

Report

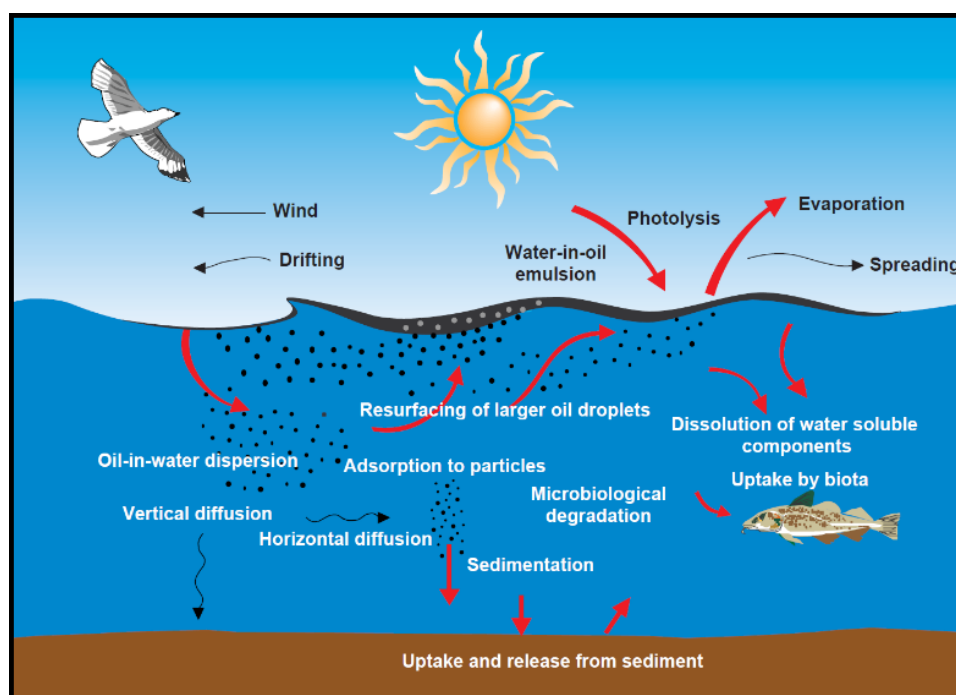
Fogelberg condensate – Weathering properties and behaviour at sea

In relation to oil spill response

Author(s)

Kristin Rist Sørheim

Thor-Arne Pettersen



SINTEF Ocean AS

Address:
Postboks 4762 Torgarden
NO-7465 Trondheim
NORWAY

Switchboard: +47 46415000

Enterprise /VAT No:
NO 937 357 370 MVA

Report

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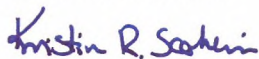
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ABSTRACT

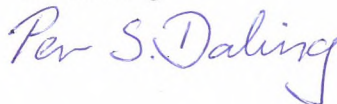
A weathering study has been conducted on Fogelberg condensate. The weathering study is based on a small-scale laboratory testing at 13 °C. The SINTEF Oil Weathering Model (OWM) is used to predict the weathering properties of Fogelberg at sea. The weathering properties of Fogelberg are discussed in relation to oil spill response.

**PREPARED BY**

Kristin Rist Sørheim

**CHECKED BY**

Per S. Daling

**APPROVED BY**

Andy Booth

for


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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. The lifetime of an oil spill at sea depends on the oil's composition, the release conditions and environmental conditions (temperature, wind, waves). Natural dispersion and evaporation are the main weathering processes that remove an oil spill from the sea surface. Based on input from the experimental weathering data of the oil, the SINTEF Oil Weathering Model (OWM) has been used to predict the properties of oil as it weathered over time. This summary gives a brief overview of the main changes predicted for Fogelberg condensate when weathered on the sea surface after a surface release.

Compared to many other Norwegian crude oils, this weathering study of Fogelberg condensate shows the following properties relevant for the behaviour, if spilled at sea:

- Fogelberg is a condensate with low density and high content of volatile that cause a rapid and high degree of evaporative loss: E.g. after 6 hours the evaporative loss is in the range of 35-50 wt.% at 5 °C, and 40-55 wt. % at 15 °C.
- The combination of the low contents of wax (2.8 wt.%) asphaltenes (<0.01 wt.%), density (0.799 g/mL) the condensate forms unstable low viscous emulsions (e.g.< 100 mPa.s after 6 hours) that has a high degree of natural dispersion in breaking waves conditions (> 5-10 m/s).
- The OWM predictions indicate a relative short lifetime in breaking waves conditions (10-15 m/s) of 3 -12 hours. In calm weather conditions (2-5 m/s) the lifetime is predicted to be > 3 days
- In summer conditions, the low emulsified residue (visc. < 100 mPa.s) will likely not solidify, however, in very calm weather and winter conditions the residue may form semi-solid lumps/material due to the high pour point of the residues (+24 to + 27 °C) after about 0.5 to 1 day weathering at sea.

The low-viscous loose emulsions will easily release water during recovery and storage. A concentration of 500 ppm of emulsion breaker was just as efficient as 2000 ppm relative to the oil to break the emulsions. However, the stability of the emulsions was poor, and use of emulsion breaker may therefore not be a preferable option on recovered emulsions that have been less than a day at sea.

The mass balance show that the oil/emulsion is naturally removed from the sea surface within 6 hours in high wind speeds (15 m/s) at winter (5 °C) and similar within 3 hours at 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) at 5 and 15 °C as much as ~35 % of the oil may still remain on the sea 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 Fogelberg, the flash point is predicted to exceed the sea temperature within the first 15 minutes at wind speeds (10-15 m/s), and in 0.5-1 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. Fogelberg reaches this limit (60 °C) in approx. 6 hours after a spill at calm wind speed (2 m/s) at summer and 9 hours in winter conditions respective, and more rapidly at higher wind speeds. A "safety" zone should be established early and downwind from the spill site before any response actions in case of an acute oil spill involving free gas. In a response operation, explosimeters should be utilized to measure concentrations of free gas to minimize the risk for fire and explosion hazard at the spill site.

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. This study shows that the emulsion viscosities of Fogelberg is well below 1000 mPa.s for several days if spilled at sea at 5 and 15 °C. The abovementioned

factors should therefore be taken into account to minimize the risk for boom leakage during mechanical recovery e.g. reducing the towing speed.

Fogelberg is assumed to have a high degree of natural dispersion in the water column, particularly in breaking waves conditions (> 5-10 m/s wind speed). In calm weather conditions (non-breaking waves < 2-5 m/s wind speed), the use of artificial energy (water flushing /Fi-Fi monitors) may increase the dispersion efficiency for thin oil films (< 0.2-0.3 mm). Due to the expected high degree of natural dispersion the benefit for use of dispersant may be limited, but could be used with following high-capacity water flushing in calm weather conditions (non-breaking waves, where the oil film thickness can be > 0.2-0.3 mm).

Short summary response options for surface release

Lifetime of surface oil with no response: The OWM predictions indicate a relative short lifetime in breaking waves conditions (10-15 m/s) of 3 -12 hours. In calm weather conditions (2-5 m/s) the lifetime is predicted to be > 3 days.

Mechanical recovery:

- In calm weather conditions (< 5m/s) Fogelberg has a potential for mechanical recovery assuming a film thickness > 0.1mm.
- However, the efficacy may be reduced because of the risk of boom leakage due to low emulsion viscosities (< 1000 mPa.s)

Use of chemical dispersants:

- Limited efficiency for use of dispersant in breaking waves (10-15 m/s) due to high degree of natural dispersion of the oil film into the water column.
- In calm weather (< 2-5 m/s) with film thickness > 0.1 mm, the use of dispersant may have an option possible in combination with water-flushing (e.g., from Fi-Fi monitor) to enhance effective dispersion of oil droplets into the water column.

High-capacity water flushing (mechanical dispersion):

- Water flushing may be a stand-alone method if the film thickness is <0.2-0.3 mm.

Subsea release

For a subsea release with combination with gas it is likely that the initial oil film thickness of the surfacing oil is thinner than from a surface release. However, this is dependent on the release conditions (gas-oil-ratio, release rate, water depth etc.). To evaluate response options from a subsea release scenario for Fogelberg a separate study will be performed with use of the 3-D plume model (OSCAR) and predictions of oil weathering properties with the SINTEF OWM.

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 time after the release. These past experiences and other incidents 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 oils spilled on the sea surface.

According to the Norwegian Environment Agency and the Petroleum Safety Authority Norway (Ptil) regulations for petroleum activities (Aktivitetsforskriften §59), the characterization of oils with respect to their weathering properties and fate in the marine environment should be performed for all oils coming into production. SINTEF Ocean has performed a standardized small-scale weathering study on Fogelberg condensate at 13 °C. The obtained laboratory data were further customized to predict the weathering properties of Fogelberg by use of the SINTEF Oil Weathering Model (OWM). Information about the Fogelberg field is given, below (Figure 2-1).

