assay data of Visund Sør.  Match (green value) with Visund 2009 (SINTEF Id 2008-0227) from SINTEF oil database*
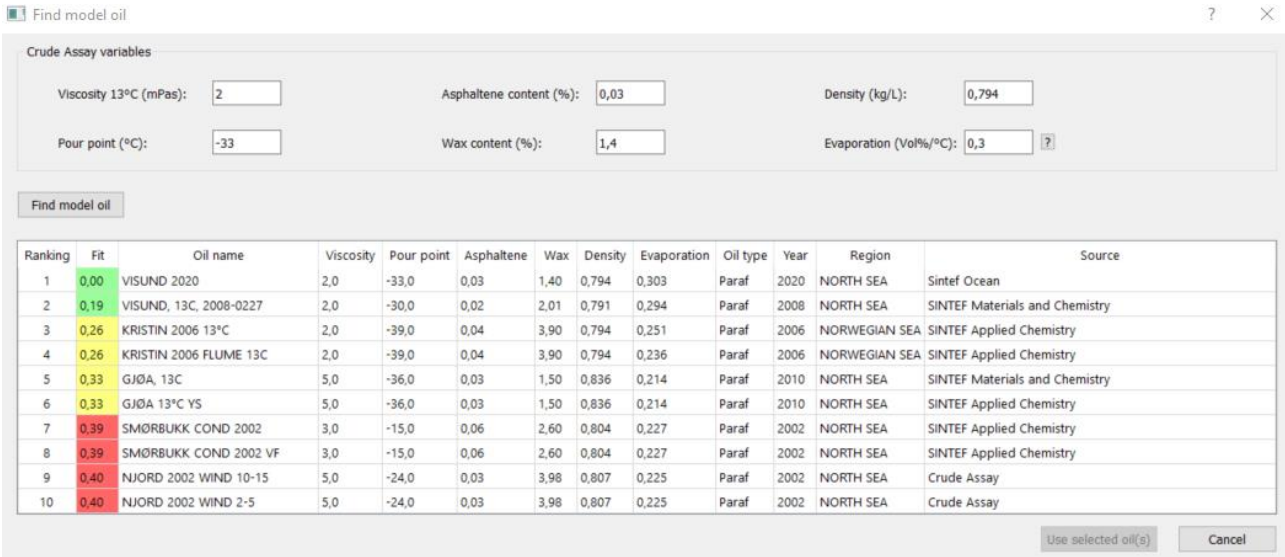
*Figure 4-21    The output crude assay data of Visund 2020.  Match (green value) with Visund 2009 (SINTEF Id 2008-0227) from SINTEF oil database*

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# 5 Comparison of OWM predictions

Weathering predictions of Visund Sør 2020 and Visund 2020 were compared with predictions of Visund 2009 (Visund 13C 2008-0227), Visund 1998 (Visund 13C 10S-1), Kvitebjørn 2019, and Kristin (Kristin 2006 13°C). Labelling of the oils from SINTEF Oil database in brackets.

The presented comparisons given in the figures below are based on predictions at sea temperature of 15 °C and wind speed of 10 m/s.

## 5.1 Evaporative loss

Evaporation is one of the natural process that helps removing spilled oil from the sea surface. Visund Sør has the highest evaporative loss (very light condensate) followed by Kvitebjørn 2019 (Figure 5-1). Visund and Visund 2009 has very similar evaporative loss, followed by Kristin. Visund 1998 has the lowest evaporative loss among these oils. The evaporative loss reflects the characteristics of the oils where the light condensates exhibit higher evaporative loss and have lower densities compared with the crude oils.
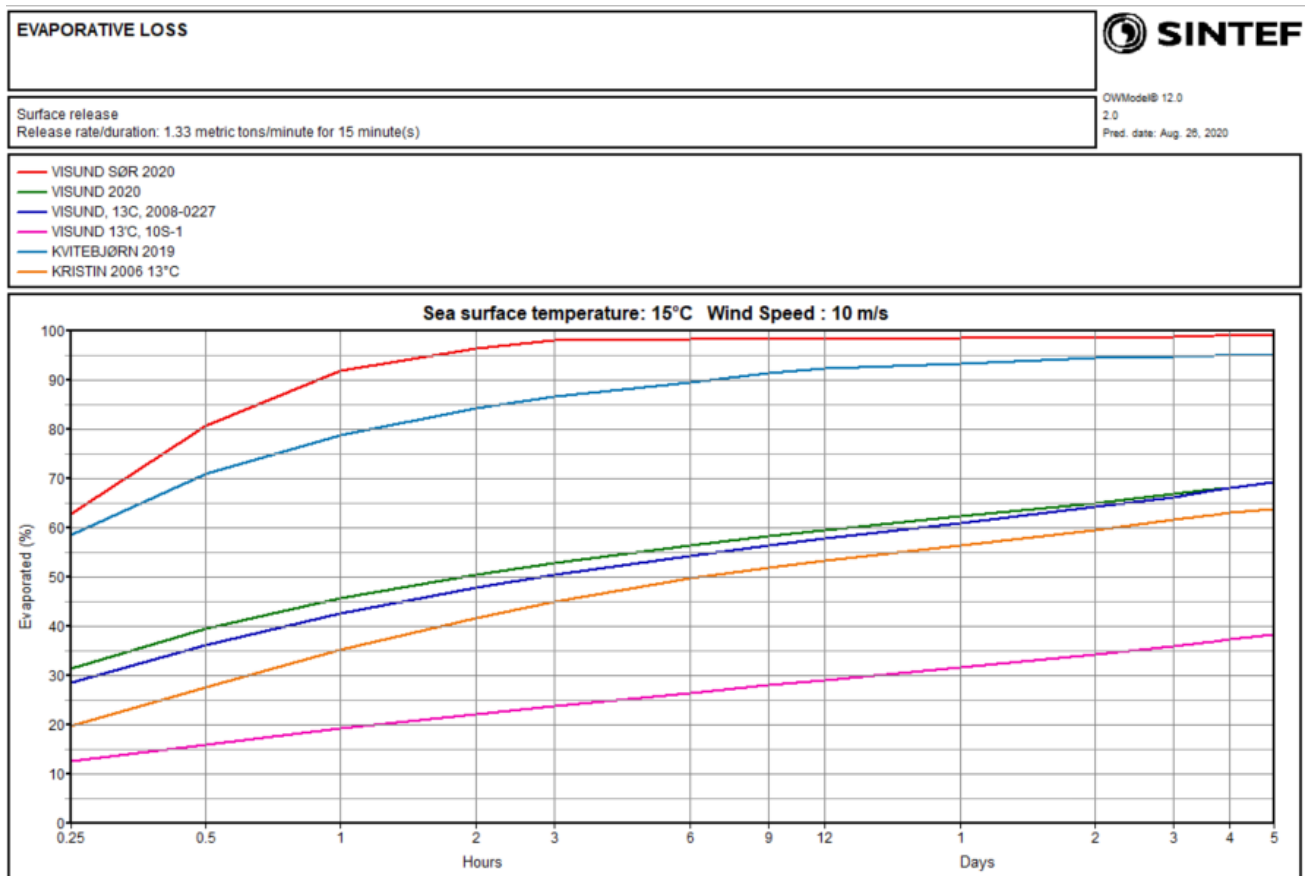


*Figure 5-1        Predicted evaporative loss at 15 °C and 10 m/s for Visund Sør and Visund  compared with other oils*

## 5.2 Flash point

When oil is spilled on the sea surface, the oil will be cooled to the ambient water temperature within a short period. The probability of fire is high if the flash point of the oil is below the sea temperature. Fire hazard is dependent upon the amounts of volatile components in the oil and the potential for fire is usually over within the first few minutes of a spill due to the rapid evaporation of those components.

The flash points of the oils in comparison are shown in Figure 5-2. The predictions show that only Kristin is expected to pose a fire hazard 15 minutes after a spill, while the other oils are above the 15 °C before this time point. Within 30 minutes, Kristin also has flash point above the fire hazard limit, as for the other oils in comparison.
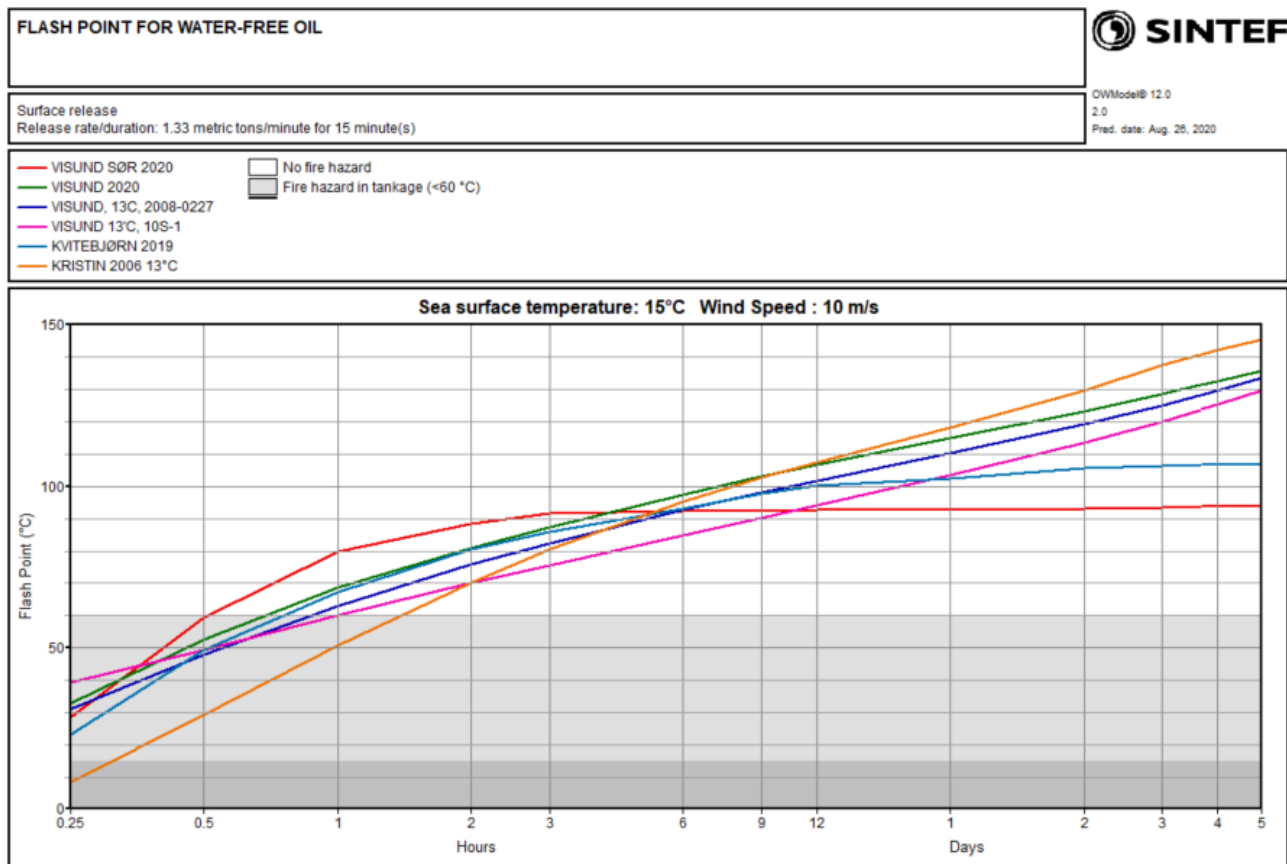


*Figure 5-2      Predicted flash point at 15 °C and 10 m/s for Visund Sør and Visund compared with other oils*

## 5.3 Pour point

The pour points of Visund Sør and Visund and the other oils in comparison are given in Figure 5-3. Visund Sør expresses the lowest pour point followed by Kvitebjørn 2019. The low pour points of the condensates reflect the low content of wax and will therefore not pose a challenge with solidification at sea and will also have a high degree of natural dispersion if spilled at sea. Visund, Visund 1998 and Kristin have higher pour points with a potential to solidify by time if spilled at sea.
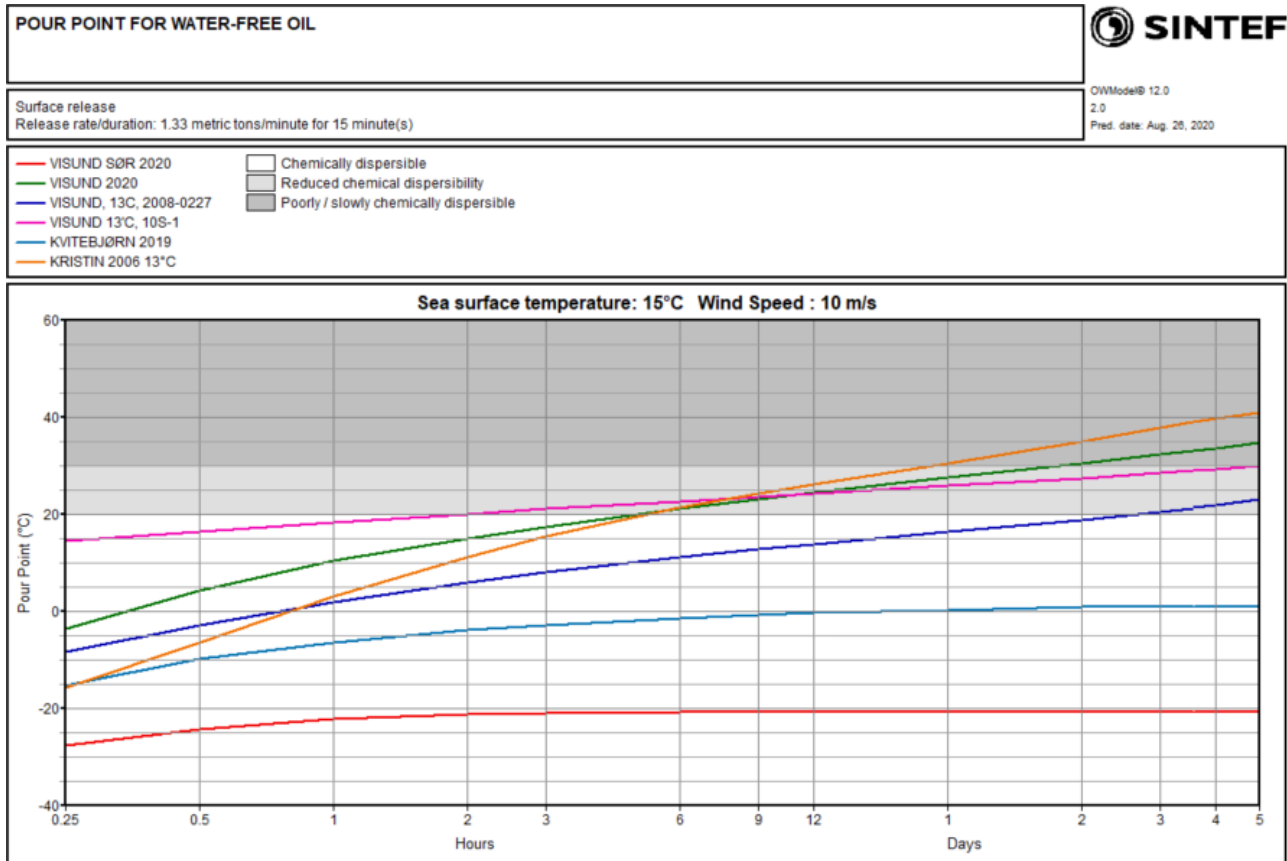


*Figure 5-3        Predicted pour point at 15 °C and 10 m/s for Visund Sør and Visund compared with other oils*

## 5.4 Water content

The water uptake of the oils in comparison are shown in Figure 5-4. Visund and Visund 2009 reach the highest water uptakes of 80 vol.% after 2 days of weathering, however Visund has a slower water uptake during the first day of weathering at sea. Visund 1998 reached a water uptake of 60 vol.%. Kristin forms more unstable emulsions and has a relatively low water uptake of 40-50 vol. %. The condensates (Visund Sør and Kvitebjørn 2019) have low or negligible water uptakes.



**WATER CONTENT** — SINTEF

OWModel® 12.0
2.0
Pred. date: Aug. 26, 2020

Surface release
Release rate/duration: 1.33 metric tons/minute for 15 minute(s)

- VISUND SØR 2020
- VISUND 2020
- VISUND, 13C, 2008-0227
- VISUND 13'C, 10S-1
- KVITEBJØRN 2019
- KRISTIN 2006 13°C

Sea surface temperature: 15°C   Wind Speed : 10 m/s
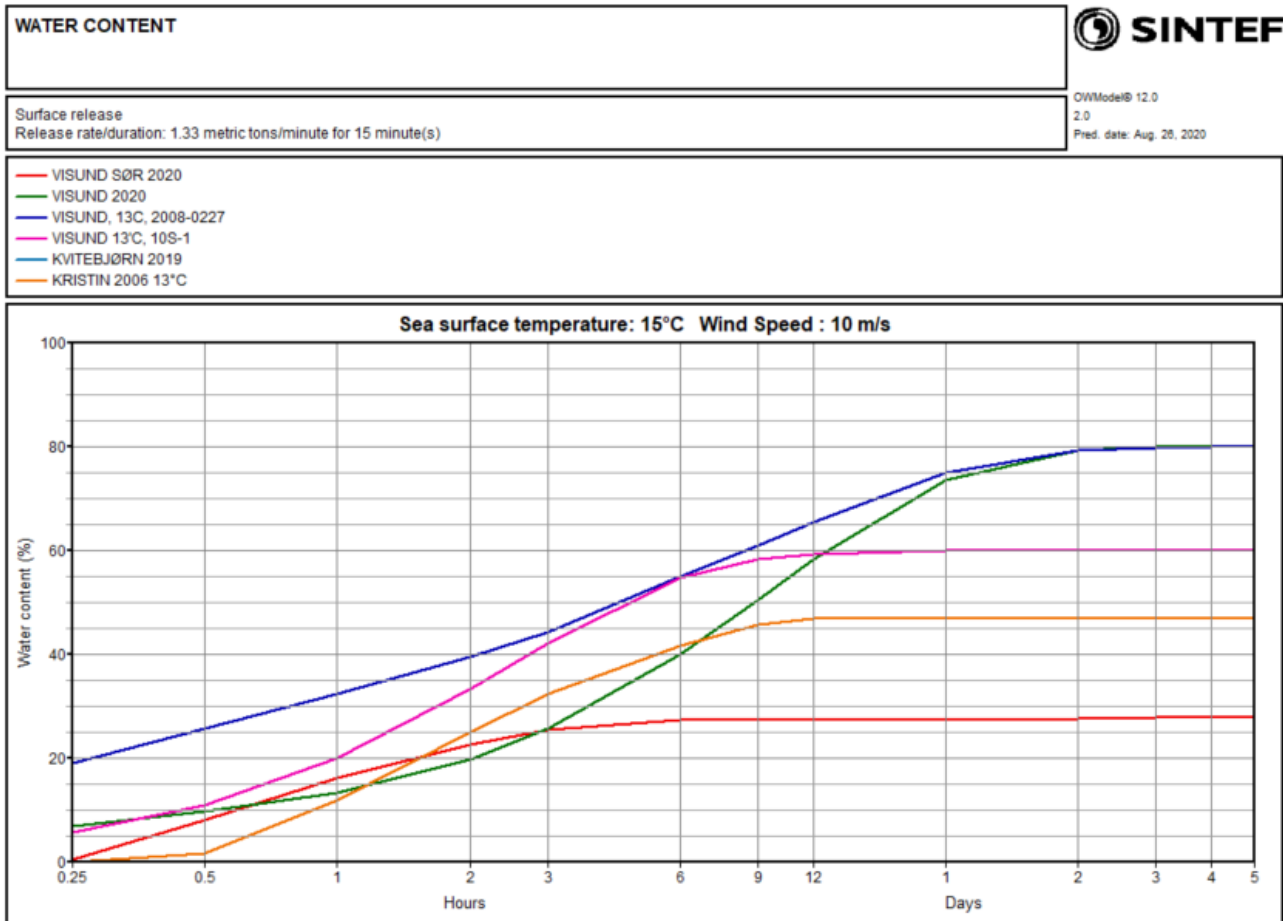
*Figure 5-4          Predicted water content at 15 °C and 10 m/s for Visund Sør and Visund compared with other oils.*

## 5.5 Viscosity

Figure 5-5 shows the predicted (emulsion) viscosities of the oils in comparison. The condensates of Visund Sør and Kvitebjørn 2019 have very low viscosities that reach approx. 10 mPa.s. The crude oils exhibit significantly higher viscosities than the condensates. The viscosities increase gradually throughout 5 days of weathering, and Visund and Visund 1998 reach the highest viscosities of 10 000-15 000 mPa.s.
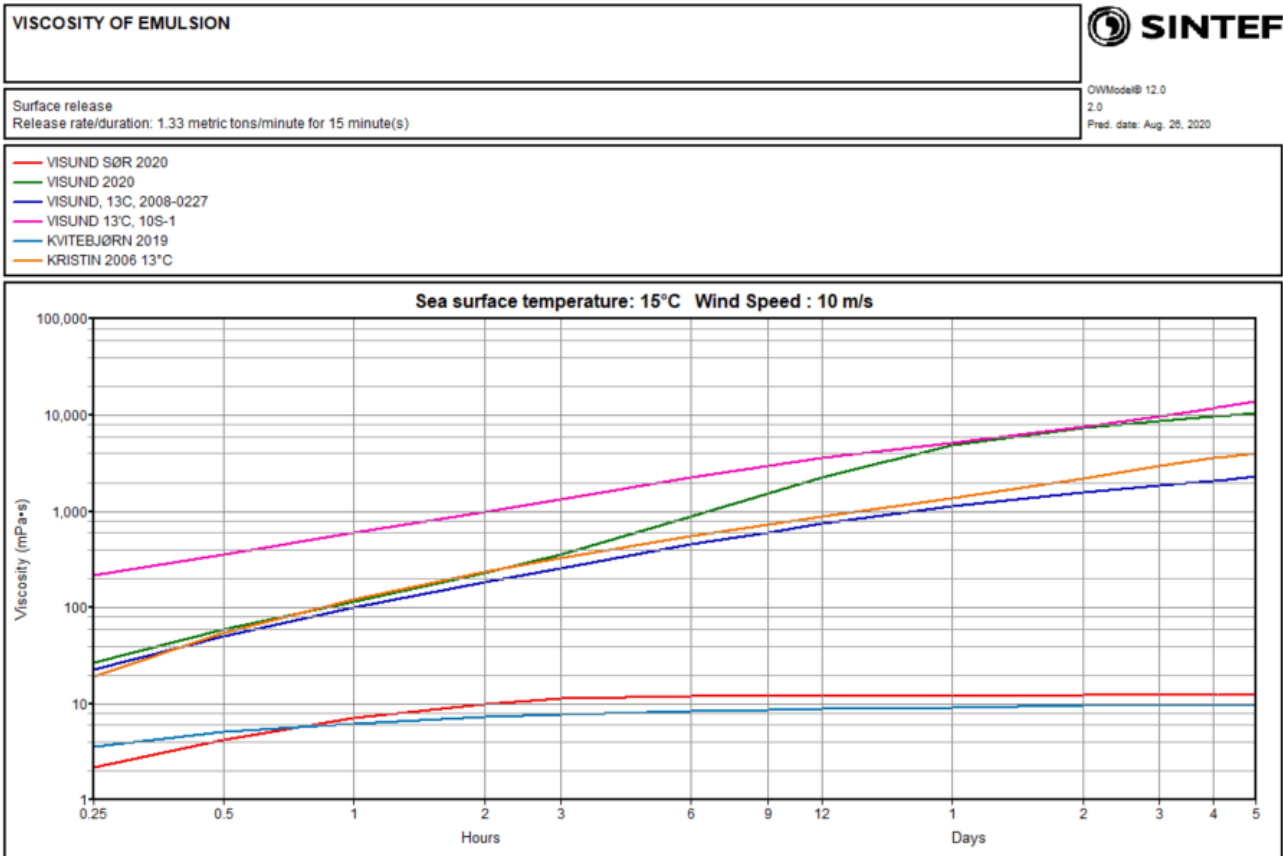


*Figure 5-5        Predicted (emulsion) viscosity at 15 °C and 10 m/s for Visund Sør and Visund compared with other oils*

## 5.6 Surface oil emulsion

The predicted surface oil emulsion is based on the evaporative loss, natural dispersion/entrainment, and emulsification, Figure 5-6 shows the predicted mass balance of remaining surface emulsion as a function of weathering. The light condensates Visund Sør and Kvitebjørn 2019 are predicted to be rapidly removed from the sea surface due to evaporation and natural dispersion within 1-2 hours, whilst the emulsifying crude oils of Visund, Visund 2009, Visund 1998 and Kristin have longer predicted lifetime on the sea surface. Visund 1998 is most persistent on the sea surface compared with the other oils.
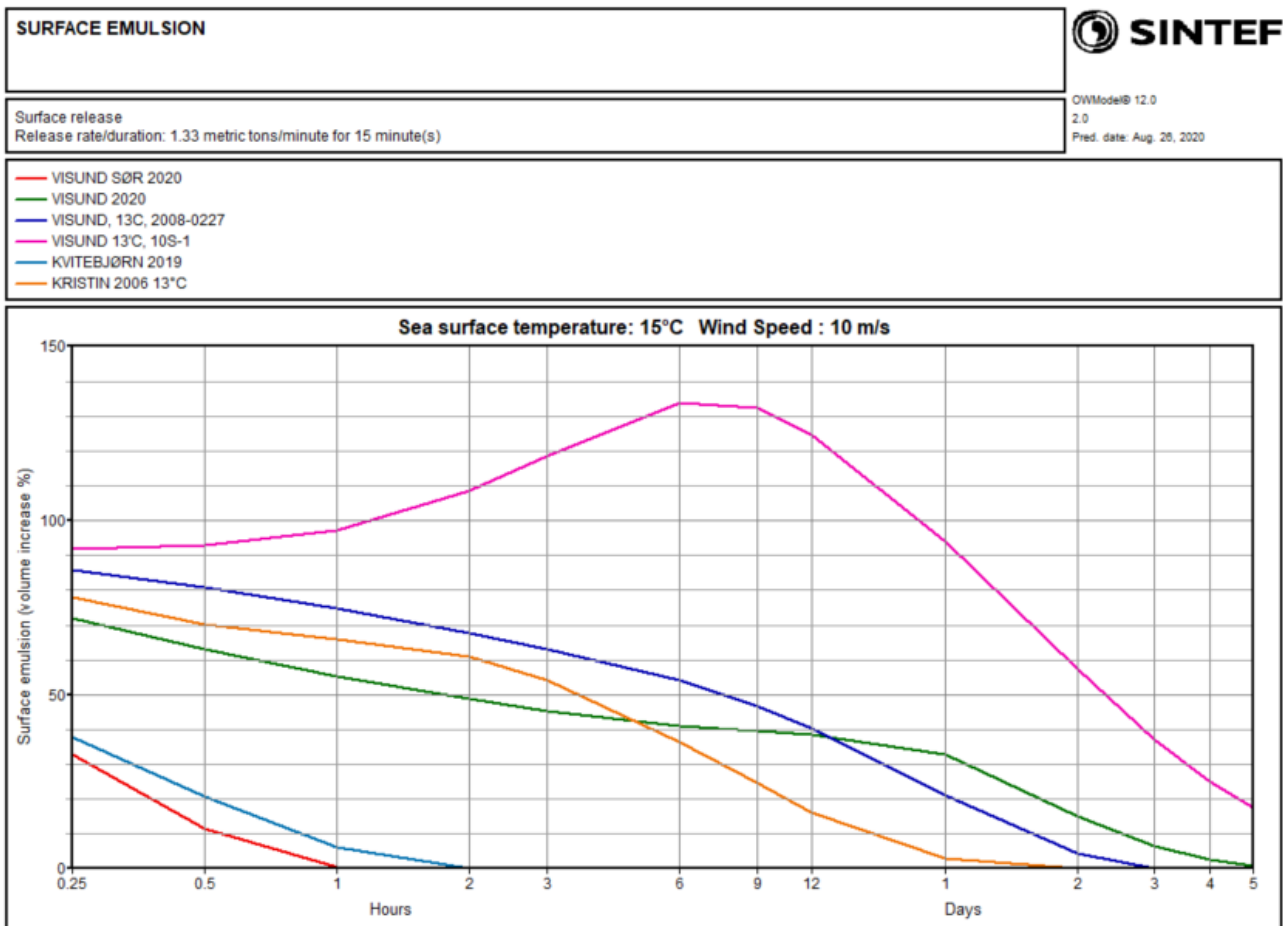


*Figure 5-6        Predicted remaining surface oil at 15 °C and 10 m/s for Visund Sør and Visund compared with other oils*

# 6 Weathering properties of Visund Sør and Visund when spilled at sea

The relative content of heavy oil components within a spilled oil increases due to weathering, and the physical and chemical properties of the oil will change over time. Knowledge about how the oil's properties change during weathering is therefore important in the management of oil spill response. Currently, mechanical recovery and the use of oil spill dispersants are the main oil spill response options at sea in the Norwegian sector, today. The potential of using water-flushing to disperse the oil is briefly discussed in this report.

## 6.1 Oil properties

**Visund Sør**

Visund Sør is a light paraffinic condensate with a density of 0.742 g/mL, with very low contents of wax (0.05 wt. %) and asphaltenes (<0.01 wt. %). Visund Sør showed low or negligible emulsifying properties, and the physico-chemical properties with high evaporative loss like other non-emulsifying condensates such as Kvitebjørn 2019. The fresh oil and its residues exhibit very low viscosities ranging from 1-7 mPa.s at shear rate $100s^{-1}$ (13 °C). In addition, the fresh condensate and residues have a low pour point of -36 °C (fresh oil) to -9 °C (250°C+ residue) with evaporation of the lightest compounds. The weathering properties indicate that the condensate rapidly will be spread on the sea surface to thin oil films ($\leq 50$ µm).

**Visund**

Visund is a light paraffinic crude oil with density of 0.749 g/mL. Visund has low content of wax (1.4 wt. %) and asphaltene (0.03 wt. %), compared with other Norwegian crude oils. The fresh oil exhibits low viscosity of 2 mPa.s at shear rate $100s^{-1}$ (13 °C) but increases significantly by evaporation. The fresh crude oil has low pour point of -33 °C that increases significantly from 0 to +24 °C for the residues after evaporation of the lightest compounds. Visund forms stable water-in-oil (w/o) emulsions that may reach a maximum water uptake of about 80 vol. %.

## 6.2 Flash point – Fire/explosion hazard

Flash point refers to the lowest temperature at which a fuel or oil can vaporize to form an ignitable mixture in the air. In case of an oil spill on the sea surface, the (heated) oil rapidly will be cooled to the ambient seawater temperature within a short period of time. The potential for fire/explosion hazard will be at its greatest if the flash point of the spilled oil is <u>below</u> the seawater temperature

The flash points for **Visund Sør** is expected to surpass the sea temperature within a few minutes at 5 and 15 °C, at wind speeds of 10 and 15 m/s predicted with the standardized surface release as shown in Figure 4-5. At calmer weather conditions (2 and 5 m/s) care should be taken during the first hour. Similar, the flash points for **Visund** is expected to surpass the sea temperature within a few minutes at 5 and 15 °C, at wind speeds of 10 and 15 m/s predicted with the standardized surface release as shown in Figure 4-14. At calmer weather conditions (2 and 5 m/s) care should be taken during the first 0.5-1 hour.

However, the release rate may influence on the rate of evaporation, and for considerably larger (batch) release rates e.g. 100 times higher (8000 $m^3$/h), the rate of evaporative loss is thus reduced. For Visund Sør, the time when the flash point has surpassed the sea temperature has now increased to 1.5-3 hours at 2 and 5 m/wind speed (Figure 6-1). For Visund, the time when the flash point has surpassed the sea temperature has now increased to 1.5-2.5 hours at 2 and 5 m/wind speed (Figure 6-2).

Moreover, some vessels/storage tanks engaged in oil recovery operations may not be classified to carry liquids with flash points lower than 60 °C, e.g. towing vessels, smaller cargo, or other vessels available in the emergency. This means that fuels or oils with the flash point less than 60 °C, are for those type of vessels not permitted as cargo. However, this limit is not considered as relevant for oil recovery vessels with A-class certification for transport of liquids (Class I/II, flashpoints < 60 °C), according to NFPA classification of

Flammable and Combustible Liquids (http://www.thetankshop.ca). Refers to flash point predictions in chapter 4 (Figure 4-5 and Figure 4-14 for Visund Sør and Visund.