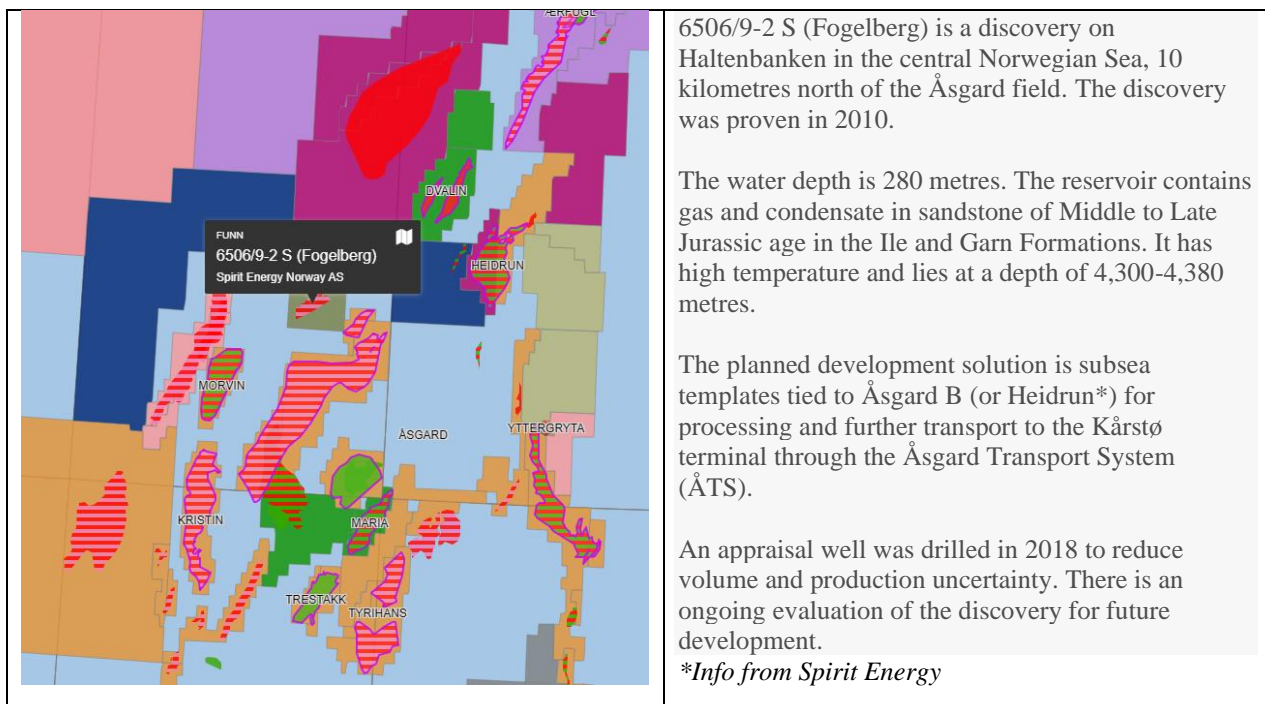


Figure 2-1 Fogelberg PL 433: <https://www.norskpetroleum.no/en/facts/discoveries/65069-2-s-fogelberg/>

3 Small-scale laboratory testing of Fogelberg condensate

Description of the oil sample of Fogelberg for testing, and the experimental setup for the small-scale weathering and dispersibility study are described in Appendix B. Physico-chemical parameters and weathering properties of Fogelberg condensate were compared with a selection of other oils at Haltenbanken in Norwegian Sea: Smørbukk condensate, and Kristin and Morvin light crude oils (Table 3-1). The oils in comparison were selected in agreement with Spirit Energy.

Table 3-1 Oils compared with Fogelberg*

Oil name	SINTEF ID	Report number	Reference
Smørbukk	2002-0724	STF66 A03053	Leirvik et al. 2003
Kristin	2006-0256	A06221	Leirvik, 2006
Morvin	2007-0335	A6808	Brandvik and Leirvik, 2008

*Fogelberg : SINTEF ID 2020-8436

3.1 Gas chromatographic (GC-FID) characterization

The hydrocarbon profile of Fogelberg was analysed by use of gas chromatography (GC) coupled with Flame Ionization detector (FID). Figure 3-1 illustrates the GC-FID outputs (gas chromatograms) of the fresh oil of Fogelberg and the corresponding evaporated residues at three different degrees 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*C₄₀) are not possible to analyze with this technique.

Fogelberg is a light paraffinic condensate with high amounts of light *n*-alkanes in the range of *n*C₅-*n*C₁₃ but contains also heavier paraffins > C₂₀ reflecting a wax content. Overall, the oils in comparison (Figure 3-2) are classified as paraffinic condensates or crude oils with minor content of UCM with a main range of *n*-alkanes from *n*C₅ to *n*C₃₀.

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*C₁₇/Pristane and *n*C₁₈/Phytane ratios. Table 3-2 shows the ratios of Fogelberg in comparison with the other oils.

Table 3-2 *n*C₁₇/Pristane and *n*C₁₈/Phytane ratios*

Oil name	<i>n</i> C ₁₇ /Pristane* *	<i>n</i> C ₁₈ /Phytane**
Fogelberg	1.8	2.3
Smørbukk	2.0	2.7
Kristin	1.9	2.6
Morvin	1.7	3.0

*Ratios > 1 typical for paraffinic oils, ratios < 1 typical for biodegraded /naphthenic oil.

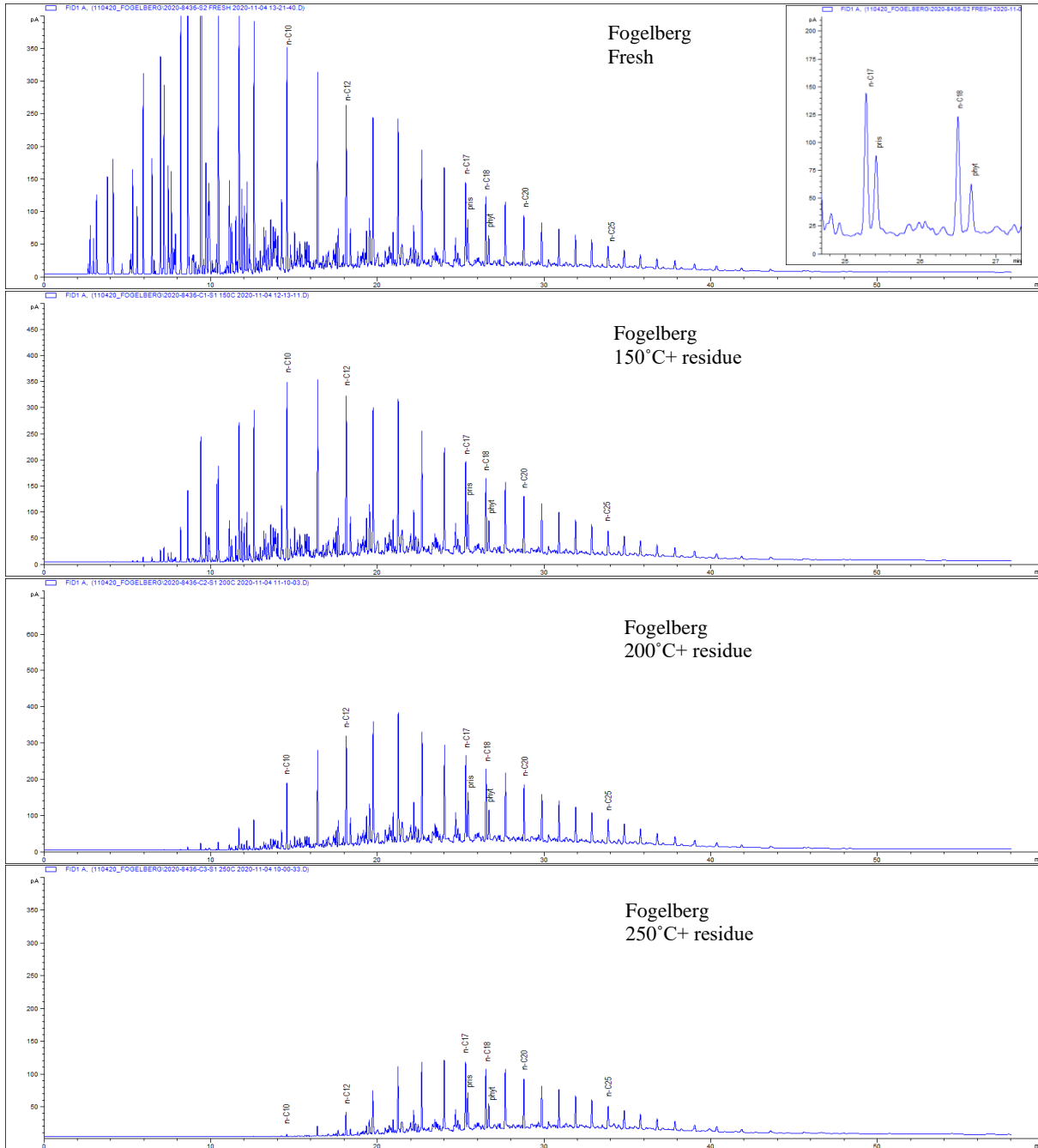


Figure 3-1 GC-FID chromatograms of fresh sample and evaporated residues of Fogelberg

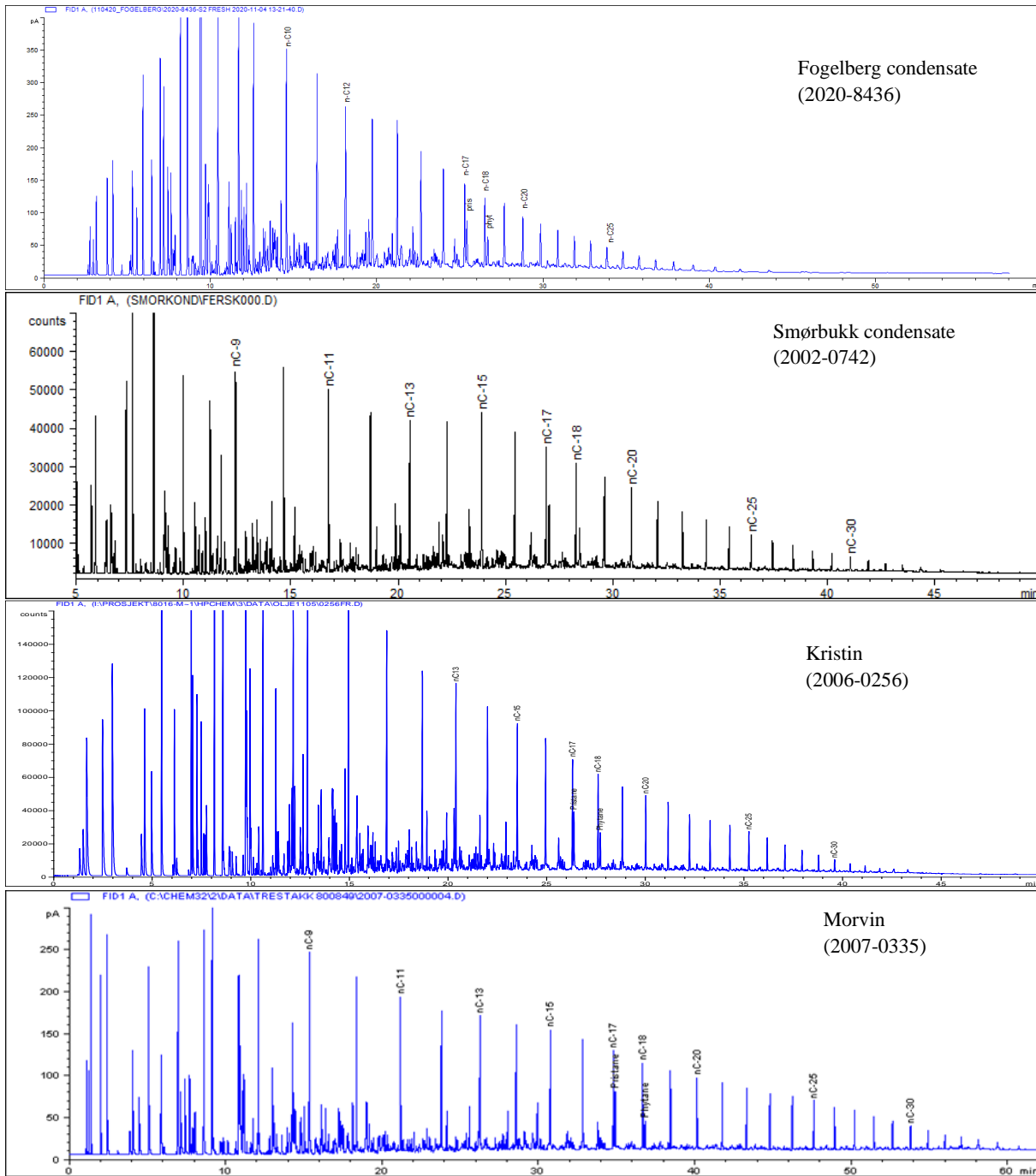


Figure 3-2 GC-FID chromatograms for fresh oils of Fogelberg in comparison with Smørbukk condensate, Kristin, and Morvin. The retention times differ between the chromatograms due to different temperature programs (relative comparison)