As a general recommendation after an acute oil spill involving free gas (e.g. from a subsea release), a "safety" zone should be established early on and downwind from the spill site before response actions are initiated. 1-hour drifting time of slick (from the source) has e.g. been suggested in Norway before oil spill response operations are initiated in open sea waters. Shorter waiting times have been predicted related to fire/explosion hazard related to the flash point. The following precautions should be taken:

- Prior to the initiation of spill response operations, an evaluation of fire/explosion hazard must always be conducted at the site
- Explosimeters should be utilized continuously and one should be aware of the possibility for varying release rates if "free" gas is involved
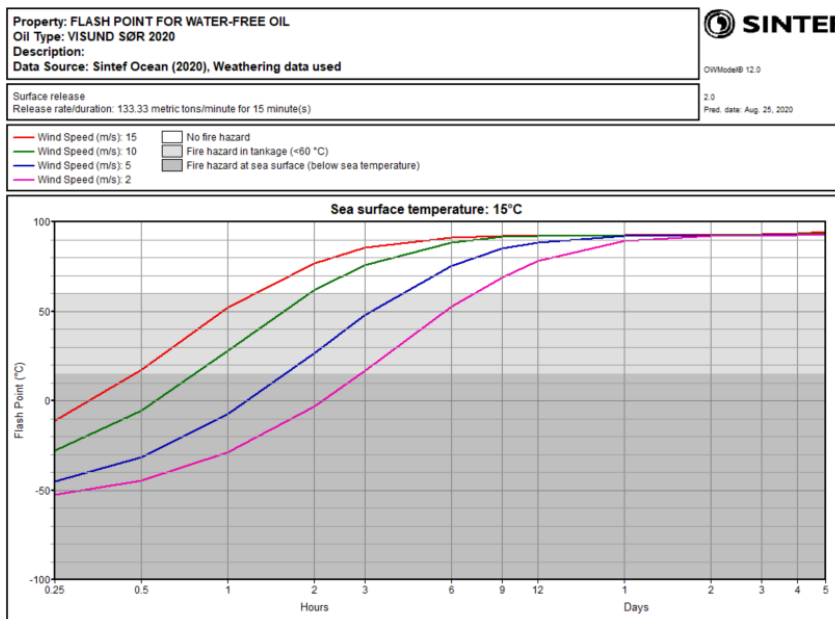


*Figure 6-1        Predicted flash points for Visund Sør at 15 °C (8000 $m^3$/ h)*
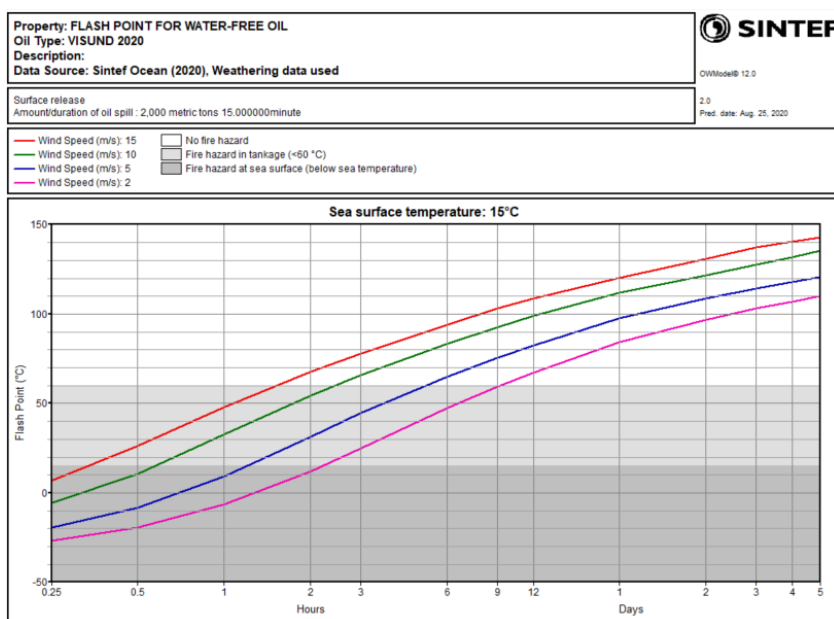


*Figure 6-2        Predicted flash points for Visund at 15 °C (8000 $m^3$/ h)*

## 6.3 Solidification

Pour point depends on the oil's wax content and the amounts of light components that can keep the wax components dissolved in the oil phase. In addition, contents of asphaltenes prevent or reduce precipitation and lattice formation and hence lowers the pour point. High pour points may prevent the dispersant to soak into the oil slick and influence the dispersant effectiveness and may also reduce the potential for flowability towards weir skimmers. In cases when high viscosities are not a limiting factor, high pour points may cause solidification (elastic properties) when oil is spilled on the sea surface. High pour point may therefore imply solidification on the sea surface immediately after the release, and this is pronounced when the pour point is typically 5-15 °C above sea temperature and in cold temperatures.

**Visund Sør** exhibits low pour points and is not expected to pose any solidification (elastic properties) when weathered at sea at 5 and 15 °C within 5 days after a spill, see also the predictions in Figure 4-6 (chapter 4).

**Visund** has a potential to solidify when weathered at sea at 5 and 15 °C within 5 days after a spill, see also the predictions in Figure 4-15.

## 6.4 Natural dispersion and evaporation

The lifetime of an oil spill at sea depends on the oil's composition, the release conditions (e.g. on the surface, underwater) and environmental conditions (temperature, wind, waves). Natural dispersion and evaporation are the main weathering processes that remove an oil spill from the surface. The remaining surface oil after a release is dependent on the wind speeds and typically oils are more persistent on the sea surface with lower wind.

**Visund Sør**
Figure 6-3 shows the remaining surface oil over time for different wind speeds and temperatures for Visund Sør. Only minor difference in lifetime between 5 and 15 °C for this condensate. At low wind speed of 2 m/s, no oil remains on the sea surface after 1 day of weathering, and similar 0.5-hour at 15 m/s wind speed.
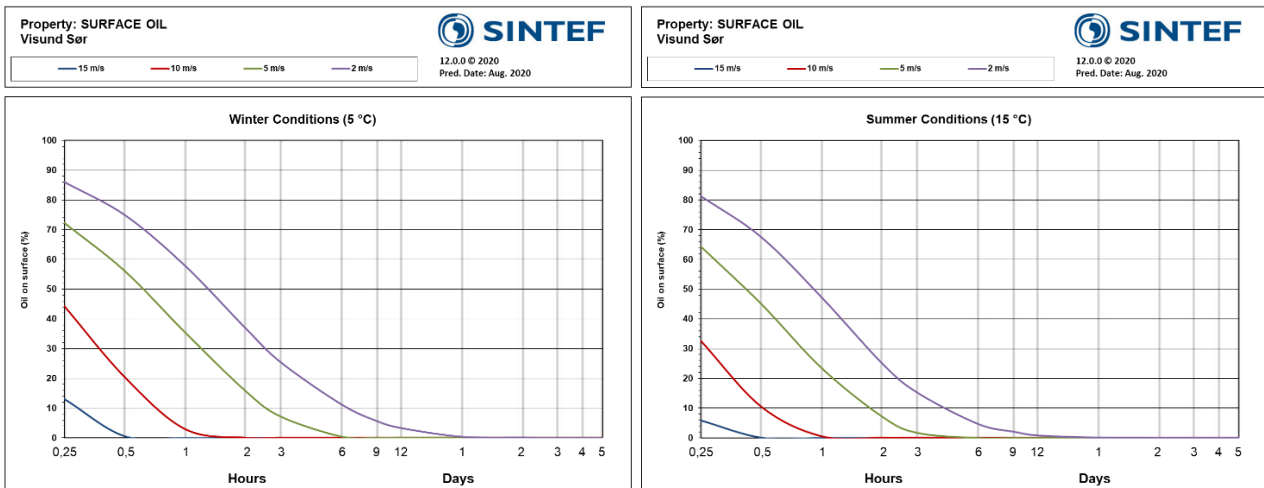


*Figure 6-3        Remaining surface oil for Visund Sør at 5 and 15  °C*

**Visund**
Figure 6-4 shows the remaining surface oil over time for different wind speeds and temperatures for Visund. Minor differences in lifetime between 5 and 15 °C. At high wind speed of 15 m/s, no oil remains on the sea surface after 1 day of weathering at 15 m/s wind speed. At calmer weather conditions 2-5 m/s wind speeds (no-breaking waves), the remining surface oil is about 25-40 % at summer and winter conditions.
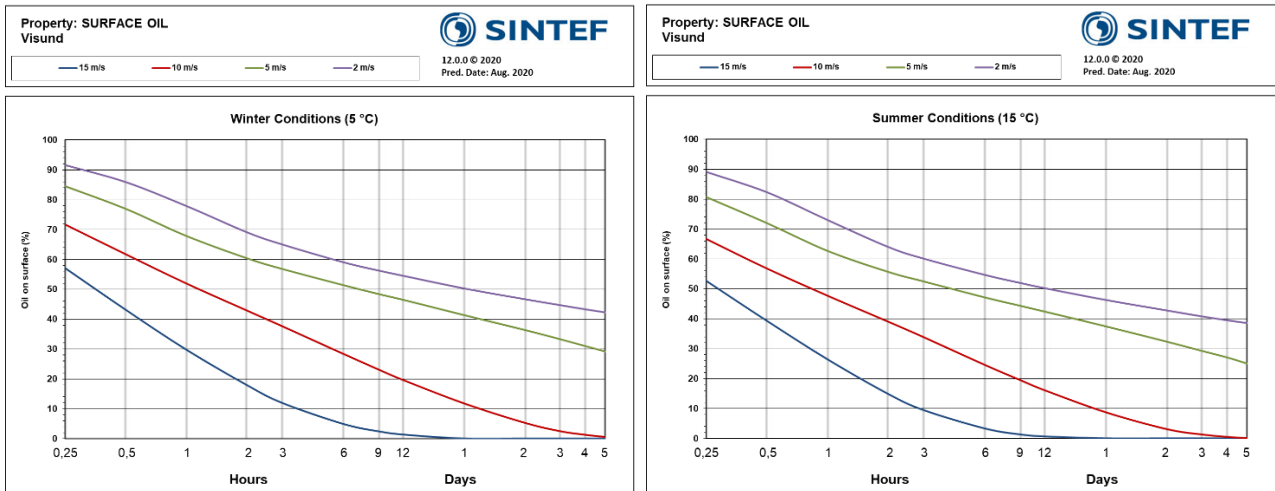
Figure 6-4    *Remaining surface oil for Visund at 5 and 15 °C*

## 6.5 Film thickness from surface release

Mechanical recovery requires normal minimum film thicknesses > 0.1-0.2 mm. Film thicknesses > 0.05-0.1 mm are considered for application of oil spill dispersants, as lower film thicknesses are likely to disperse naturally. However, other factors than film thickness should be considered when evaluate response options, as described in the next chapters. Figure 6-5 and Figure 6-6 show the predicted film thicknesses for Visund Sør and Visund, respective at different wind speeds.
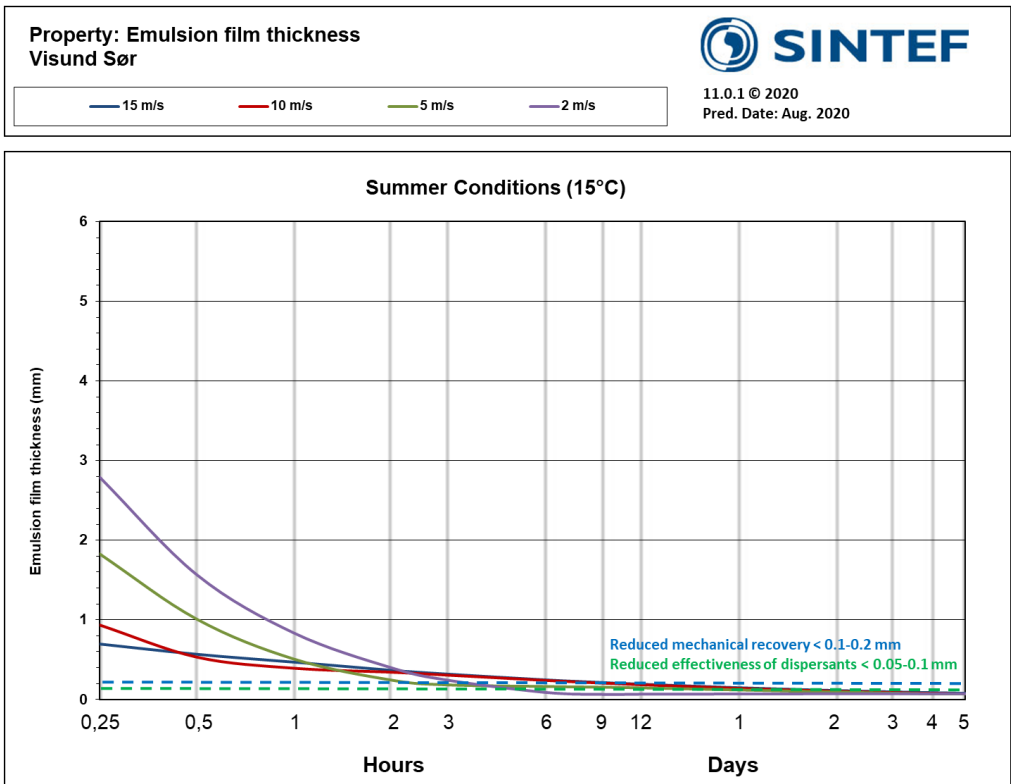


Figure 6-5    *Predicted film thickness of Visund Sør after 5 days of weathering (surface release)*
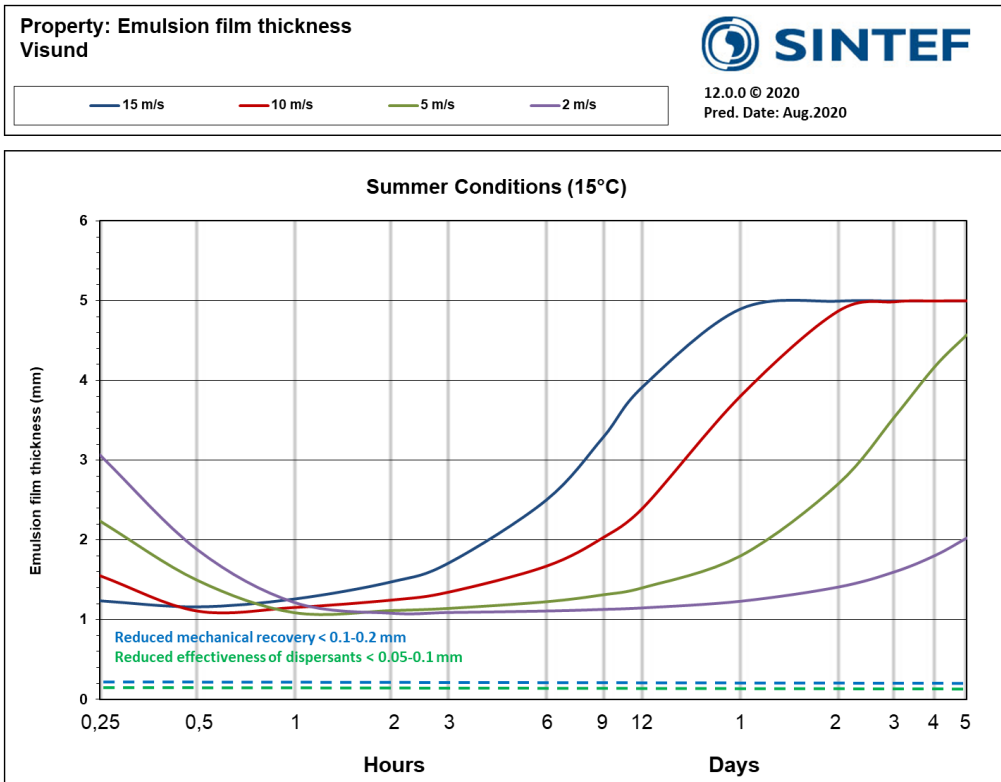
*Figure 6-6        Predicted film thickness of Visund after 5 days of weathering (surface release)*

## 6.6  Mechanical recovery by boom and skimmer

Experiences from Norwegian field trials with booms have demonstrated that the effectiveness of various mechanical clean-up operations may be reduced due to the high degree of leakage of the confined oil or emulsion from the oil spill boom.

Boom leakage is particularly pronounced if the viscosity of the oil or the w/o-emulsion is lower than 1000 mPa.s (Nordvik et al., 1992). The lower viscosity limit for an optimal mechanical clean-up operation has therefore been estimated to 1000 mPa.s. However, other factors like the operational speed of recovery vessel and current weather conditions will also influence on the risk of boom leakage. Therefore, it may be possible to recover surface oil (emulsion) in calm weather conditions with viscosities lower than this limit (1000 mPa.s). Previously studies at SINTEF have shown that weir skimmers may reduce recovery rates (m³/h) when skimming oils with viscosities in the range 15-20 000 mPa.s (Leirvik et al., 2001). Moreover, NOFO is operating with viscosity limits for skimmer efficiency as followed: primary use  of weir skimmers (< 20 000 mPa.s), combination of weir and high-visc. skimmer (20-50 000 mPa.s), and primary high visc. skimmer (> 50 000 mPa.s).