3.2 Asphaltenes and wax content of the fresh and weathered residues

The content of asphaltene and wax of Fogelberg in comparison with the other oils are given in Table 3-3. Fogelberg (fresh oil) has a low content of wax (2.8 wt.%) and a very low content of asphaltenes (<0.01 wt.%). The wax content of Fogelberg is most like Smørbukk condensate, whilst the low asphaltene is most like Kristin.

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

Oil type	Residue	Asph* (wt. %)	Wax (wt. %)
Fogelberg	Fresh	<0.01	2.8
	150°C+	0.01	4.0
	200°C+	0.01	5.1
	250°C+	0.01	7.0
Smørbukk condensate	Fresh	0.06	2.6
	150°C+	0.08	3.4
	200°C+	0.10	4.5
	250°C+	0.13	5.7
Kristin	Fresh	0.02	6.8
	150°C+	0.03	9.7
	200°C+	0.04	12.0
	250°C+	0.05	15.0
Morvin	Fresh	0.05	5.4
	150°C+	0.06	6.9
	200°C+	0.07	8.3
	250°C+	0.09	10.4

*n-heptane (nC₇) precipitation

3.3 Physical properties of the fresh and weathered residues

The physical properties of Fogelberg are listed in Table 3-4 in comparison of the other oils Smørbukk condensate, Kristin, and Morvin. Figure 3-3 shows the fresh oil and the evaporative residues of Fogelberg.

Fogelberg has the highest evaporative loss (62 vol. %) followed by Kristin, Smørbukk condensate and Morvin. All the oils in comparison are low density oils in the range of 0.799-0.817 g/mL. Fogelberg has a relatively high pour point of +6 °C (fresh oil) that increases rapidly to considerably higher pour points with increasing evaporative loss (range +24 to +27 °C for the residues). Smørbukk condensate, Kristin, and Morvin also exhibit high pour points, particularly for the 250°C+ residue. The viscosity of the fresh oil of Fogelberg increases with increasing evaporation, but the viscosity of the 250°C+ residue is about 10-times lower compared with the other oils.



Figure 3-3 A: From left to right: fresh oil, 150°C+, 200°C+ and 250°C+ residues. B: 250°C+ residue with visible wax precipitation

Table 3-4 Physical properties of Fogelberg in comparison with others oil (Smørbukk cond., Kristin, and Morvin)

Oil type	Residue	Evap. (vol. %)	Residue (wt. %)	Density (g/mL)	Flash point (°C)	Pour point (°C)	Visc. (mPa.s) 13°C (10 s ⁻¹)
Fogelberg	Fresh	0	100	0.799	-	6	8
	150°C+	32	70	0.825	39	18	152
	200°C+	48	55	0.837	77	24	270
	250°C+	62	40	0.849	113	27	627
Smørbukk condensate	Fresh	0	100	0.804	-	-15	3
	150°C+	27	76	0.832	34	3	140
	200°C+	45	58	0.849	75	15	941
	250°C+	57	46	0.861	118	21	5830
Kristin	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
Morvin	Fresh	0	100	0.817	-	-27	15
	150°C+	24	79	0.844	45	12	377
	200°C+	37	37	0.858	83	18	1456
	250°C+	51	52	0.871	125	27	10276

--:No data

The True Boiling Point curves (TBP) of Fogelberg in comparison with Smørbukk condensate, Kristin, and Morvin are shown in Figure 3-4.

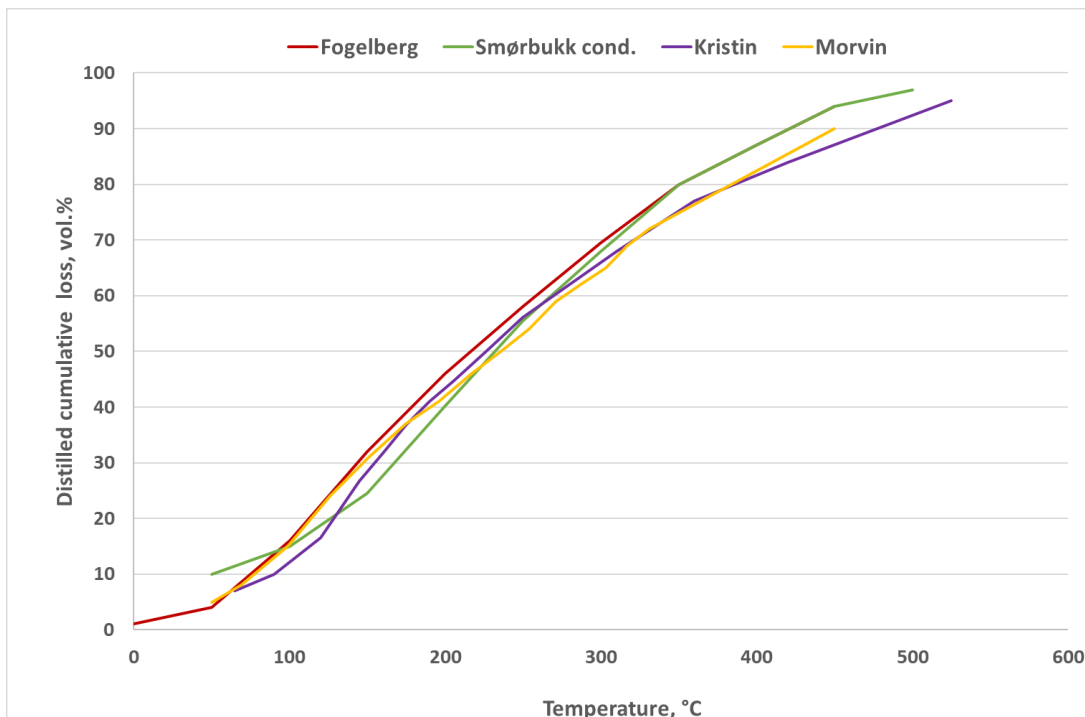


Figure 3-4 TBP of Fogelberg in comparison with other oils

3.4 Viscosity of fresh oil and water-free residues with different shear rates

The viscosity describes the oils ability to resist gradual deformation by increasing shear, where viscosities of so-called *Newtonian* oils remain 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 Fogelberg fresh oil and water-free residues are given in Table 3-5 with increasing shear rates (10, 100 and 1000 s^{-1}) at 13 °C. The residues of Fogelberg residues clearly exhibit *non-Newtonian* behaviour at 13 °C, i.e. viscosities depending on the shear rates.

Table 3-5 Viscosities of fresh oil and residues of Fogelberg with increasing shear rate (s^{-1})

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})
	Fresh	8	3	3
Fogelberg	150°C+	152	33	12
	200°C+	270	77	27
	250°C+	627	243	69

3.5 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).

3.5.1 Water uptake and maximum water content

Fogelberg does not form typical stable water-in-oil emulsions based on its emulsification properties. For 150 and 200°C+ residues insignificant water uptake or formation of emulsion were observed after 24 rotation time. For the 250°C+ residue, the condensate forms low viscous unstable (loose) emulsion with large water droplets when mixed with water, mainly due to the wax content and minor content of stabilizing components, like the asphaltenes. Figure 3-5 shows the final emulsion formation of Fogelberg after 24 hours rotation time. The figure shows from left to right two emulsions prepared from the residues of 150°C+, 200°C+ and four emulsion of 250°C+, respectively.

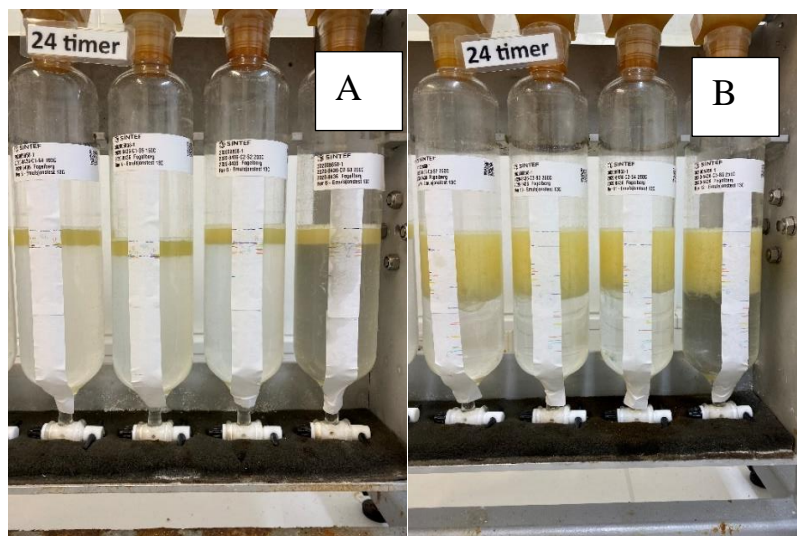


Figure 3-5 A: No water uptake for 150 and 200°C+ residues after 24 hours rotating time
B: Loose emulsion formation for 250°C +C residue after 24 hours rotation time

The rate of water uptake (kinetic) was also studied by use of the rotating cylinder method, as described above. 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 half of the maximum water uptake (vol. %) in 24 hours (rotating time). The $t_{1/2}$ for 150, 200 and 250°C+ residues of Fogelberg are also given in Table 3-6. The analysis showed that when the energy that makes the seawater to incorporate into the was oil stopped the emulsions easily broke and released water and was particularly pronounced for the 150 and 200°C+ residues.

Table 3-6 Water uptake (kinetics) of evaporated residues of Fogelberg at 13 °C

Mixing time	150°C+ * (Vol. % water)	200°C+ * (Vol. % water)	250°C+ * (Vol. % water)
Start	0	0	0
5 min	11	69	58
10 min	12	38	62
15 min	11	33	64
30 min	0	19	68
1 hour	0	15	71
2 hours	0	6	74
4 hours	0	3	74
6 hours	0	4	77
24 hours	0	2	76
t_{0.5}	0.01**	0.01	0.05

* Depending on the spill scenario, 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

**Estimated value

3.5.2 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. Treatment of emulsion breaker (Alcopol O 60%) had however negligible beneficial effect on Fogelberg due to the unstable emulsions. Use of emulsion breaker may therefore not be necessary to break up the emulsion and release free water on Fogelberg. The emulsion stability was studied by quantifying the amount of water released from the emulsion after 24 hours settling time, followed by 10 rotations. Fogelberg formed unstable emulsion after 24 hours settling time, as shown in Figure 3-6, and the first main row in Table 3-7.



Figure 3-6 150, 200 and 250°C + residues after 24 hours settling time and 10 rotations

Table 3-7 Stability of emulsion and the effectiveness of emulsion breaker 13 °C of Fogelberg

Residue	Emulsion breaker	Water-in-oil emulsion (vol. %) at 13 °C		Stability ratio (R_{stab})**
		Reference	24 hours *	
150°C+	None	0	0	0
200°C+	None	2	0	0
250°C+	None	76	3	0.01
150°C+	Alc. O 60 % 500 ppm	0	0	0
200°C+	Alc. O 60 % 500 ppm	2	0	0
250°C+	Alc. O 60 % 500 ppm	76	14	0.05
150°C+	Alc. O 60 % 2000 ppm	0	0	0
200°C+	Alc. O 60 % 2000 ppm	2	0	0
250°C+	Alc. O 60 % 2000 ppm	76	6	0.02

ppm: parts per million

*: w/o-emulsion after 24 hours rotation and 24 hours settling

** Stability ratio (R_{stab}) 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

R_{stab} : Volumetric water to oil ratio (24 hours)/ Volumetric water to oil ratio (ref)

3.5.3 Viscosity of emulsions

The viscosities of the emulsified residues are given in Table 3-8.

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

Residue	Water content (vol. %)	Viscosity (mPa.s), Fogelberg 13 °C		
		10 s ⁻¹	100 s ⁻¹	1000 s ⁻¹
Fresh	0	8	3	3
150°C+	0	152	33	12
200°C+	0	270	77	27
250°C+	0	627	243	69
150°C+	0	46	11	n.a
200°C+	0	153	27	n.a
250°C+	75*	89	16	n.a

n.a: Not applicable * Unstable emulsion

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 Fogelberg was conducted at 13 °C, and the analytical data were further used as input to the SINTEF Oil Weathering Model (OWM). The experimental design for the study is described in Appendix B. The input data of Fogelberg 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 3-7. 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.

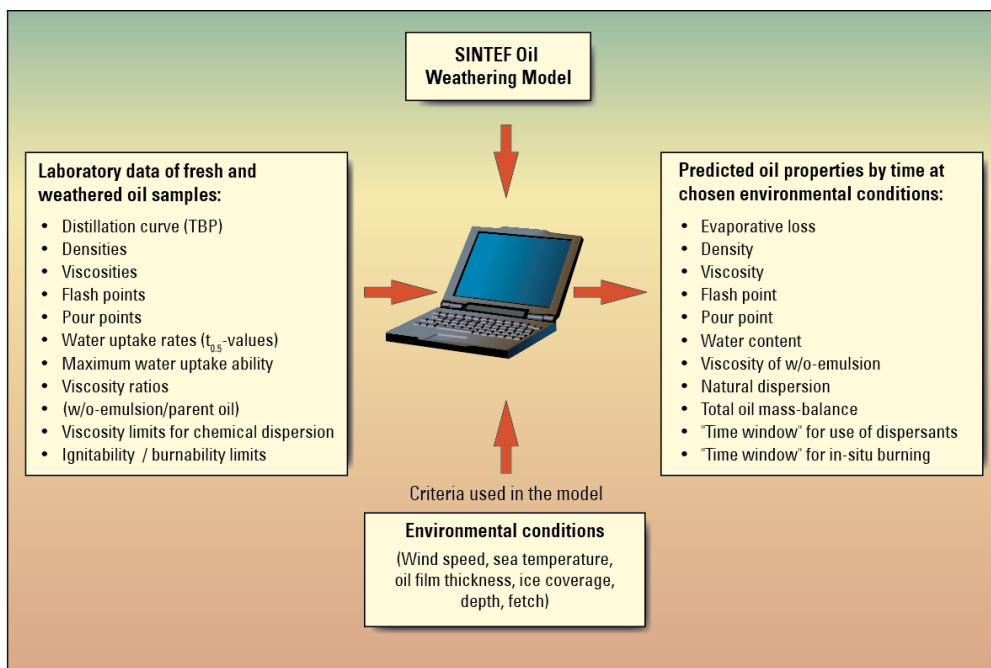


Figure 3-7 Schematic input data to the SINTEF OWM and the predicted output oil properties

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 in OWM are categorized as condensate (non-emulsifying oil), low emulsifying oil/condensate, emulsifying oil, heavy bunker fuel or refined distillate. The categorization is based on the experimental results

obtained in the laboratory. The terminal film thicknesses vary among these categories based on experimental (field) experience. Fogelberg is categorized as a condensate.

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 Fogelberg 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 3-9.

Table 3-9 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 Fogelberg

Input to SINTEF OWM

Oil type:	Condensate
Geographical area:	Norwegian Sea
Terminal oil film thickness:	0.05 mm
Release rate:	1.33 metric tonnes per min. in 15 min, a total of 20 metric tonnes (80 m ³ /hour or 1900 m ³ /day)
Seawater temperatures:	5 and 15 °C
Wind speeds:	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 remaining 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 gives an example of predicted weathering properties for Fogelberg.

Table 3-10 Example of weathering properties for Fogelberg obtained from the OWM predictions after 6 hours of weathering at 2, 5 and 10 m/s wind speed at 15 °C

Weathering properties	6 hours 15 °C 2 m/s	6 hours 15 °C 5 m/s	6 hours 15 °C 10 m/s
Evaporation, wt. %	40	46	52
Flash point, °C	62	76	93
Pour Point, °C	21	23	25
Water content, vol. %	8	25	42
Emulsion viscosity, mPa.s *	50	60	75
Mass balance / Oil on surface wt. %	60	50	10

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

Property: EVAPORATIVE LOSS
Oil Type: FOGELBERG CONDENSATE
Description: Fogelberg Condensate
Data Source: Sintef Ocean (2020), Weathering data used

OWModel© 12.1

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

2.0
 Pred. date: Jan. 20, 2021

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

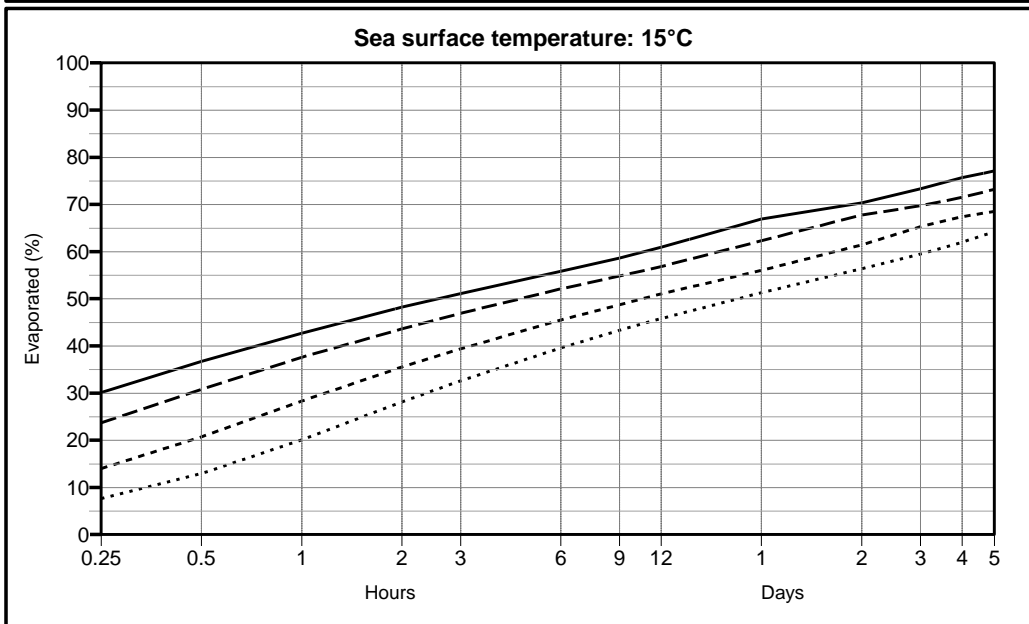
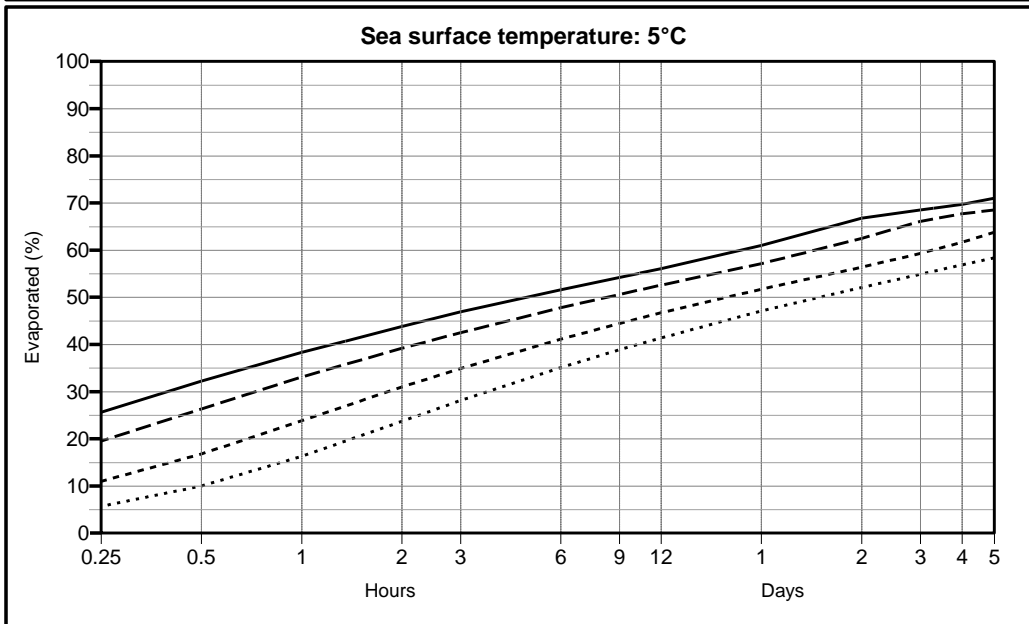