**Visund Sør**

The predicted mass balance of Visund Sør indicates that the condensate has short lifetime at sea particularly in high wind speeds, with a high degree of evaporative loss and natural dispersion. In calm weather conditions, mechanical recovery may have a potential close to release assuming film thicknesses > 0.1-0.2 mm. However, the remaining oil/residue on the sea surface has low viscosities around 10 mPa.s (negligible emulsification) and low pour point (no solidification). Visund Sør is therefore assumed to have limited efficiency and low efficacy for containment for mechanical recovery due to considerable boom leakage with a limit of 1000 mPa.s

**Visund**

The emulsion viscosities of Visund are shown in Figure 6-7 at 5 and 15 °C. For example, the emulsion viscosity exceeds 1000 mPa.s after 6 hours at 10 m/s wind speed but may be stretched to about 12 hours in calm wind conditions (2 m/s), at both temperatures. Visund has a wide window of opportunity for traditional weir-skimmer head due to viscosities < 20 000 mPa.s after 5 days of weathering at summer and winter conditions.
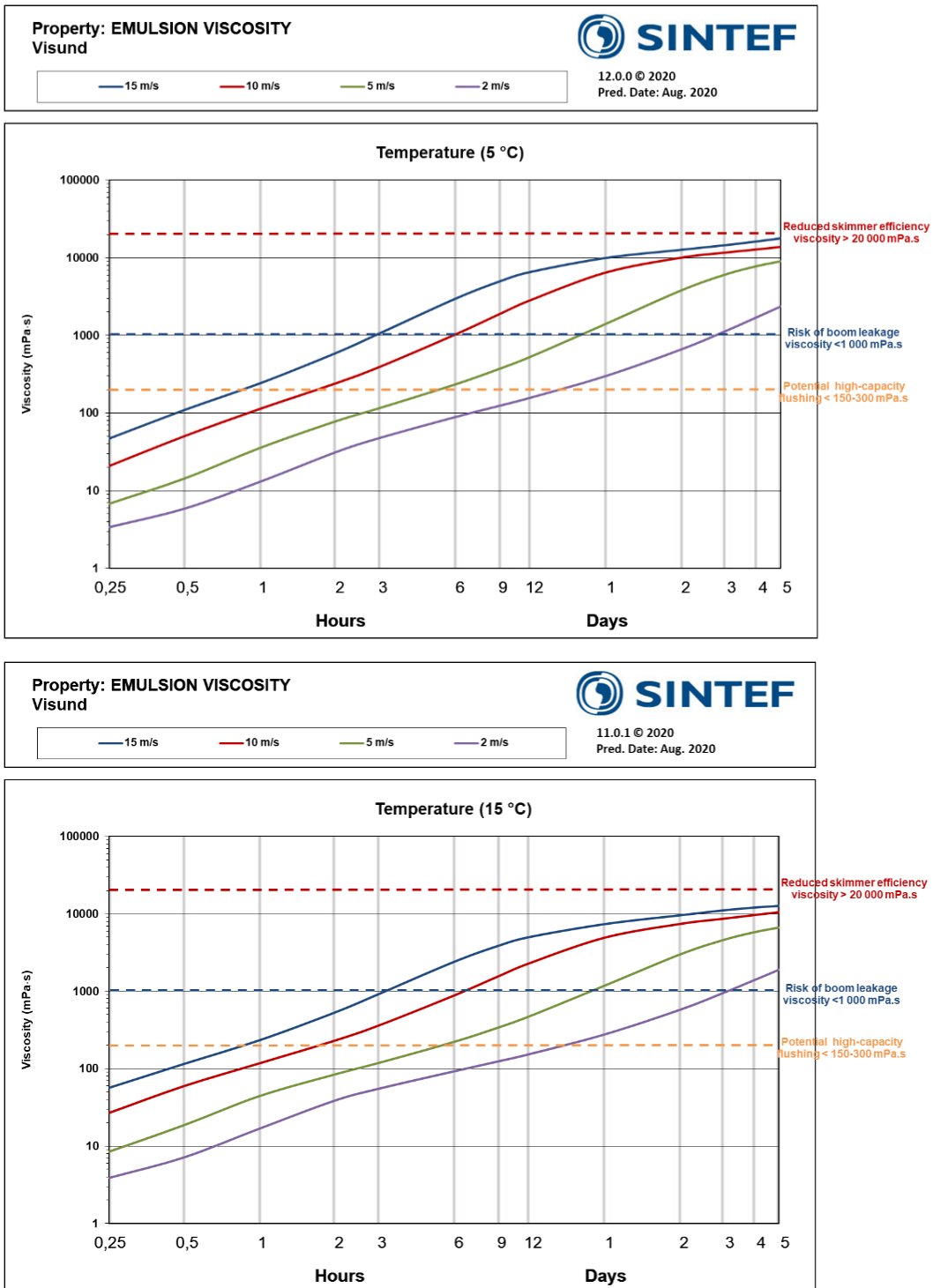




*Figure 6-7*        *Expected time window for effective use of booms and skimmers and high-capacity water flushing (see chapter 6.8) as a function of emulsion viscosity of Visund at 5 and 15 ºC*

## 6.7 Chemical dispersion

**Visund Sør**

Dispersibility testing on Visund Sør was not conducted in agreement with Equinor. High degree of natural dispersion and evaporative loss indicate that the lifetime at sea is short for Visund Sør, particularly in high wind speeds (breaking waves > 5 m/s). Use of dispersants could reduce the lifetime at sea in non-breaking waves conditions (< 5 m/s). In a spill operation (batch release) the use of dispersants may have a potential assuming that the thickness is higher than 0.1 mm to enhance natural dispersion. However, it is expected low efficiency potential for low film thicknesses, as the dispersant droplets may fall through the oil phase into the sea water. In addition, applying dispersants assuming a very thin oil film < 0.05-0.1 mm is not normally recommended due to high degree of herding.

**Visund**

Visund has a potential for use of oil spill dispersant from aircraft and /or vessel . The window of opportunity for use of dispersant Dasic NS is presented in Figure 6-8. The viscosity limit for effective dispersant use was estimated to 2000 mPa.s in the laboratory (low energy IFP-test). The viscosity limit for when the emulsified oil is not considered to be dispersible was not reach by use of the high energy MNS-test but was estimated to 7000 mPa.s

Visund has reduced dispersibility for viscosities between 2000-7000 mPa.s after 1.5 to 4-5 days hours at 5 m/s wind speed at 5 and 15 °C (Figure 6-8). In cases were the oil (emulsion) is expected to be reduced dispersible, an additional energy or use of a higher dispersant dosage and/or repeated dispersant application is recommended to possible enhance the dispersant efficiency. Providing additional energy through use of Fi-Fi systems, thrusters or MOB boats after dispersant application may increase the dispersion rate in calm weather conditions. Moreover, the oil /emulsion is poorly dispersible after 12 hours  to 1-day at 15 m/s but has a considerably longer time window in lower wind speeds.

In cases when  high viscosity of the spilled oil is not a limiting factor, high pour point may cause solidification (elastic properties) at sea. Solidification typically arises at 5-15 °C above the sea temperature.  High pour points could reduce the dispersant effectiveness, where the dispersant droplets have a reduced ability to diffuse into the oil and may appear as droplets on the surface of the solidified wax and be washed of by wave activity. In certain weather conditions, e.g. in very calm wind, the low emulsification rate may enhance formation of solidified lumps, particularly at 5 °C. In a spill situation, the use of a simplified dispersibility testing kit is therefore recommended to assess the potential for chemical dispersion.
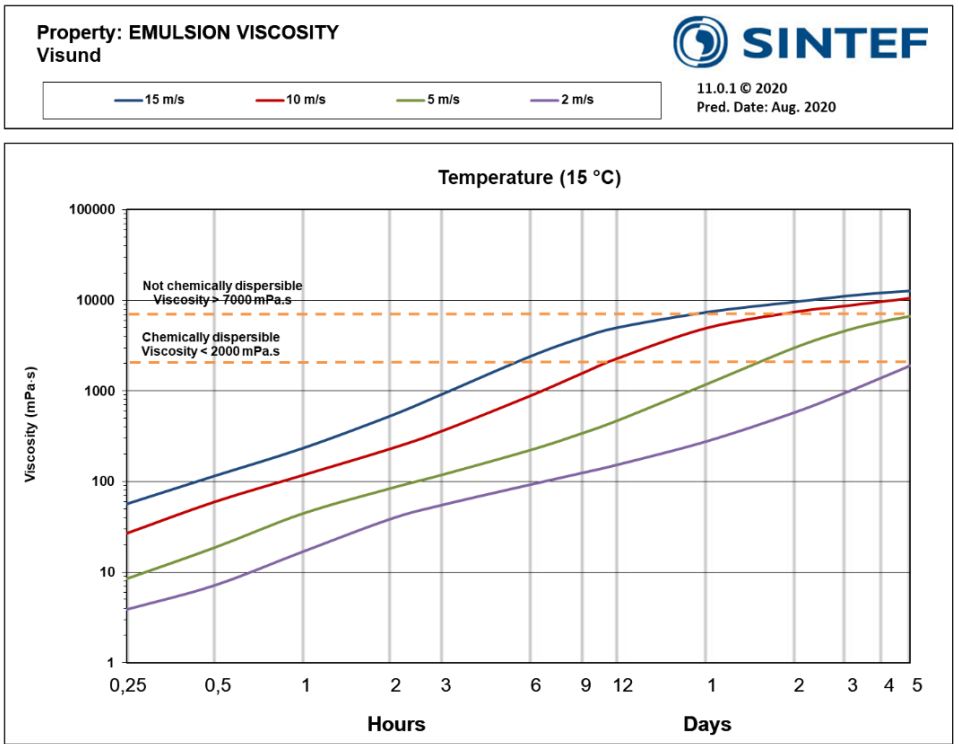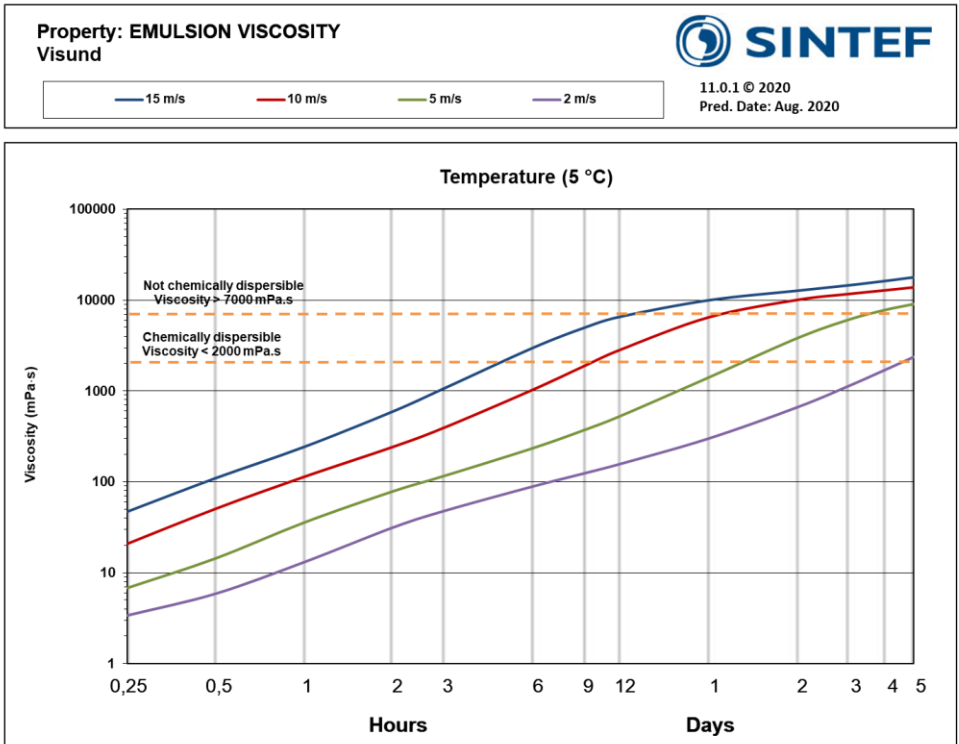
*Figure 6-8      Expected time window for effective use of dispersants as a function of emulsion viscosity of Visund at 5 and 15 °C*

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## 6.8 Mechanical dispersion by high-capacity water flushing

In general, mechanical dispersion by high-capacity water flushing could have a potential for oil spill with thin (initial) film thickness up to 0.2 - 0.3 mm and viscosities < 150 - 300 mPa.s. In such cases, water flushing from high-capacity water flush boom and/or firefighting (Fi-Fi) systems could possibly break up the oil/residue into smaller droplets and enhance the dispersion into the water column. Water flushing could also be used in combination with application of dispersant in calm weather condition to enhance dispersant efficiency with use of artificial energy. This technology was tested in a full-scale trial (NOFO Oil-on-Water trial) in 2016 and described by Daling et al., 2017 and Sørheim et al., 2017 but is not implemented as a part of the oil spill response in Norway, today.

**Visund Sør**: Water flushing could be an option after some hours from a batch release when the condensate has spread on the surface and produce thin films < 0.2 - 0.3 mm (see Figure 6-5 ). The low viscosities of Visund Sør is not a limited factor for mechanical dispersion.

**Visund**: Mechanical dispersion by water flushing is not considered as a main strategy for the oil spill response due to the formation of high emulsion film thicknesses (Figure 6-6) by emulsification, even the oil has low emulsion viscosities in the very early stage after an oil spill, as shown in Figure 6-7. Emulsification of Visund is the limiting factor for this strategy in a surface oil spill.

## 6.9 Summary recommendation of response options

**Visund Sør**

Visund Sør is a light condensate that will not form stable water-in-oil (w/o) emulsions if spilled at sea. The condensate will have a high degree of evaporation and spreading on the sea surface that has a potential to reach low thin film thicknesses (≤50 µm). Due to high wind speeds (breaking waves, 10-15 m/s) the condensate will easily be dispersed into to the water column within few hours. In lower wind speeds (non-breaking waves, 2-5 m/s) natural dispersion will be slower. However, the viscosity will be low for any remaining oil/residue on the sea surface, and low pour points will not cause the oil/residue to solidify.

- Mechanical recovery:
  - The viscosity is low even at some days on the sea surface, and it is considered as too low for efficient confinement in a booming operation and pose a risk for boom leakage
  - Mechanical recovery may have a potential close to release assuming film thickness > 0.1-0.2 mm in calm weather conditions
- Use of chemical dispersant:
  - Film thicknesses < 0.1 mm is too low for effective dispersant treatment
  - For a surface (batch) release dispersant may be possible in a very early phase in calm weather conditions if the thickness > 0.1 mm
- High-capacity water flushing (mechanical dispersion):
  - The predicted viscosities are well below 150-300 mPa.s which is the estimated upper limit for treatment of high-capacity water flushing
  - The predicted film thickness is below 0.2-0.3 mm after some hours which is the upper limit for effective use of water flushing
  - Water flushing is therefore a possible option to be considered for the remaining oil/residue after some hours in calm weather conditions
  - Combination of high-capacity water flushing and dispersant application in cases of film thicknesses > 0.3 mm
- Monitoring and remote sensing:
  - Short lifetime at sea is expected in increasing wind speeds (> 5 m/s) and monitoring and remote sensing may be evaluated as a satisfactory practical "response" option

**Visund**

Visund Sør is a low-density crude oil that forms stable water-in-oil (w/o) emulsions if spilled at sea. The emulsion thicknesses are not considered as a limiting factor for either mechanical recovery or chemical dispersion from a surface release. The response strategies could be applied separately, or a combined response strategy of chemical dispersion and mechanical recovery could be beneficial. Visund has a potential for solidification at sea due to high pour points of the water free residues, and in such cases the dispersant effectiveness is likely reduced.