Figure 3-8 Evaporative loss of Fogelberg predicted at sea temperatures of 5 and 15 °C

Property: VISCOSITY OF EMULSION
Oil Type: FOGELBERG CONDENSATE
Description: Fogelberg Condensate
Data Source: Sintef Ocean (2020), Weathering data used

OWModel© 12.1

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

2.0
 Pred. date: Jan. 20, 2021

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

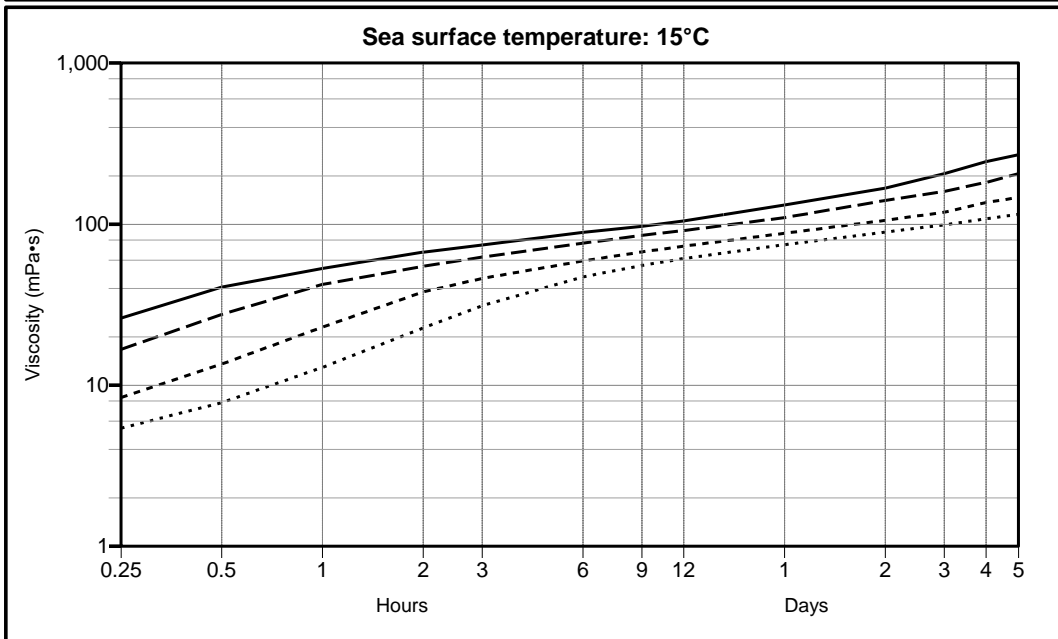
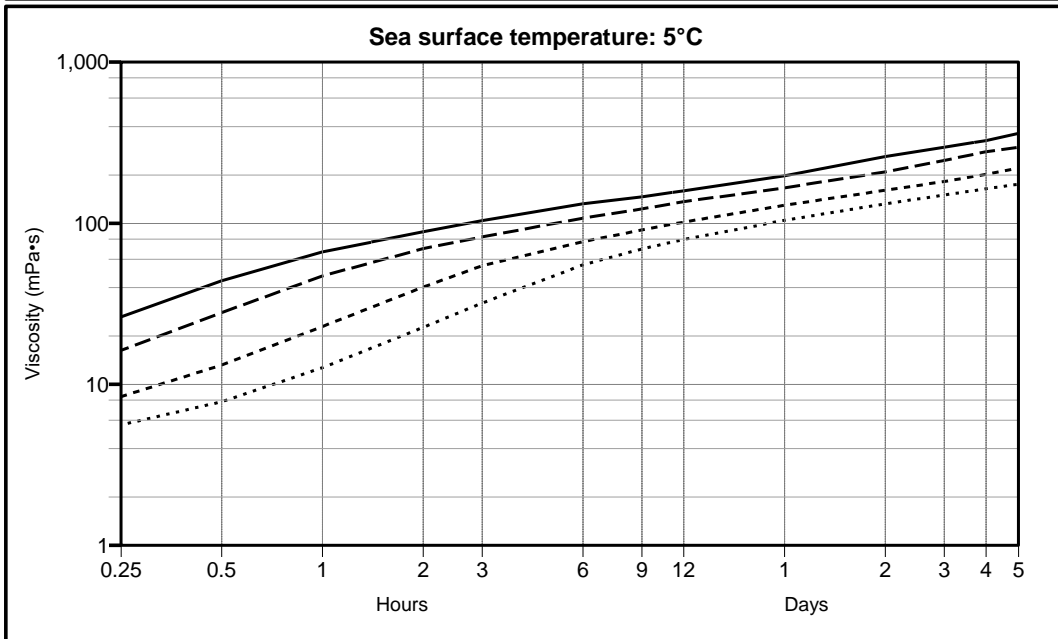


Figure 3-9 Viscosity of Fogelberg predicted at sea temperatures of 5 and 15 °C, shear rate 10 s⁻¹

Property: WATER CONTENT
Oil Type: FOGELBERG CONDENSATE
Description: Fogelberg Condensate
Data Source: Sintef Ocean (2020), Weathering data used

OWModel© 12.1

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

2.0
 Pred. date: Jan. 20, 2021

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

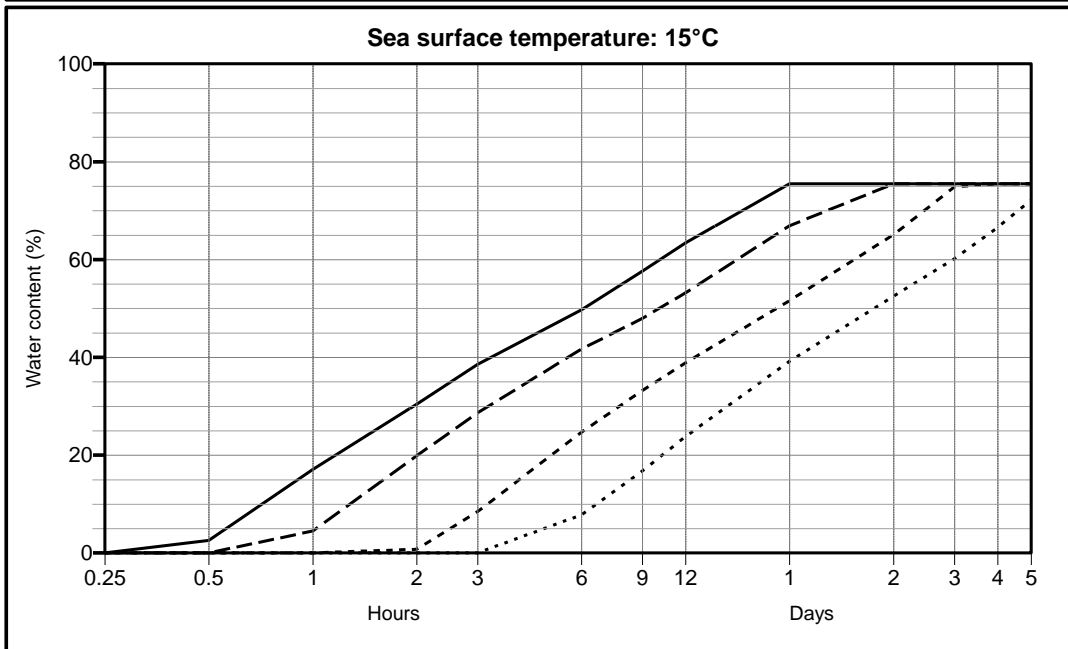
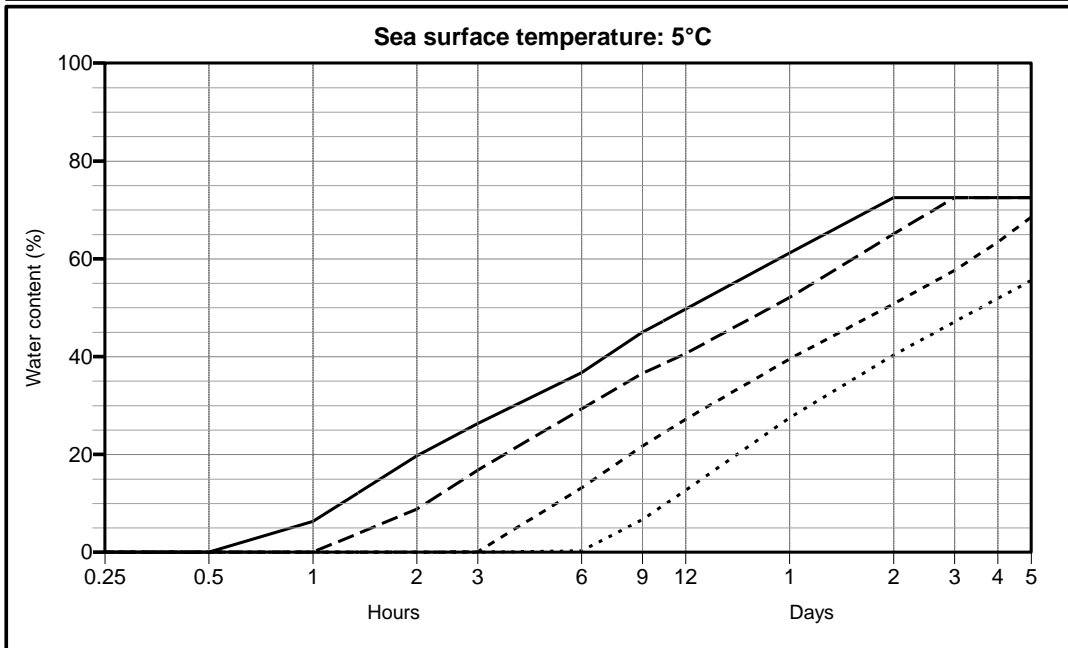


Figure 3-10 Water uptake Fogelberg predicted at sea temperatures of 5 and 15 °C

Property: FLASH POINT FOR WATER-FREE OIL
Oil Type: FOGELBERG CONDENSATE
Description: Fogelberg Condensate
Data Source: Sintef Ocean (2020), Weathering data used

OWModel© 12.1

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

2.0
 Pred. date: Jan. 20, 2021

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

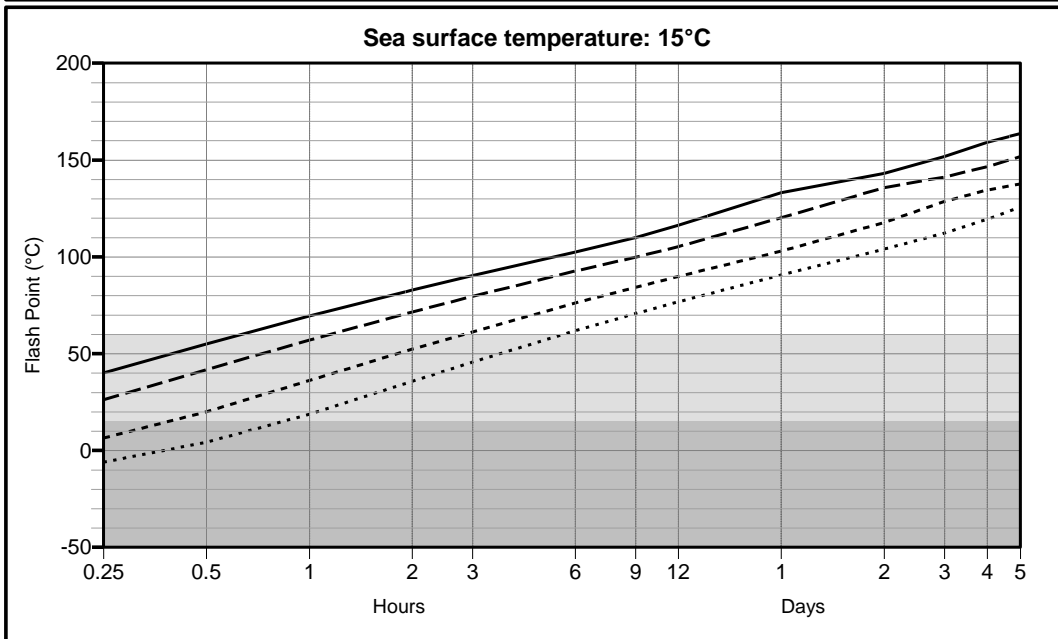
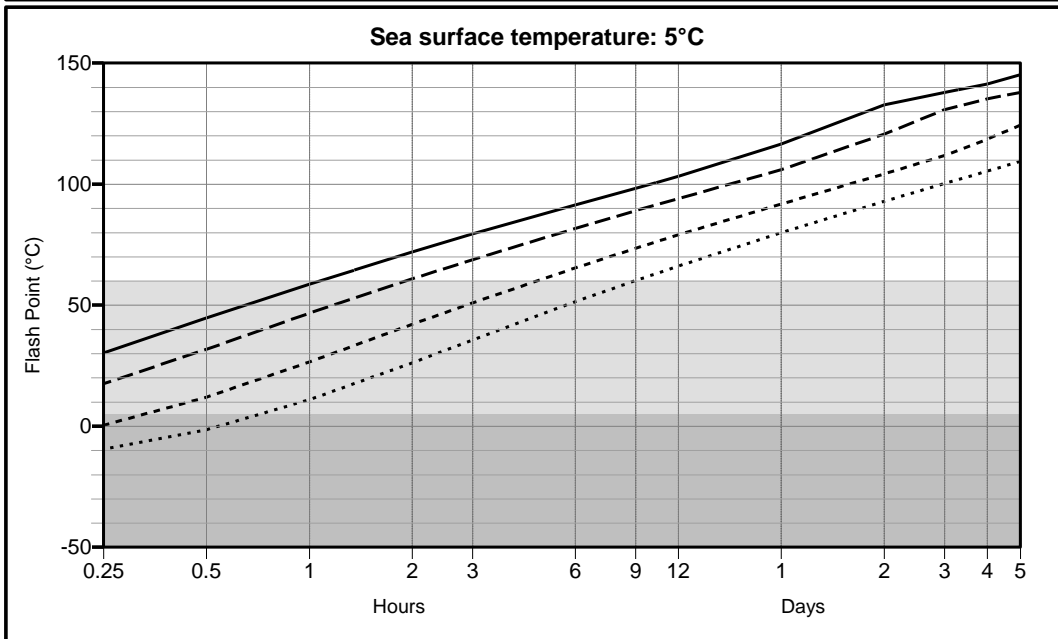


Figure 3-11 Flash point of Fogelberg predicted at sea temperatures of 5 and 15 °C

Property: POUR POINT FOR WATER-FREE OIL
Oil Type: FOGELBERG CONDENSATE
Description: Fogelberg Condensate
Data Source: Sintef Ocean (2020), Weathering data used

OWModel© 12.1

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

2.0
 Pred. date: Jan. 20, 2021

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

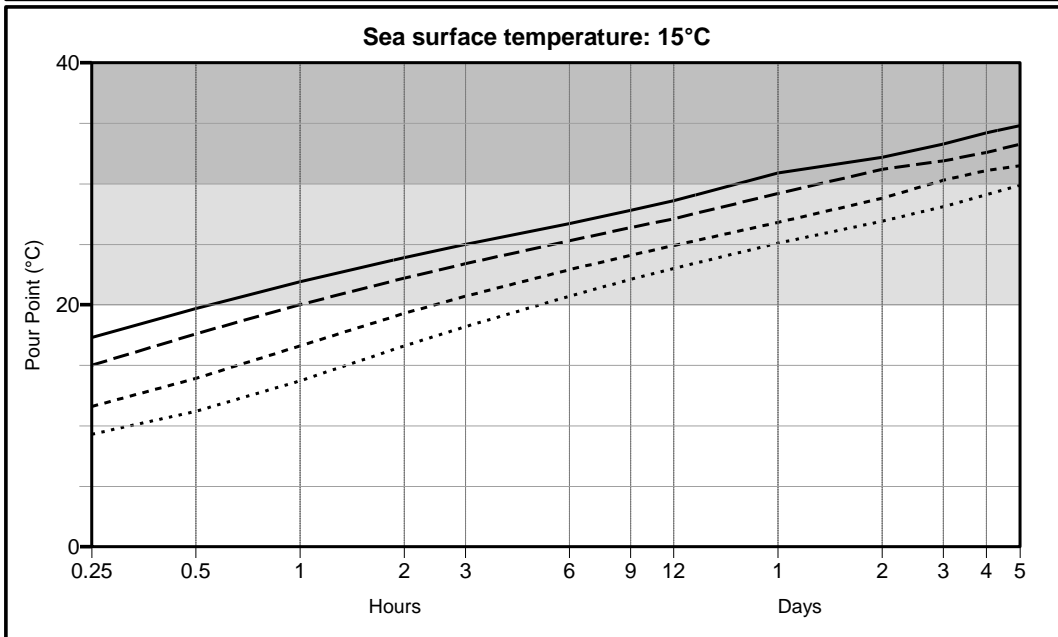
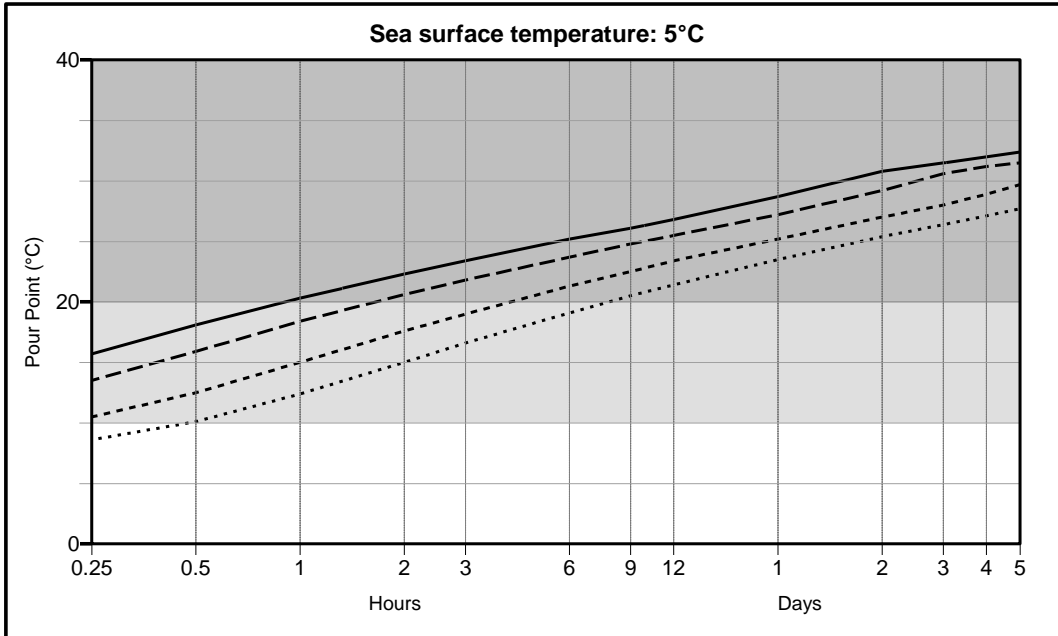


Figure 3-12 Pour point of Fogelberg predicted at sea temperatures of 5 and 15 °C

Property: MASS BALANCE
Oil Type: FOGELBERG CONDENSATE
Description: Fogelberg Condensate
Data Source: Sintef Ocean (2020), Weathering data used