- Mechanical recovery:
  - Wide window of opportunity for mechanical recovery with use of skimmers, such as the Transrec equipped with traditional weir-skimmer head for emulsion viscosities < 20 000 mPa.s
  - Boom leakage and reduced recovery is expected for viscosities < 1000 mPa.s
- Use of chemical dispersant:
  - Visund is found to be easily dispersible adding the dispersant Dasic NS for viscosities < 2000 mPa.s (DOR 1:25) and estimated not/poorly dispersible for viscosities > 7000 mPa.s.
  - In the field, additional energy or higher DOR and/or repeated dispersant application may increase dispersant effectiveness when viscosities are between 2000 mPa.s and 7000 mPa.s
- High-capacity water flushing (mechanical dispersion):
  - The emulsification is the limiting factor for this strategy in a surface oil spill
  - The predicted film thickness is > 0.2-0.3 mm which is the estimated upper limit for effective use of water flushing
  - Water flushing is  therefore not  a preferable response option for Visund
- Monitoring and remote sensing:
  - Monitoring and remote sensing should be used a support in a response operations also for Visund

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## A  The behaviour of oil on the sea surface

### A.1  The chemical composition of crude oils and condensates

Crude oil is a complex mixture of thousands of chemical components. The relative compositions vary, giving rise to crude oils with different chemical and physical properties. The components found in crude oil are classified into two main chemical groups: hydrocarbons and non-hydrocarbons see Figure A-1
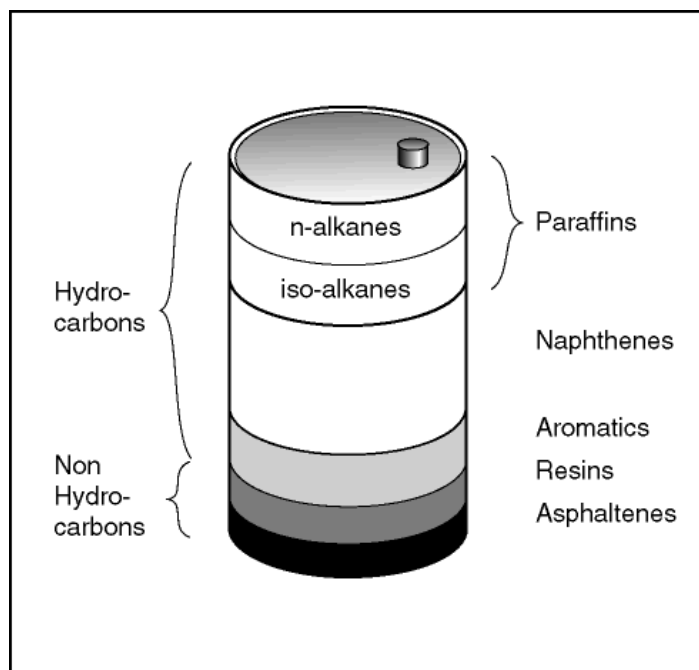


*Figure A-1        The chemical composition of crude oils*

### A.1.1  Hydrocarbons

Most compounds in crude oils are hydrocarbons, which are composed of hydrogen (10-15 wt. %) and carbon (85-90 wt. %). These range from simple, volatile gases, such as methane with only one carbon atom to large, complex molecules with more than 100 carbon atoms. The hydrocarbons in crude oils include saturated and unsaturated molecules in linear, branched and cyclic configurations. Hydrocarbons are further classified into aliphatic and aromatic compounds. The two main groups of aliphatic compounds are paraffins and naphthenes.

**Paraffins**

Paraffins include *n*-alkane and *iso*-alkane aliphatic compounds. Waxes are an important subgroup of paraffins, containing more than 20 carbon atoms. The wax components of a crude oil will be present in a solution at elevated temperatures. At low temperatures, they may precipitate from the solution. These are principally n-alkanes. The wax content of crude oils can vary from 0.5 wt.% up to 40 or 50 wt.% in extreme cases, although the majority of the world's crude oils have a wax content of 2-15 wt.%.

**Naphthenes**

This group includes cycloalkanes containing one or more saturated rings. Each ring may have one or more paraffinic side chains, which are chiefly five- and six-membered rings.

**Aromatics**

Aromatics are a specific type of unsaturated cyclic hydrocarbons. Benzene, toluene and xylenes are examples of mono-ring aromatics, naphthalenes are di-ring aromatics and polycyclic aromatic hydrocarbons (PAH) contain three or more aromatic rings.

## A.1.2 Non-hydrocarbons

In addition, hydrogen and carbon, some organic compounds in crude oils also contain small amounts of oxygen, nitrogen or sulphur, as well as some trace metals such as vanadium and nickel. These compounds are referred to as heteroatom organic compounds because they contain a heteroatom, which is any atom that is not carbon or hydrogen. The two most important groups of heteroatom organic compounds are resins and asphaltenes.

**Resins**

Compared to the hydrocarbons, resins are relatively polar and often have surface-active properties. Resins have molecular weights ranging from 700-1000. Carboxylic acids (naphthenic acids), sulphoxides and phenol-like compounds can be found in this group as well.

**Asphaltenes**

Asphaltenes are is a complex group of poorly characterized chemical compounds that consist of condensed polycyclic aromatic compounds. They are large molecules with 6-20 aromatic rings and side chains (molecular weight 1,000-10,000). Asphaltenes may be classified as "hard" or "soft" based on the method of determination. Crude oils may contain up to 6 wt. % "hard" and 10 wt. % "soft" asphaltenes (Peregrino:13.4 wt.%)

## A.2 Main oil categories – Related to weathering

Different oil types can have extremely different compositions, which impact their physical properties and effect their behaviour after a spill at sea.
Oils that are subject to weathering can roughly be divided into 3 main categories:
- Crude oils
- Light oils
- Condensates

**Crude oils** contain relatively more of the heavier components than light oils or condensates. Crude oils can be weathered in the laboratory to mimic natural weathering that occurs on the sea surface. The laboratory weathered crude oil identified as 250˚C+ residue, corresponds to 0.5 to 1 week after a spill at sea, and contains less than 50% of its original volume due to evaporation. The heavier components allow the formation of stable water-in-oil (w/o) emulsions, which reduces oil spreading at the sea surface. The final (terminal) film thickness of a crude oil depends on the emulsion's physical properties, and will be in the order of 1 mm.

**Light oils** and crude oils are not specifically differentiated in reservoir terminology. However, it is suitable to deal with the light oils as a separate category when referencing weathering properties. Light oils have a high content of low molecular weight hydrocarbons. When subjected to laboratory weathering, the 250˚C+ residue of light oils may lose 50-70% of their total volume due to evaporation. In contrast to condensates, which only contain light components, light oils contain a mixture of light and heavy components. These heavy components may cause light crudes to emulsify in water, but these w/o emulsions are, however, very unstable. A light oil will spread less than a condensate, with a final film thickness of approximately 0.5 mm.

**Condensates** only contain low molecular weight hydrocarbons and are considered extremely volatile. Laboratory weathered condensates, such as the 250˚C+ residue, typically lose more than 70% of their initial volume. Condensates do not contain components such as asphaltenes or heavier waxes and will not emulsify significant amounts of water. The spreading of condensates is relatively fast, and can result in a final film thickness of approximately 0.05 mm.

## A.3 Physical properties of crude oils

The physical properties of specific oils are a result of their chemical composition. The most important physical properties in oil spill scenarios are discussed below.

**Density**

The density of a crude oil is dependent on the density of all of its components. The density of hydrocarbons increases with increasing molecular weight. Furthermore, paraffinic oils have lower density than those containing larger amounts of high molecular weight aromatics, such as naphthenic and asphaltenic oils. Specific gravity is defined as the oil density at 60°F (15.5°C) divided by water density at 60°F. In American literature, the density of the oil is often expressed as °API, where:

$$°\text{API} = \frac{141.5}{Secific\ gravity} - 131.5$$

In the present study, the density of the oil is presented as specific gravity.
The density of fresh crude oils normally lies in the range 0.78 to 0.95 g/mL (50 to 10 °API).

## A.3.1 Rheological properties

The viscosity of crude oils expresses its resistance to flow and is of special interest when pumping oil. **Absolute viscosity** also known as dynamic viscosity) is a measure of internal resistance. In the SI system, absolute viscosity has units of N s/m$^2$, Pa s or kg/(m s), where 1 Pa s = 1 N s/m$^2$ = 1 kg/(m s). Absolute viscosity can also be expressed in the metric CGS (centimeter-gram-second) system as g/ (cm s), dyne s/cm$^2$ or Poise, where 1 Poise = 1 dyne s/cm$^2$ = 1 g/(cm s) = 1/10 Pa s = 1/10 N s/m$^2$. https://www.engineeringtoolbox.com/dynamic-absolute-kinematic-viscosity-d_412.htmlThe industry often uses centipoise, as the *Poise* is normally too large, 1 Poise = 100 cP and 1 cP = 0.001 N s/m$^2$. The viscosity of fresh crude oils can vary from less than 1 to more than 2000 mPa.s (cP) at ambient sea temperature. In comparison, water has an "absolute" viscosity of 1 cP and syrup's is 120 000 cP at 20°C.

**Kinematic viscosity** is absolute viscosity divided by density. 1 centistoke (cSt) = 1 cP / density. Because the density of weathered oils and emulsion are typically 0.9 – 1 g/mL, the units cSt and cP will often have similar values. Viscosity is temperature dependent. For liquids, the viscosity decreases with increasing temperatures. Viscous and waxy crude oils can exhibit non-Newtonian behaviour (viscosity varies with shear rate), especially close to, or below, their pour point. Water-in-oil (w/o) emulsions exhibits this non-Newtonian behaviour with shear thinning. In an oil spill situation, an emulsion may be liquid under turbulent conditions at sea, but can become much more viscous, or even semi-solid in calmer water conditions, or on beaches. Thus, the measurements of the viscosity of w/o-emulsions must be carried out under strictly controlled conditions (defined shear rates and thermal and mechanical history of the sample). At SINTEF, a shear rate of 10 s$^{-1}$ is routinely used for expressing viscosity data on w/o-emulsions.

The viscosity of an oil increases with evaporation since the heavier, more viscous components remain in the residue (Mackay et al., 1982). The difference in viscosity for crude oils is approximately 3 to 2000 mPa.s for fresh crude oils and several hundred/thousand mPa.s for their residues. Water-in-oil (w/o) emulsions are generally more viscous than the parent crude oil; this is illustrated in Figure A-2.
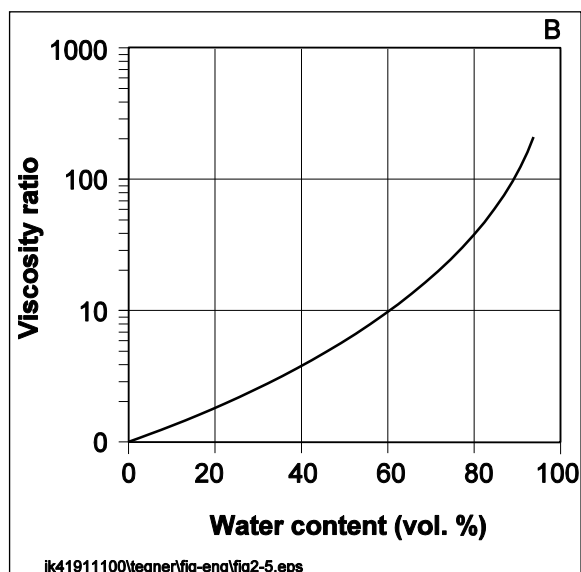
*Figure A-2*       *Example of viscosity ratio as a function of water content*

### A.3.2 Pour point

The temperature at which oil ceases to flow when cooled without disturbance under standardized conditions in the laboratory is defined as the oil's pour point (ASTM-D97). The method accurately determines the temperature at which the oil become semi-solid under the specified laboratory conditions. Due to the movement at the sea surface, the oil may remain a liquid at sea at temperatures as low as *5 to 15ºC lower* than the pour point of the oil. The pour point of oil with high wax content will increase dramatically with evaporation as the lower weight molecules, which contribute to keeping the wax in solution, evaporate. The pour point for oils with high wax contents can reach 30°C, while low viscous naphthenic oils may have pour points as low as - 40°C. In an oil spill clean-up situation, the pour point provides essential information for when determining the efficiency of various skimmers, pumping rates and the use of dispersing agents.

### A.3.3 Distillation curve

The distillation curve, which is obtained by measuring the vapour temperature as a function of the amount of oil distilled, shows the relative distribution of volatile and heavier components in the oil. The boiling point of a chemical component depends on its vapour pressure, which is a function of its molecular weight and chemical structure. Low molecular weight oil components have a higher vapour pressure, thus lower boiling points than higher molecular weight components of a similar type. Aromatic compounds boil at a higher temperature than paraffinic compounds of the same molecular weight, and *iso*-alkanes boil at a lower temperature than the equivalent *n*-alkanes. Hence, the distillation curve is an indicator of the relative amount of different chemical components, principally as a function of molecular weight, but also as determined by the chemical composition.

### A.3.4 Flash point

The flash point is the lowest temperature at which the gas or vapour generated by the heating of oil will form an ignitable mixture in air. The flash point depends on the proportion of low molecular weight components. Fresh crude oils normally have a low flash point (from -40°C to 30°C).From a safety point of view, flash points are most significant at, or slightly above, the maximum temperature that may be encountered in storage or transport. The flash point is an approximate indicator of the relative fire and explosion hazard of oil.

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> ***Rule of thumb:***
> *In the presence of an oil slick at sea, a fire and/or explosion hazard exists when the oil's flash point is close to or lower than the sea temperature.*

Natural weathering processes such as evaporation and emulsion formation contribute to reducing the potential hazard by increasing the flash point. Thus, it will be a relatively short fire and/or explosion danger in the initial stages of oil spill.In the laboratory, the flash point is measured in a closed system with the components in the oil and gas equilibrated. In the field, however, the weather situation will influence the flammability of the air above the slick. The gas concentration will be high just above the oil film in calm weather and high temperatures, whereas the concentration will be low in cold and windy weather due to dilution and transport and a lower degree of evaporation.

## A.4  The behaviour of crude oil spilled at sea

This chapter gives a general description of the main weathering processes when oil is spilled at sea. There are many natural processes take place that change the volume and chemical properties of the oil. These natural processes are evaporation, water-in-oil (w/o) emulsification, oil-in-water (o/w) dispersion, spreading, sedimentation, oxidation and biodegradation. A common term for all these natural processes is weathering. The relative contribution of each process varies during the duration of the spill. The weathering of oil depends on the oil type (chemical and physical properties), the weather conditions (wind, waves, temperature and sunlight) and the properties of the seawater (salinity, temperature, bacterial flora, etc.).*Figure A-1* Figure A-3 illustrates the various weathering processes, and Figure A-4 shows their relative importance over time.
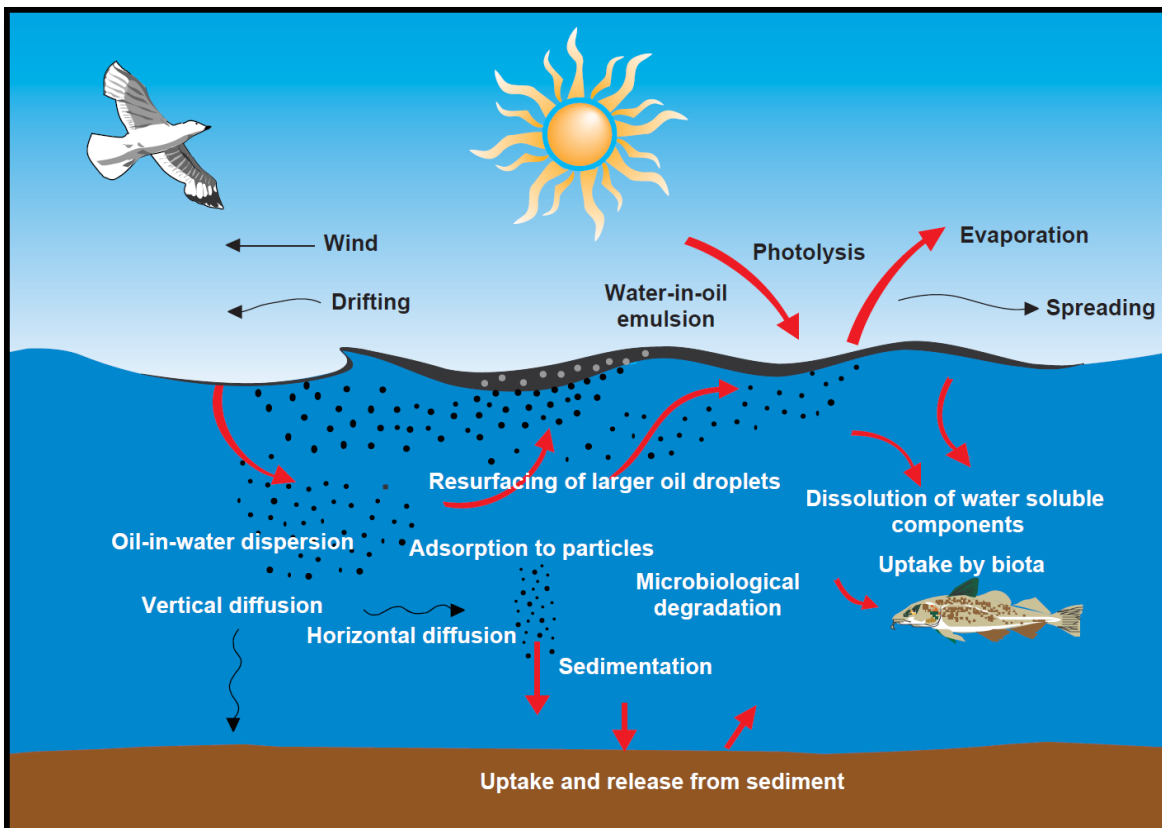