OWModel© 12.1

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

Pred. date: Jan. 20, 2021

- Evaporated
- Surface
- Naturally dispersed

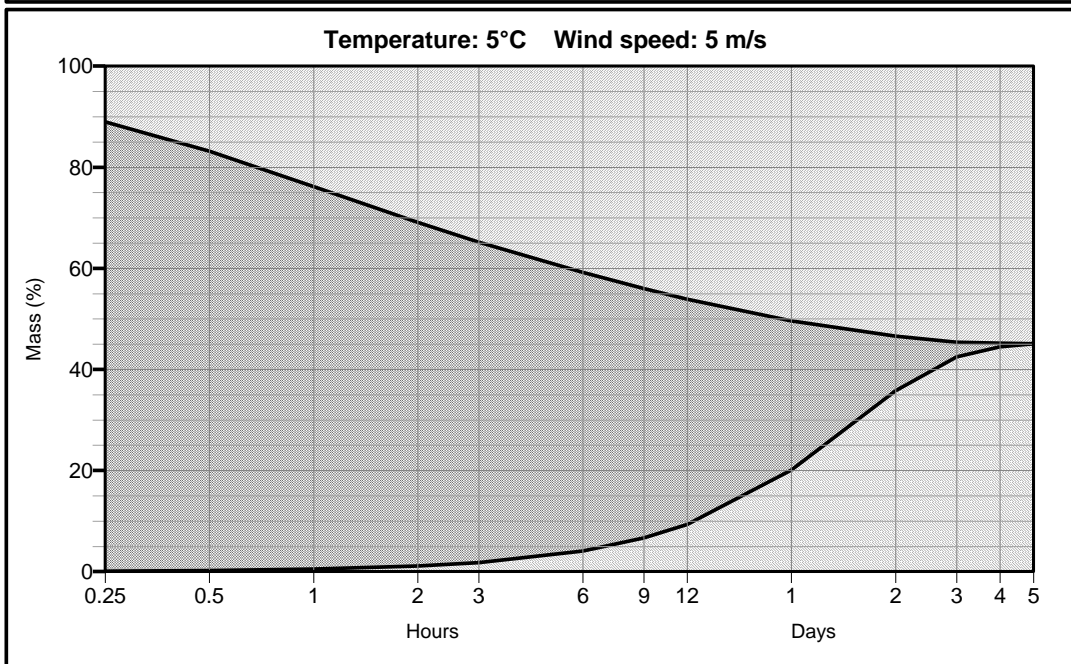
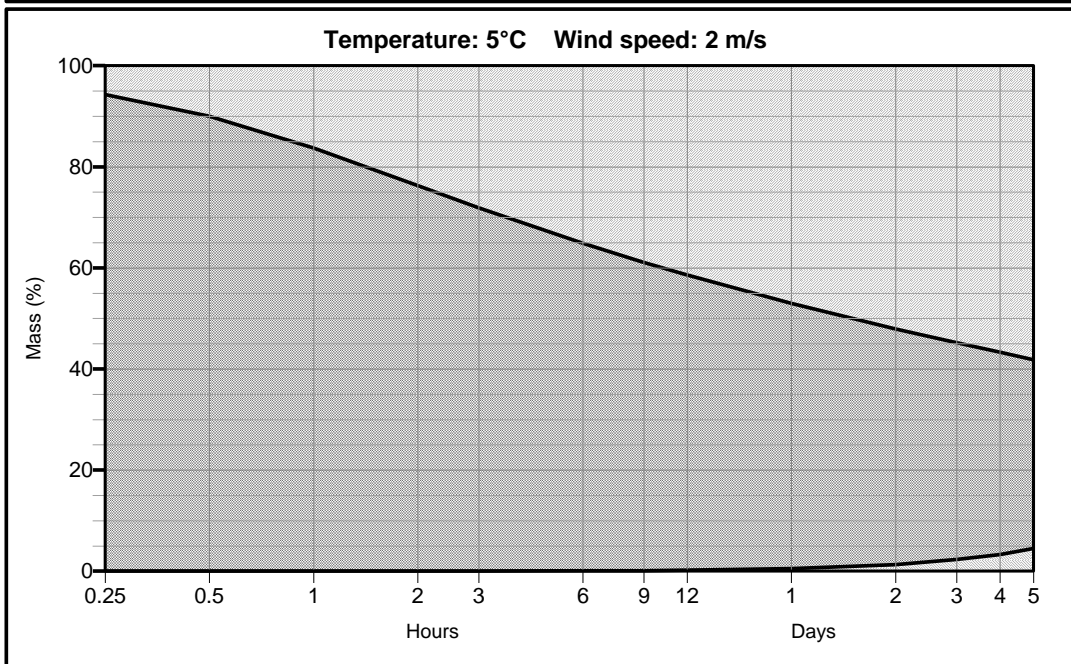





Figure 3-13 Predicted mass balance of Fogelberg predicted 5 °C, wind speeds of 2 and 5 m/s

Property: MASS BALANCE
Oil Type: FOGELBERG CONDENSATE
Description: Fogelberg Condensate
Data Source: Sintef Ocean (2020), Weathering data used

OWModel© 12.1

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

Pred. date: Jan. 20, 2021

-  Evaporated
-  Surface
-  Naturally dispersed

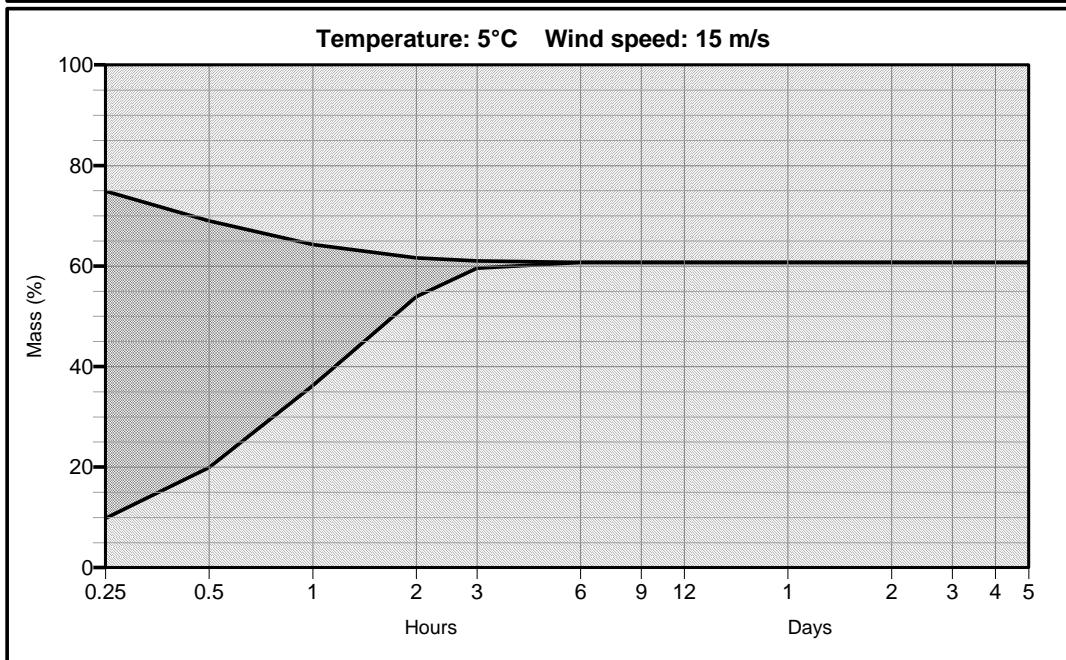
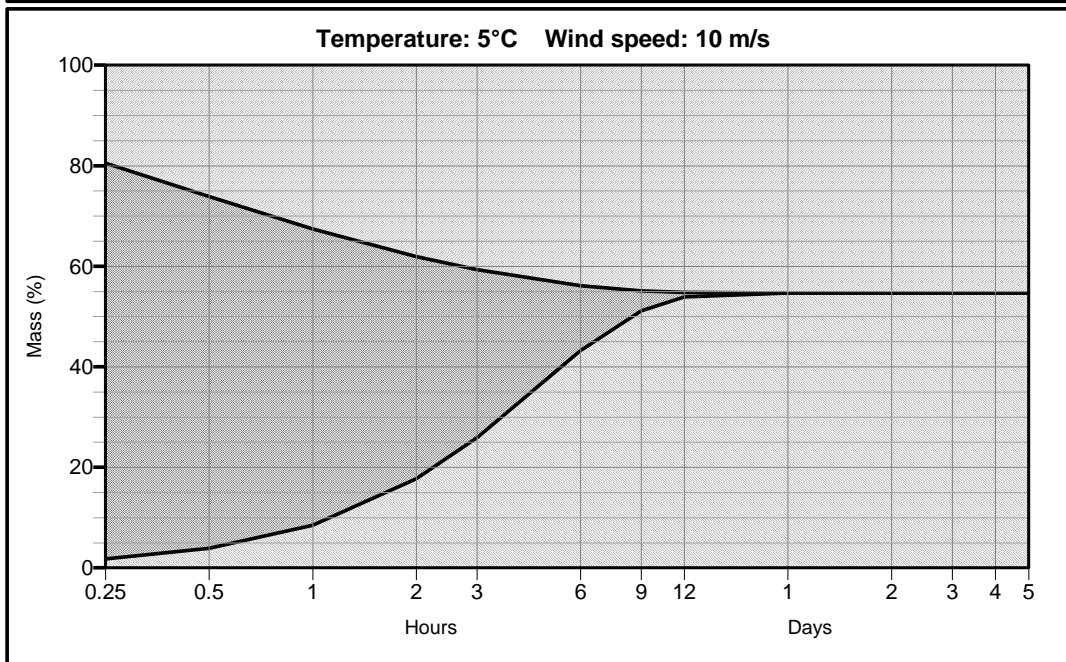


Figure 3-14 Predicted mass balance of Fogelberg predicted 5 °C, wind speeds of 10 and 15 m/s

Property: MASS BALANCE
Oil Type: FOGELBERG CONDENSATE
Description: Fogelberg Condensate
Data Source: Sintef Ocean (2020), Weathering data used