*Figure A-1        Illustrating the weathering processes that take place when oil is spilled on the sea surface*
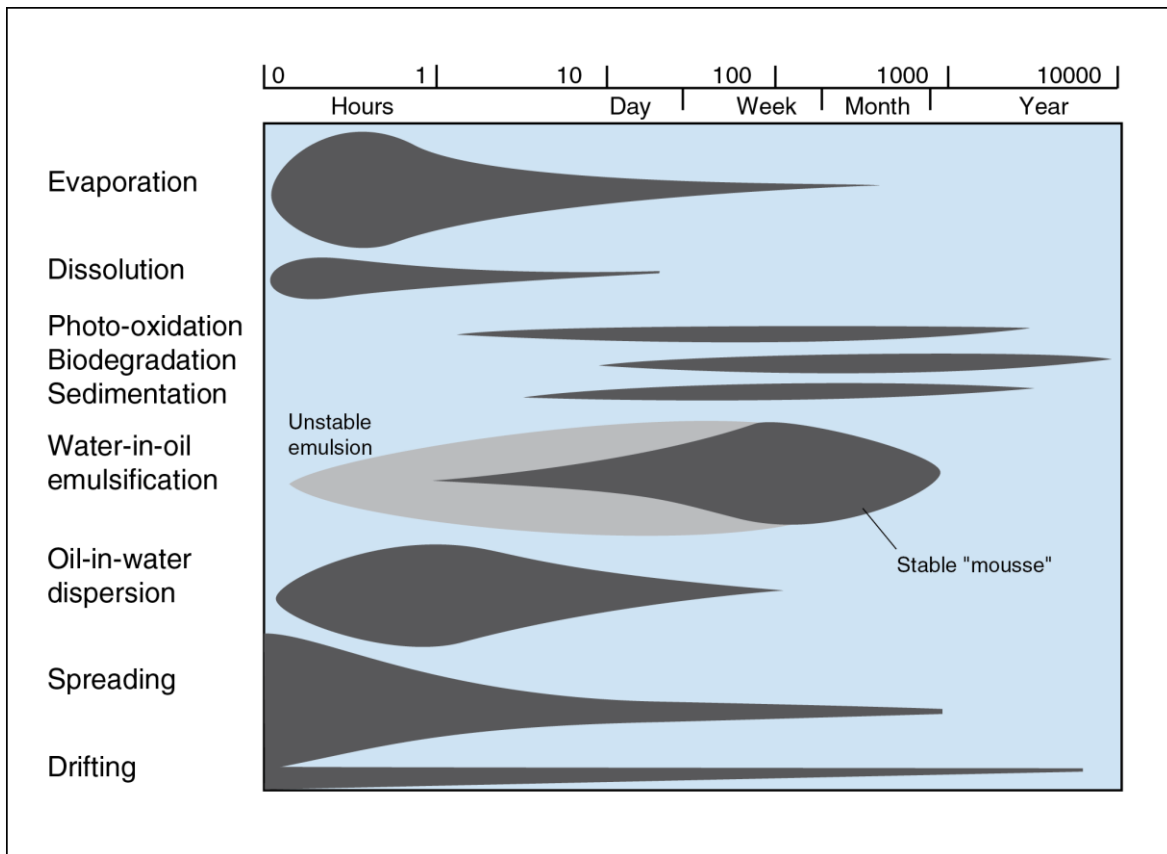
*Figure A-4       Weathering processes' relative importance over time. Note: logarithmic scale*

## A.4.1 Evaporation

Evaporation is one of the natural processes that support the removal of spilled oil from the sea surface. The evaporation process starts immediately after the oil is spilled, and the evaporation rate decreases exponentially throughout the duration of the oil spill. The evaporated amount depends on the chemical composition of the oil in addition to the prevailing weather conditions, sea temperature and oil film thickness.

The rate of evaporation varies for different oil types. Light refinery products (e.g. gasoline and kerosene) may completely evaporate after a few hours/days on the sea surface. Condensates and lighter crude oils can lose 50% or more of their original volume during the first days after an oil spill. The most significant difference caused by evaporation is the loss of volatile and semi-volatile compounds, which increases the relative amounts of higher molecular weight compounds. With evaporations, the chemical and physical properties of the remaining oil will change. The density, viscosity, pour point and wax and asphaltene content, will all increase with increased evaporation.

## A.4.2 Spreading

Oil spilled at sea will spread on the sea surface. Spreading is often the dominant process in the initial stages of an oil spill and decreases as the viscosity and density of the remaining oil increases. The spreading process is also reduced if the oil's pour point is 5-15°C below the sea temperature.

Oceanographic conditions (e.g. wind, waves and currents) affect the spreading process. The oil slick will be broken into "wind rows" aligned in the direction of the wind, see Figure A-5. The thickness of the oil slick varies, often differing by a factor of several thousand. Experience has shown that most of the total oil slick area consists of a thin film (<1 μm oil thickness) that only contains 10% of the oil volume. Most of the oil

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volume (~90%) is in small patches of w/o emulsions with a film thickness of 1 to 5 mm, which often constitutes less than 10% of the total oil slick area.
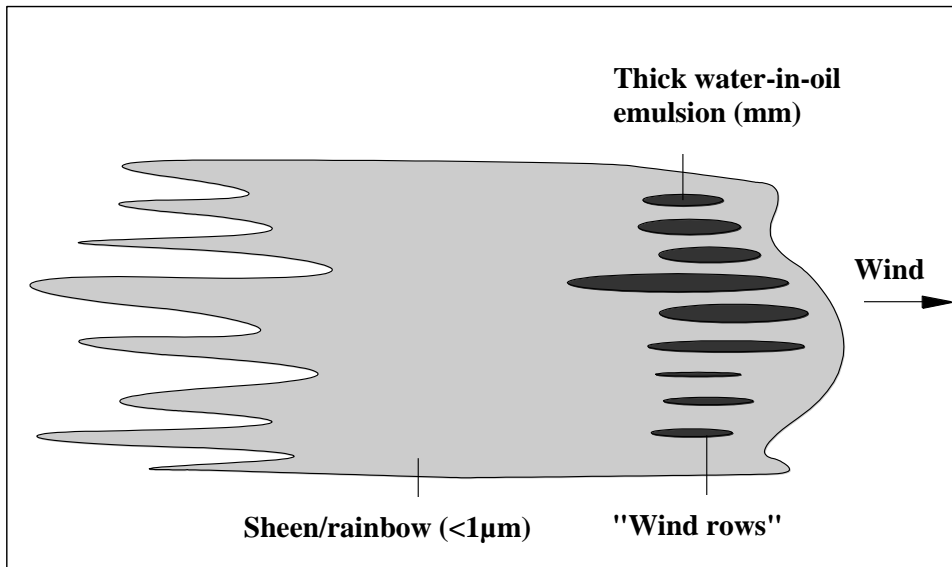


*Figure A-2      The spreading of oil spilled on the sea surface and the distribution within the oil slick*

## A.4.3  Drift of an oil slick

The oil slick will drift as the weathering processes continue. The wind and current conditions cause the oil slick to drift, as illustrated in Figure A-6. Waves and wind create a current in the mass of water which amounts to approximately 3% of the wind speed at the sea surface. The influence of the wind decreases rapidly with the depth of the water below the surface. At 1 to 2 meters the current reduces to approximately 1% of the wind speed. This means that oil on the surface of the open sea, will move faster than the water below (e.g. Reed and Turner, 1991; Reed et al., 1994). In the absence of wind, the oil drift is governed by the prevailing (background) current.
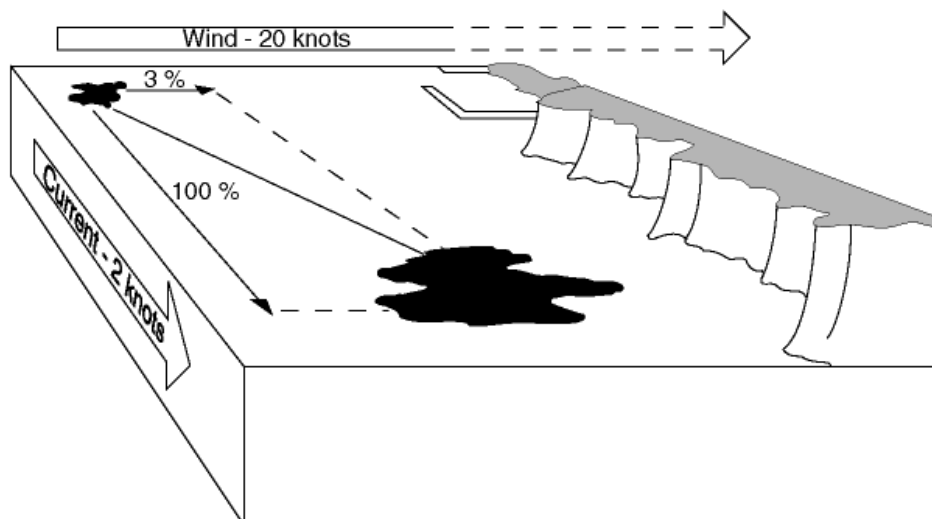


*Figure A-6      An illustration showing how wind and current can influence the drifting of an oil slick*

## A.4.4  Water-in-oil (w/o) emulsion

The formation of water-in-oil emulsions significantly affects the behaviour and clean-up of oil spilled at sea. Because of emulsification, the total emulsion volume may increase to as much as six times the original spilled oil volume depending on the properties of the oil. The formation of w/o emulsions also contributes to keeping

oil on the sea surface. A w/o emulsion normally has a higher viscosity than the parent crude oil, so the emulsification process will therefore retard/delay evaporation and the natural dispersion process.

The minimum criterion for the formation of w/o emulsions is the presence of breaking waves (i.e. a wind speed of >5 m/s). Nonetheless, a slow water uptake can also take place during calmer weather. Figure A-7 shows how wind speed influences the w/o formation rate.

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

The maximum water uptake will vary for different crude oils. Tests performed at SINTEF have revealed that the maximum water uptake is independent of the prevailing weather conditions if the lower energy barrier for the formation of w/o emulsions is exceeded. The rate, however, depends highly on the weather conditions. In the laboratory, the $t_{1/2}$-value is determined, which is the time in hours it takes before the oil has emulsified half of its maximum water content. The w/o emulsion formation rate depends on the oil's chemical composition, which varies for different oil types.
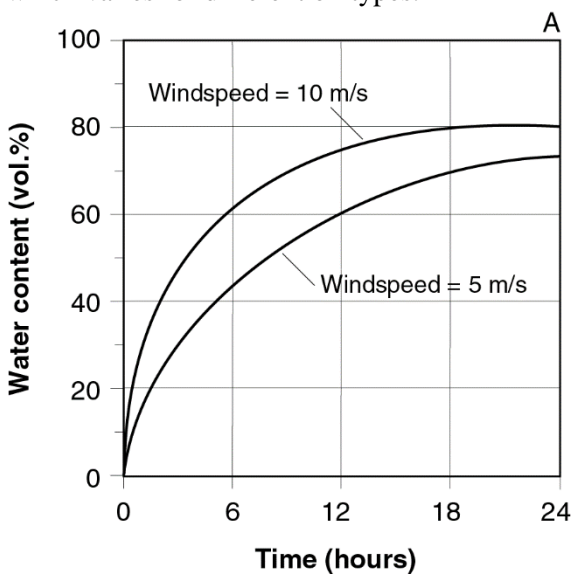


*Figure A-7        Example of how weather conditions influence the w/o emulsion formation for typical oils*

The stability of the w/o emulsion depends on the water droplet size, since not all water droplets in the emulsion are stable. Larger water droplets may be reduced in size by the flexing, stretching and compressing motion of the slick due to wave action, whereas the largest droplets may coalesce and be squeezed out of the w/o emulsion. After a certain period, the emulsion may only contain small water droplets with diameters of 1 to 10 μm, yielding a more stable emulsion.
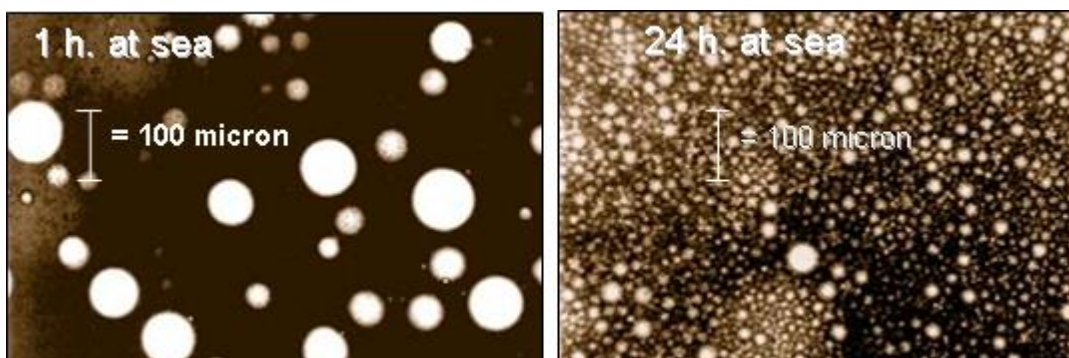


*Figure A-3        Microscope pictures of w/o emulsion after (A) 1 h. and (B) 24 h. in a rotating cylinder*

Thus, the formation of emulsions is the result of water retention by oil as an effect of both viscous and interfacial forces. The interfacial forces are the most important, and asphaltenes are largely responsible for this. Resins are similar compounds to asphaltenes and can stabilize an emulsion, but not to the same extent.

Resins and asphaltenes have both hydrophobic and hydrophilic properties and will concentrate at the interface between the water and oil, thereby forming a layer that stabilizes the water droplets. The hydrophobic properties can lead to the concentration of wax along the water droplets, which further stabilizes the interfacial "skin" layer. The interfacial layer between the oil and water forms a physical barrier that hinders the coalescence of the water droplets and will stabilize the w/o emulsion. The stabilization of the water droplets by asphaltenes and wax is shown in Figure A-9.
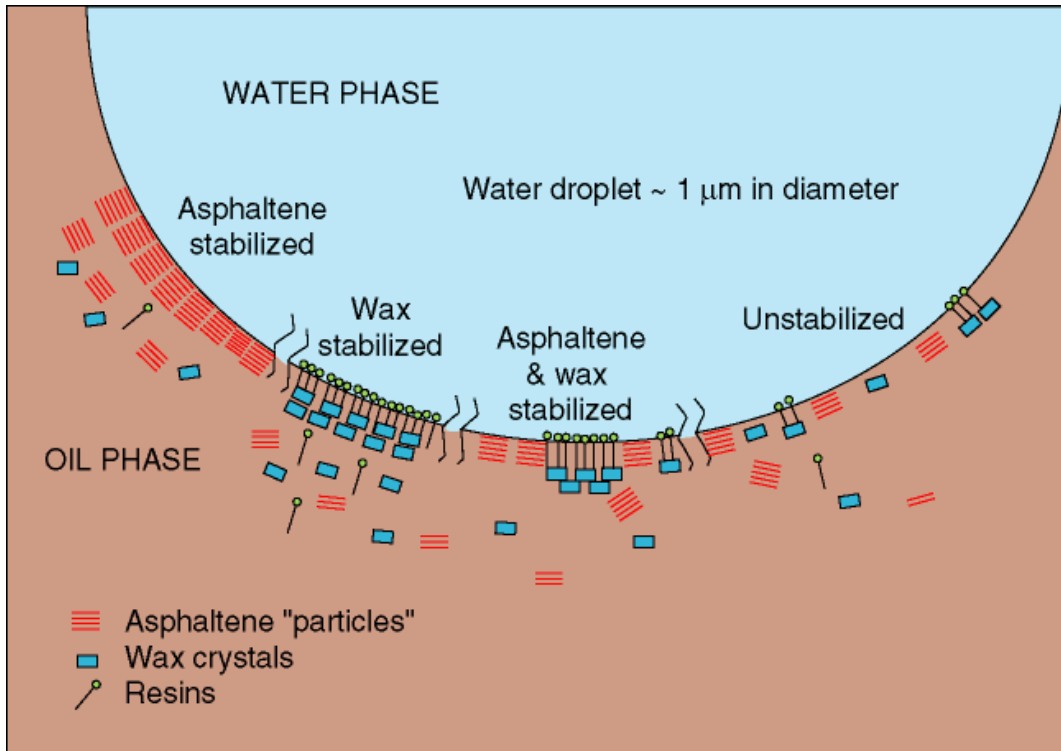


*Figure A-4        Interfacial layer stabilized by wax and asphaltenes in w/o emulsion*

Oils that contain large amounts of wax and small amounts of asphaltenes can form w/o emulsions stabilized by a continuous phase's rheological strength (viscosity and elasticity) due to wax structure formed by precipitated wax. Wax stabilized emulsions are characterized by large water droplets and are fairly stable when stored, although they may break down when stress is applied and/or when the emulsion is heated to, e.g. 40-50°C.

Crude oil and sea water interfacial tension (IFT) plays a key role in the process of oil droplet formation. The need to understand and control droplet formation in dispersant system is extremely important. Addition of dispersants reduces the interfacial tension between oil and water that subsequently promotes the formation of a larger number of small oil droplets when surface waves entrain oil into the water column. These small submerged oil droplets are then subject to transport by subsurface currents and other natural removal processes, such as dissolution, volatilization from the water surface, biodegradation, and sedimentation resulting from interactions with suspended particulate material.

## A.4.5  Oil-in-water (o/w) dispersion

Natural oil-in-water (o/w) dispersion will take place if there is sufficient energy on the sea surface, i.e. if there are breaking waves present. The waves will break the slick into small oil droplets (~1 µm - 1 mm in diameter), which are then mixed into the upper water column. The largest oil droplets will resurface and form a thin oil

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film (typically <50 µm). This thin oil film will be rapidly dispersed again by breaking waves as smaller droplets into the water column and will be available for rapid biodegradation.

The natural dispersion rate depends highly on oil type and can be one of the main processes that determine the lifetime of an oil slick on the sea surface. Natural o/w dispersion will gradually decrease with time since the evaporation of the lighter compounds will increase the viscosity of the remaining oil.

The purpose of applying chemical dispersing agents is to increase, or enhance, the natural dispersion rate. Dispersants reduces the interfacial tension between water and oil and thus promote natural o/w dispersion. When effective chemical dispersion is achieved, small oil droplets are formed, with typical diameters ranging from 5 to 100 µm. These are retained in the upper layers of the water column by the prevailing turbulence of wave action.

## A.4.6 Water solubility

The water solubility of saturated hydrocarbons is generally very low, while lower molecular weight aromatic compounds are water-soluble to some extent; particularly aromatics, such as BTEX, 2-ring PAH and paraffin's up to $C_7$) have a potential to be dissolved in the water column (McAuliffe, 1987). Within the various types of hydrocarbons, the water solubility decreases from aromatics to naphthenes and from *iso*-alkanes to *n*-alkanes. In each series, the water solubility decreases with *increasing* molecular weight.

Evaporation and the release of oil components into the water mass are competitive processes since most of the water-soluble components are also volatile. The evaporation process is approximately 10 to 100 times faster than the release in the water column. The concentration of soluble oil components into the water column during an oil spill is quite low (< 1 mg/L), while the dissolution of oil components into the water column does not contribute to removing the oil from the sea surface. However, the water-soluble fraction is of great interest since it has a high bioavailability and thus the potential to cause acute toxic effects on marine organisms.

## A.4.7 Photo-oxidation

Under the influence of sunlight, some of the oil components will slowly oxidize to resins and finally asphaltenes. The photo-oxidized components will stabilize the w/o emulsions and influence the oil's persistence on the sea surface. After a long period of weathering at sea, tar balls (mainly consisting of asphaltenes) may be formed. These tar balls break down very slowly, both at sea and on beaches.

## A.4.8 Biodegradation

Seawater contains an abundance of microorganisms that can break down all types of oil components. Various microorganisms prefer specific oil components as their energy source. Bacteria prefer to degrade oil in contact with water and the rate of biodegradation depends on the water/oil interface area. The interface area increases as the oil is spread over the sea surface in a thin layer or by chemical or natural dispersion of oil into the water column. Important factors influencing the biodegradation rate are temperature, the concentration of available nutrients (i.e. nitrogen and phosphorus), oxygen, oil type and the degree of weathering. Low molecular compounds are degraded more rapidly than the high molecular weight/heavier compounds in the oil, thus giving the following order for biodegradation: straight-chain *n*-alkanes > branched *iso*-alkanes > cyclic alkanes > cyclic naphthenes > aromatics> resins > asphaltenes (Perry, 1984).

At sea, the formation of oil droplets by natural or chemical enhanced dispersion will increase the biodegradation rate in the water mass by 10 to >100 times compared to surface oil due to increased water/oil interfacial area. When immobilised on hydrophobic synthetic fabrics, n-alkanes biodegraded within 2-4 weeks at North Sea conditions (13°C; Brakstad and Løding, 2005). Some small PAHs dissolved in water can be degraded within a few days (Brakstad and Faksness, 2000), but high molecular-weight oil compounds associated with particulate oil biodegrade more slowly and some very high molecular-weight compounds (equivalent to the heavy residues in crude oil that are used to make bitumen) may not biodegrade to any significant degree.

### A.4.9 Sedimentation

Crude oil and oil residues rarely sink into the water mass since there are few oils that have a density higher than water, even after extreme weathering. Oil can sink by sticking to materials present in the water mass. W/o emulsions that have a higher density value (e.g. emulsified bunker fuel oils) can more easily stick to a material, particularly if coming to the shore, and can sink to the bottom if washed out again from the shore. In connection to sub-sea blowout at the sea bottom, it is assumed that some of the oil droplets generated in the plume may adsorb to suspended particles or encounter with the seabed sediment. This can cause some sedimentation of oil droplets to the seabed near the release. It is assumed that sub-sea dispersant treatment will reduce the potential for such sedimentation, due to lower adsorption /stickiness to sediment particles.

### A.4.10 Deep water releases

Size distribution of the oil droplets formed during a subsurface release strongly influences the subsequent fate of the oil in the environment. Large droplets (typically larger than 5 mm) reach the surface after a couple of hours rise time from a depth of approximately 1000 m, while smaller droplets (down to 0.5 mm) may rise for up to a day before they will come to the surface. Fine droplets (below 100 microns) may stay in the water for weeks or even month before they eventually reach the surface. However, factors like vertical turbulence mixing in the water column, density stratification and cross flows will contribute to keep such fine small droplets submerged for even prolonged periods (Johansen et al., 2003). In case of deep-water releases, large droplets (mm range) will usually rise to the surface and form an oil layer with sufficient thickness to emulsify (form water-in-oil emulsions). This is usually caused by loss of buoyancy and more horizontal entrainment of the gas/oil/water plume due to dissolution of gas, possible hydrate formation, cross currents and density layers. However, large droplets (mm range) will leave the entrained plume and rise to the surface, illustrated in Figure A-10. This was observed both during the "DeepSpill" experiments in 2000 (Figure A-11) and the DWH oil spill in 2010 (Figure A-12). This emulsification will be dependent on oil properties and environmental conditions, such as temperature and sea state.
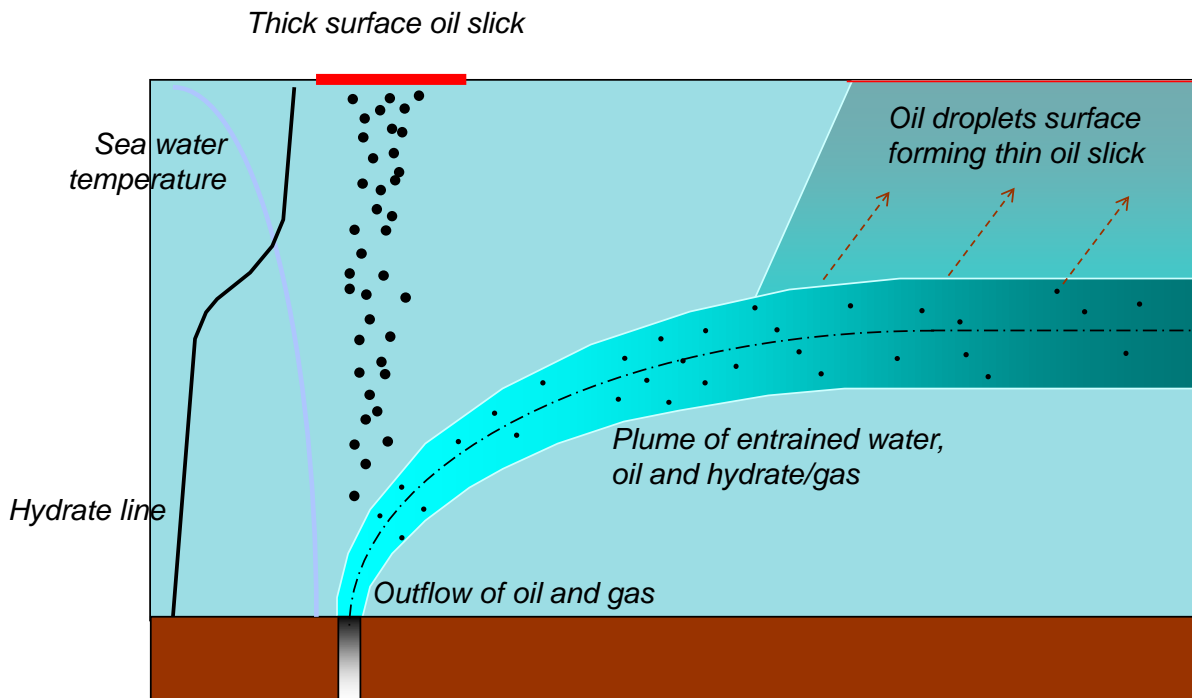


*Figure A-5      Illustration of possible creation of thick surface oil slick (> 200 µm) from deep-water release of oil*

Figure A-6    *Surface oil slick (initial thickness > 200 µm) from the experimental deep-water release "DeepSpill" in 2000. Surface oil is emulsifying like an oil slick from a surface batch release (from Leirvik et al., 2011)*
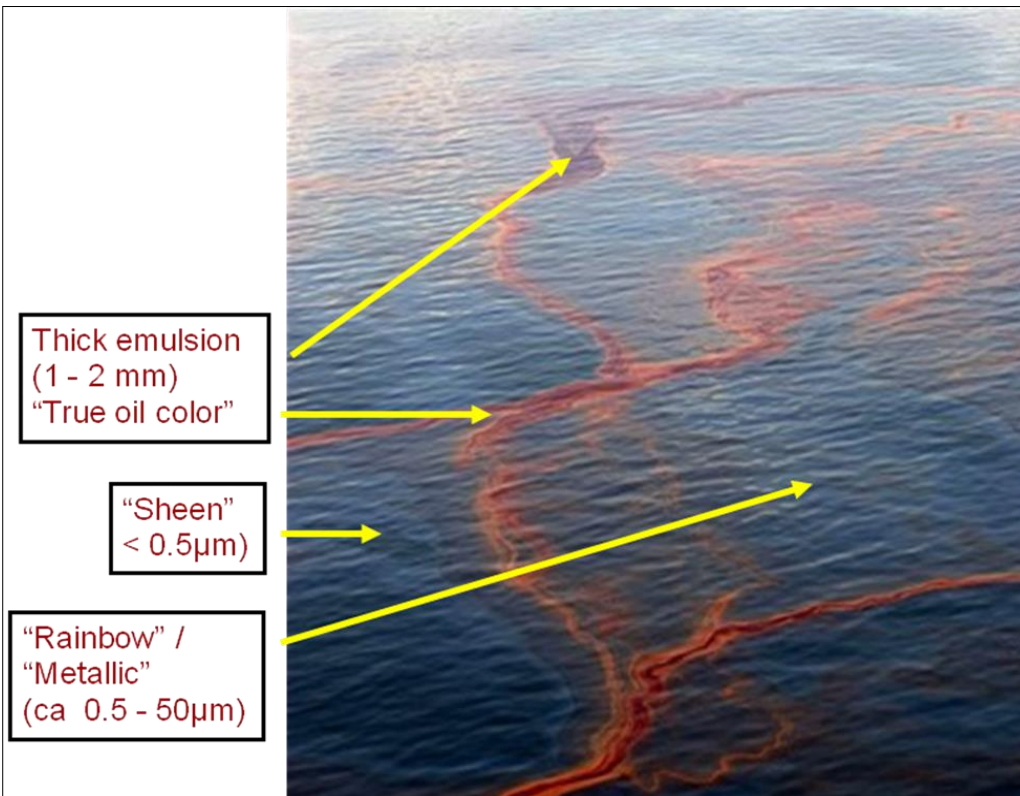


Figure A-7    *Surface oil slick (initial thickness > 200 µm) from the DWH deep-water release. Surface oil is emulsifying like an oil slick from a surface batch release*

## A.4.11 Shallow releases

In case of a sub-surface release of oil and gas in shallower water (<500 meter) the buoyancy of the rising water/gas/oil plume is usually sufficient to reach the surface. The gas will be released to the atmosphere, while the large volumes of water will set up a horizontal current that will create a wide and thin surface oil slick (see Figure A-13 and Figure A-14, Rye et al., 1997). This surface oil slick could be too thin to emulsify (< 200 microns) and evaporation and natural dispersion will be the predominant weathering processes.
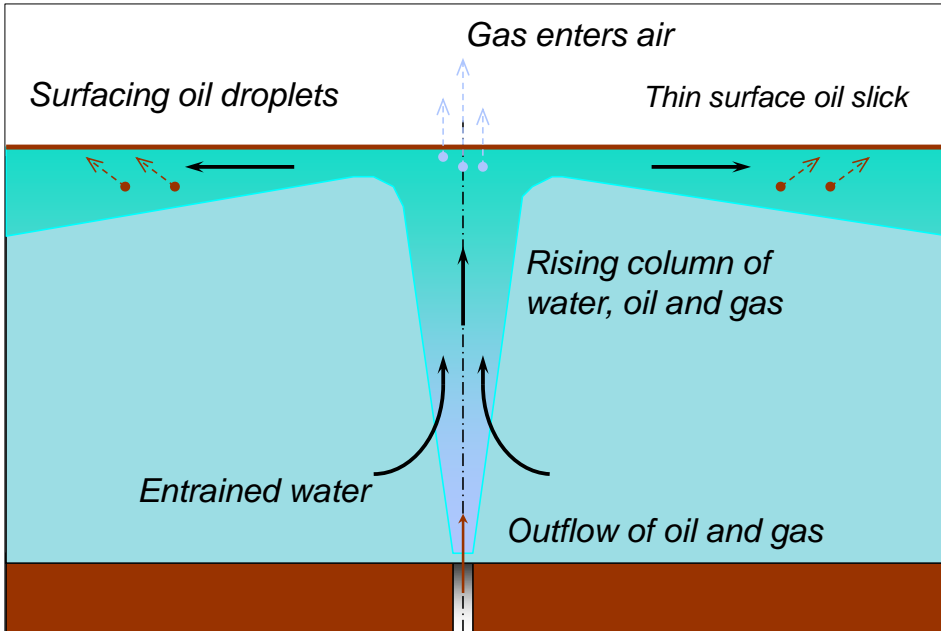


Figure A-8    *Illustration of possible creation of thin surface oil slick (< 200 µm) from a shallow subsurface release (<500 m)*
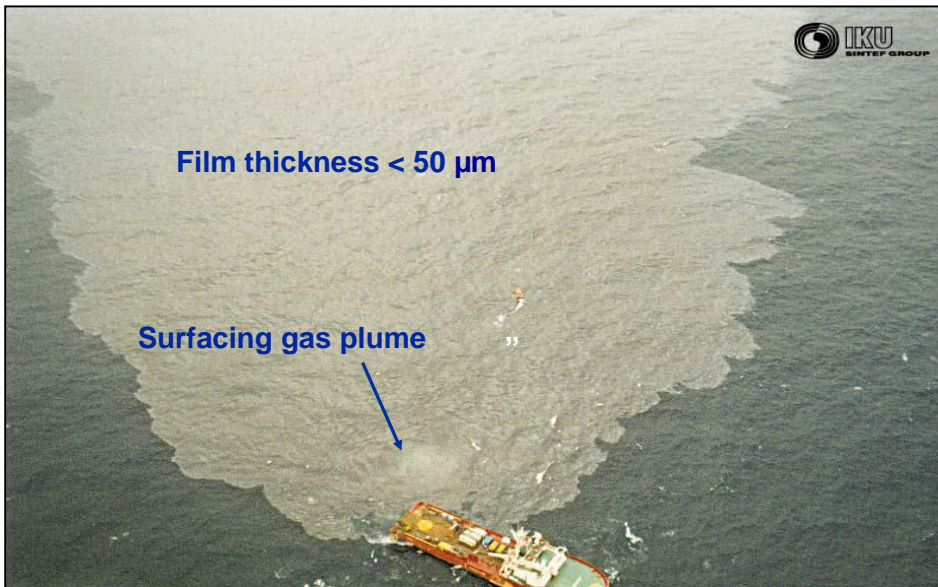


Figure A-9    *Surface oil slick (< 50 µm) from experimental subsurface release at 106 m in 1996. The surface oil did not emulsify and had a very limited lifetime (hours) due to the low film thickness and high rate of natural dispersion (even at < 10 m/s wind)*

## B  Experimental setup

### B.1  Oil samples and test temperature

- 2 x 20 Litres of Visund  Sør condensate arrived at SINTEF Ocean 2020-03-12 (Figure B-1). The oil was given the unique SINTEF ID 2020-3891. The weathering study (small-scale) were performed at 13 °C.

- 2 x 20 Litres of Visund  crude oil arrived at SINTEF Ocean 2020-04-17 (Figure B-2). The oil was given the unique SINTEF ID 2020-4737. The weathering study (small-scale) were performed at 13 °C.



Mongstad-Gullfaks O050C.
Mongstad Sør.

*Figure B-1        2 x 20 Litres of Visund Sør condensate received SINTEF Ocean*



Info fra fraktbrev: Prøvene er en samleprøve av samtlige brønner, og følgendebrønner var i drift ved prøvetakingstidspunktet:
Visund Nord (C2-C4-D2-D4)
A18 / Al9 / A20/ A21/ A23/ A24/ A30/ A32/ A34

*Figure B-2        2 x 20 Litres of Visund crude oil received SINTEF Ocean*

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## B.2 Small-scale laboratory testing

To isolate and map the various weathering processes at sea, the crude oil was exposed to a systematic, stepwise procedure developed at SINTEF (Daling et al., 1990). The general procedure is illustrated in Figure B-3.



WOR: Water to Oil Ratio

WOR=1: 50 vol.% water

WOR=3: 75 vol.% water

*WOR=max: the maximum water content*
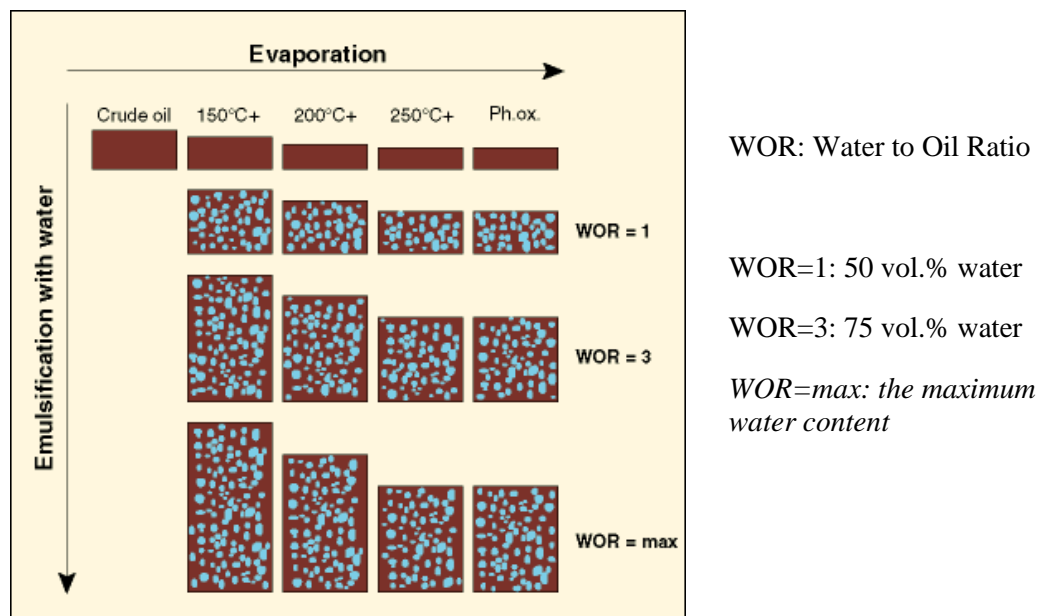
*Figure B-3          Small-scale laboratory weathering flow chart of oil*

### B.2.1 Evaporation

The evaporation procedure used is described in Stiver and Mackay (1984). Evaporation of the lighter compounds from the fresh oil was carried out as a simple one-step distillation to vapour temperatures of 150 °C, 200 °C and 250 °C, which resulted in oil residues with an evaporation loss corresponding to approximately 0.5-1-hour, 0.5-1 day and 0.5-1 week of weathering on the sea surface. These residues are referred to as 150°C+, 200°C+ and 250°C+, respectively.

### B.2.2 Physical and chemical analysis

The viscosity, density, pour point and flashpoint of the fresh and water-free residues was analysed. In addition, wax content and "hard" asphaltenes was measured for the 250°C+ residue. Viscosity for all the w/o emulsions was determined. The analytical methods used are given in Table B-1 and Table B-2.

*Table B-1          Analytical methods used to determine the physical properties*

| Physical property | Analytical method | Instrument |
|---|---|---|
| Viscosity | McDonagh et al, 1995 | Physica MCR 300 |
| Density | ASTM method D4052-81 | Anton Paar, DMA 4500 |
| Pour point | ASTM method D97 | - |
| Flash point | ASTM D 56-82 | Pensky-Martens, PMP1, SUR |

*Table B-2: Analytical methods used to determine the chemical properties*

| Chemical property | Analytical method |
|---|---|
| Wax content | Bridiè et al, 1980 |
| "Hard" asphaltene | IP 143/90 |

### Chemical characterization by GC-FID and GC-MS

- The distribution of hydrocarbons ($nC_5$-$nC_{40}$) was analysed using a Gas Chromatograph coupled with a Flame Ionisation Detector (GC-FID). The Gas Chromatograph used was an Agilent 6890N with a 30m DB1 column.
- The analysis and quantification of PAHs, phenols, and alkylated phenols ($C_0$-$C_4$) were completed using an Agilent 6890 Gas Chromatograph coupled with a, 5973 MSD detector (GC-MS) operating in SIM mode (Selected Ion Monitoring)

The volatile components were in the range of $nC_5$-$nC_{10}$ and were quantified by use of PT-GC-MS (Purge and Trap Gas chromatograph Mass Spectrometer operating in full-scan mode and using a modified version of the EPA 8260 analysis method).

## C Input data to SINTEF Oil Weathering Model (OWM)

The laboratory data used as input to the SINTEF OWM for Visund Sør and Visund are given in Table C-1 to Table C-5. The oil weathering predictions were based on the laboratory data at 13 °C.

*Table C-1    Physical and chemical properties for Visund Sør and Visund*

| Properties of fresh oil | Visund Sør 2020 | Visund 2020 |
|---|---:|---:|
| Density (g/mL) | 0.742 | 0.794 |
| Pour point (°C) | -36 | -33 |
| Reference temperature (°C) | 13 | 13 |
| Viscosity at ref. temp. (mPa·s = cP) * | 1 | 2 |
| Flash point (°C) | - | - |
| Asphaltenes (wt. %) | 0.01 | 0.03 |
| Wax Content (wt. %) | 0.05 | 1.4 |
| Dispersible for visc. < | - | 2000 |
| Not dispersible for visc. > | - | 7000 |

*\* Measured at shear rate 100 s$^{-1}$*

*Table C-2    True boiling point (TBP) curve of Visund Sør*
             *\*TBP based on simdist (Intertek Sunbury, IP545):*

| Temp. °C | Visund Sør Vol. % * |
|---:|---:|
| 28 | 6 |
| 49 | 13 |
| 72 | 23 |
| 92 | 34 |
| 101 | 40 |
| 116 | 50 |
| 139 | 64 |
| 152 | 71 |
| 175 | 81 |
| 223 | 93 |
| 250 | 96 |
| 271 | 98 |
| 345 | 99.9 |
| 406 | 100 |
| 450 | 100 |

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*Table C-3    True boiling point (TBP) curve of Visund*
*\*TBP based on simdist (Intertek Sunbury, IP545):*

| Temp °C | Visund Vol.%* |
|---|---|
| 28 | 4 |
| 60 | 10 |
| 90 | 18 |
| 111 | 27 |
| 135 | 36 |
| 162 | 45 |
| 189 | 52 |
| 218 | 59 |
| 250 | 66 |
| 279 | 71 |
| 304 | 76 |
| 335 | 80 |
| 374 | 85 |
| 411 | 89 |
| 440 | 91 |
| 475 | 94 |
| 517 | 96 |
| 557 | 98 |
| 609 | 99.5 |
| 650 | 99.8 |
| 681 | 100 |

*Table C-4    Lab weathering data for Visund Sør, 13 °C*

| Properties | Fresh | 150°C+ | 200°C+ | 250°C+ |
|---|---|---|---|---|
| Boiling Point Temp. (°C) | - | 165 | 217 | 284 |
| Vol. Topped (%) | 0 | 67 | 86 | 95 |
| Weight Residue (wt. %) | 100 | 35 | 16 | 5.3 |
| Density (g/mL) | 0.742 | 0.790 | 0.813 | 0.839 |
| Pour point (°C) | -36 | -36 | -30 | -9 |
| Flash Point (°C) | - | 31 | 68 | 83 |
| *Viscosity of water-free residue (mPa.s =cP) | 1 | 1 | 3 | 7 |
| *Viscosity of 50% emulsion (mPa.s = cP) | - | - | - | - |
| *Viscosity of 75% emulsion (mPa.s = cP) | - | - | - | - |
| *Viscosity of max water (mPa.s = cP) | - | *5* | *10* | 19 |
| Max. water cont. (vol. %) | - | *5* | *10* | 29 |
| (T1/2) Halftime for water uptake (hrs) | - | *0.1* | *0.1* | *0.1* |
| Stability ratio | - | - | - | - |

*\* Measured at shear rate 10 s$^{-1}$*
*- No data – not measured*
*Italic: Estimated values (not measured)*

*Table C-5      Lab weathering data for Visund, 13 °C*

| Properties | Fresh | 150°C+ | 200°C+ | 250°C+ |
|---|---|---|---|---|
| Boiling Point Temp. (°C) | - | 185 | 242 | 306 |
| Vol. Topped (%) | 0 | 37 | 52 | 65 |
| Weight Residue (wt. %) | 100 | 67 | 52 | 38 |
| Density (g/mL) | 0.794 | 0.837 | 0.857 | 0.877 |
| Pour point (°C) | -33 | 0 | 15 | 24 |
| Flash Point (°C) | - | 36 | 75 | 113 |
| *Viscosity of water-free residue (mPa.s =cP) | 2 | 13 | 64 | |
| **Viscosity of 50% emulsion (mPa.s = cP) | - | - | - | - |
| **Viscosity of 75% emulsion (mPa.s = cP) | - | - | - | - |
| **Viscosity of max water (mPa.s = cP) | - | - | - | - |
| Max. water cont. (vol. %) | - | - | - | - |
| (T1/2) Halftime for water uptake (hrs) | - | - | - | - |
| Stability ratio | - | - | - | - |

*Measured at shear rate 100 $s^{-1}$*
** *Measured at shear rate 10 $s^{-1}$*
- *No data – not measured*

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## D  Chemical characterization (OSCAR oil profile)

The method for generating OSCAR oil profile is based on the quantification of semi-volatile organic hydrocarbons (SVOC) and volatile organic hydrocarbons (VOC) by GC-MS. The composition is divided into individual pseudo-component groups (OSCAR groups) representing the oil based on the TBP (True Boiling Point) and GC-MS analysis.

*Table D-1        Chemical characterization ("oil profile") of Visund Sør (fresh oil) from GC-MS analysis and TBP oil fraction*

| Wt.% | Comp. group no. | Visund Sør 2020<br>SINTEF ID 2020-3891 |
|---|---|---|
| 5.000 | 1 | C1-C4 gasses (dissolved in oil) |
| 9.000 | 2 | C5-saturates (n-/iso-/cyclo) |
| 6.628 | 3 | C6-saturates (n-/iso-/cyclo) |
| 1.372 | 4 | Benzene |
| 12.50 | 5 | C7-saturates (n-/iso-/cyclo) |
| 2.605 | 6 | C1-Benzene (Toluene) et. B |
| 24.40 | 7 | C8-saturates (n-/iso-/cyclo) |
| 2.836 | 8 | C2-Benzene (xylenes; using O-xylene) |
| 11.07 | 9 | C9-saturates (n-/iso-/cyclo) |
| 1.595 | 10 | C3-Benzene |
| 5.000 | 11 | C10-saturates (n-/iso-/cyclo) |
| 0.097 | 12 | C4 and C4 Benzenes |
| 6.894 | 13 | C11-C12 (total sat + aro) |
| 0.009 | 14 | Phenols (C0-C4 alkylated) |
| 0.197 | 15 | Naphthalenes 1 (C0-C1-alkylated) |
| 5.803 | 16 | C13-C14 (total sat + aro) |
| 0.000 | 17 | Unresolved Chromatographic Materials (UCM: C10 to C36)  0 0 0 |
| 0.000 | 37 | metabolite 1 |
| 0.000 | 38 | metabolite 2 |
| 0.119 | 18 | Naphthalenes 2 (C2-C3-alkylated) |
| 1.881 | 19 | C15-C16 (total sat + aro) |
| 0.053 | 20 | PAH 1 (Medium soluble polyaromatic hydrocrbns (3 rings-non-alkyltd;<4 rings) |
| 0.947 | 21 | C17-C18 (total sat + aro) |
| 1.000 | 22 | C19-C20 (total sat + aro) |
| 0.885 | 23 | C21-C25 (total sat + aro) |
| 0.015 | 24 | PAH 2 (Low soluble polyaromatic hydrocarbons (3 rings-alkylated; 4-5+ rings) |
| 0.100 | 25 | C25+ (total) |

*Table D-2*      *Chemical characterization ("oil profile") of Visund (fresh oil) from GC-MS analysis and TBP oil fraction*

| Wt.% | Comp. group no. | Visund 2020 SINTEF ID 2020-4737 |
|---|---|---|
| 2.000 | 1 | C1-C4 gasses (dissolved in oil) |
| 4.000 | 2 | C5-saturates (n-/iso-/cyclo) |
| 4.053 | 3 | C6-saturates (n-/iso-/cyclo) |
| 0.947 | 4 | Benzene |
| 7.000 | 5 | C7-saturates (n-/iso-/cyclo) |
| 1.681 | 6 | C1-Benzene (Toluene) et. B |
| 12.32 | 7 | C8-saturates (n-/iso-/cyclo) |
| 1.813 | 8 | C2-Benzene (xylenes; using O-xylene) |
| 5.741 | 9 | C9-saturates (n-/iso-/cyclo) |
| 1.446 | 10 | C3-Benzene |
| 5.000 | 11 | C10-saturates (n-/iso-/cyclo) |
| 0.144 | 12 | C4 and C4 Benzenes |
| 6.855 | 13 | C11-C12 (total sat + aro) |
| 0.001 | 14 | Phenols (C0-C4 alkylated) |
| 0.383 | 15 | Naphthalenes 1 (C0-C1-alkylated) |
| 8.617 | 16 | C13-C14 (total sat + aro) |
| 0.000 | 17 | Unresolved Chromatographic Materials (UCM: C10 to C36)  0 0 0 |
| 0.000 | 37 | metabolite 1 |
| 0.000 | 38 | metabolite 2 |
| 0.406 | 18 | Naphthalenes 2 (C2-C3-alkylated) |
| 5.594 | 19 | C15-C16 (total sat + aro) |
| 0.246 | 20 | PAH 1 (Medium soluble polyaromatic hydrocrbns (3 rings-non-alkyltd;<4 rings) |
| 5.754 | 21 | C17-C18 (total sat + aro) |
| 4.000 | 22 | C19-C20 (total sat + aro) |
| 5.821 | 23 | C21-C25 (total sat + aro) |
| 0.179 | 24 | PAH 2 (Low soluble polyaromatic hydrocarbons (3 rings-alkylated; 4-5+ rings) |
| 16.000 | 25 | C25+ (total) |

The SINTEF OSCAR model is a 3-dimensional Oil Spill Contingency And Response model system that calculates and records the distribution (as mass and concentrations) of contaminants on the water surface, on shore, in the water column and in sediments. The model allows multiple release sites, each with a specified beginning and end to the release. This allows time-variable releases at a given location, as well as throughout the study area. The model computes surface spreading, slick transport, entrainment into the water column, evaporation, emulsification and shore interactions to determine oil drift and fate at the surface. In the water column, horizontal and vertical transport by currents, dissolution, adsorption, settling and degradation are simulated. By modelling the fate of individual pseudo-components, changes in the oil composition due to evaporation, dissolution and degradation are accounted for. OSCAR may compute oil weathering from crude assay data, although the most reliable results are produced if the target oil has been through a standardized set of laboratory weathering procedures established by the SINTEF laboratories. Alternatively, the model may use oil-weathering properties from oils for which data already exist, selecting the oil in the oil database that most closely matches the composition of the oil of concern.

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