OWModel© 12.1

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

Pred. date: Jan. 20, 2021

- Evaporated
- Surface
- Naturally dispersed

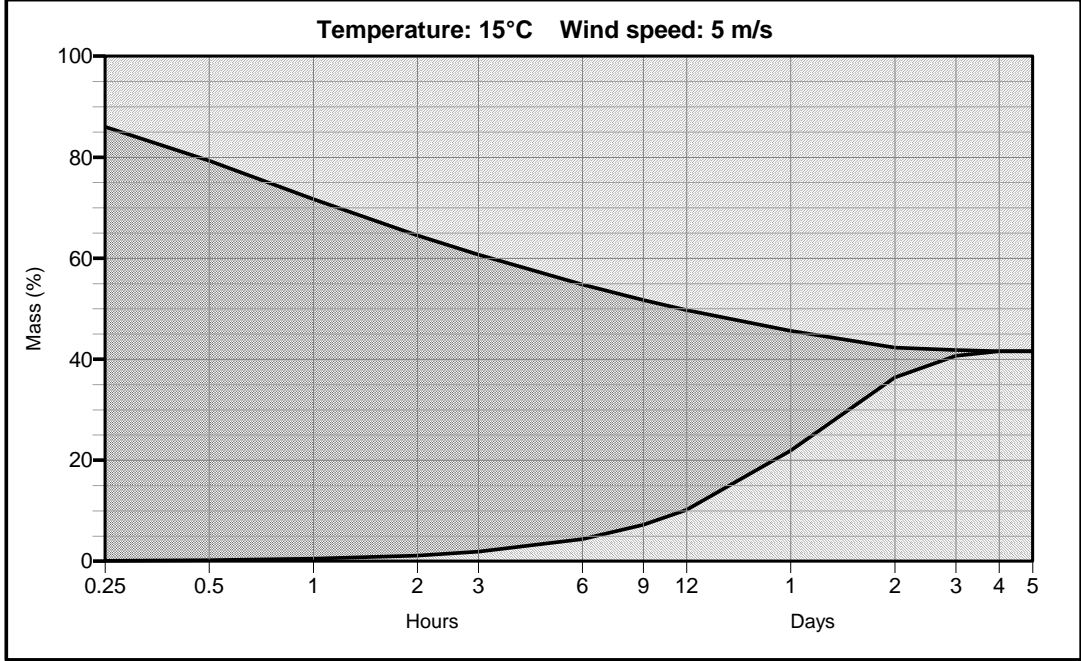
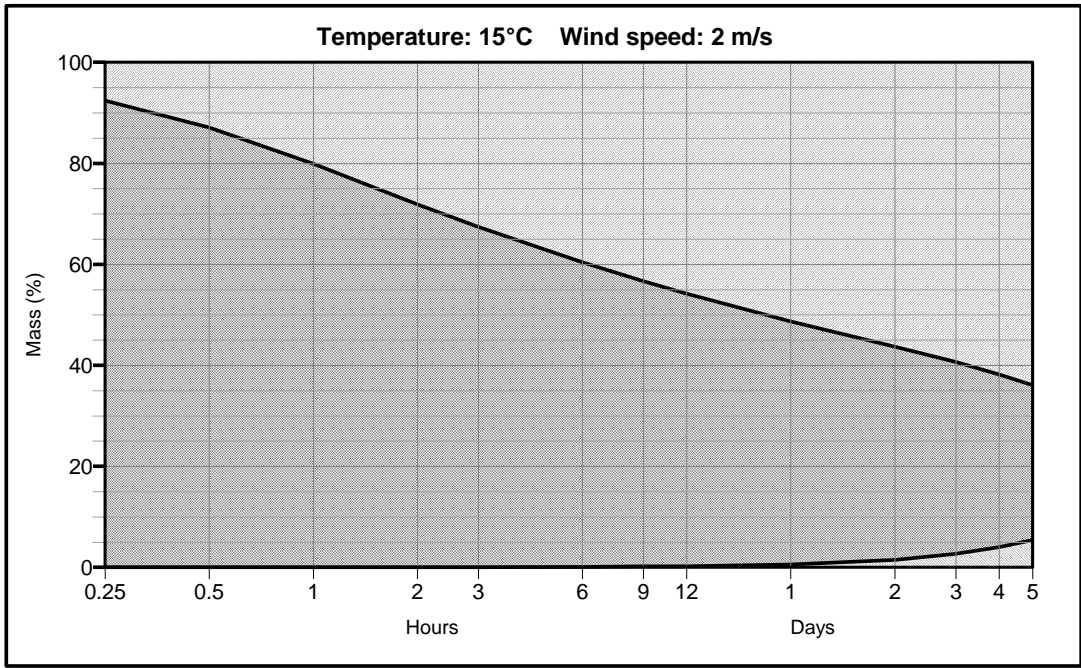





Figure 3-15 Predicted mass balance of Fogelberg predicted 15 °C, wind speeds of 2 and 5 m/s

Property: MASS BALANCE
Oil Type: FOGELBERG CONDENSATE
Description: Fogelberg Condensate
Data Source: Sintef Ocean (2020), Weathering data used

OWModel© 12.1

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

Pred. date: Jan. 20, 2021

-  Evaporated
-  Surface
-  Naturally dispersed

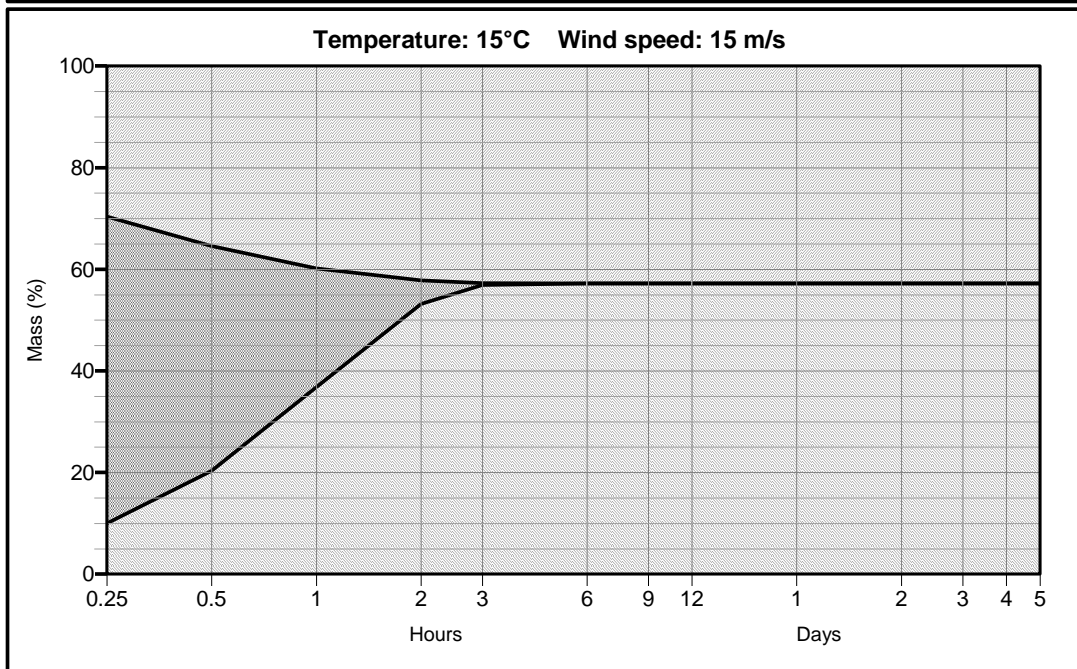
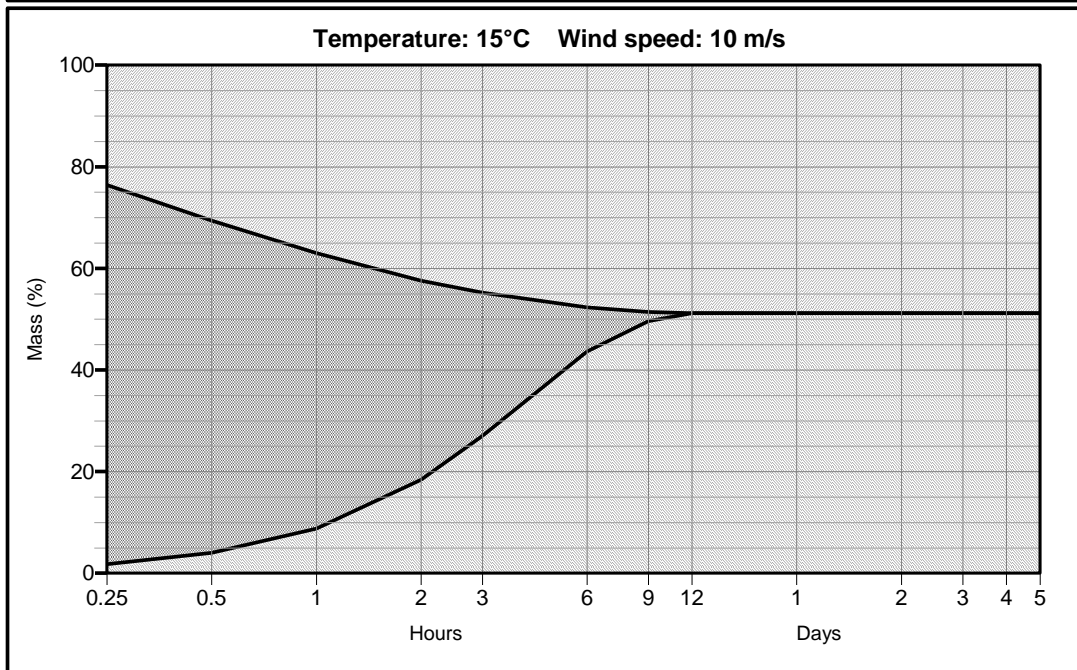


Figure 3-16 Predicted mass balance of Fogelberg predicted 15 °C, wind speeds of 10 and 15 m/s

5 Comparison of OWM predictions

Weathering predictions of Fogelberg were compared with predictions of Smørbukk condensate, Kristin, and Morvin. The predictions are based on 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. Fogelberg has a slightly higher evaporative loss compared with Smørbukk condensate, Kristin and Morvin. Among these oils, Morvin has the lowest evaporative loss, as shown in Figure 5-1, whilst Morvin followed by Maria have lower evaporative loss. The evaporative loss reflects the characteristics of the oils where condensates /light oils normally exhibit higher evaporative loss and have lower densities compared with heavier crude oils.

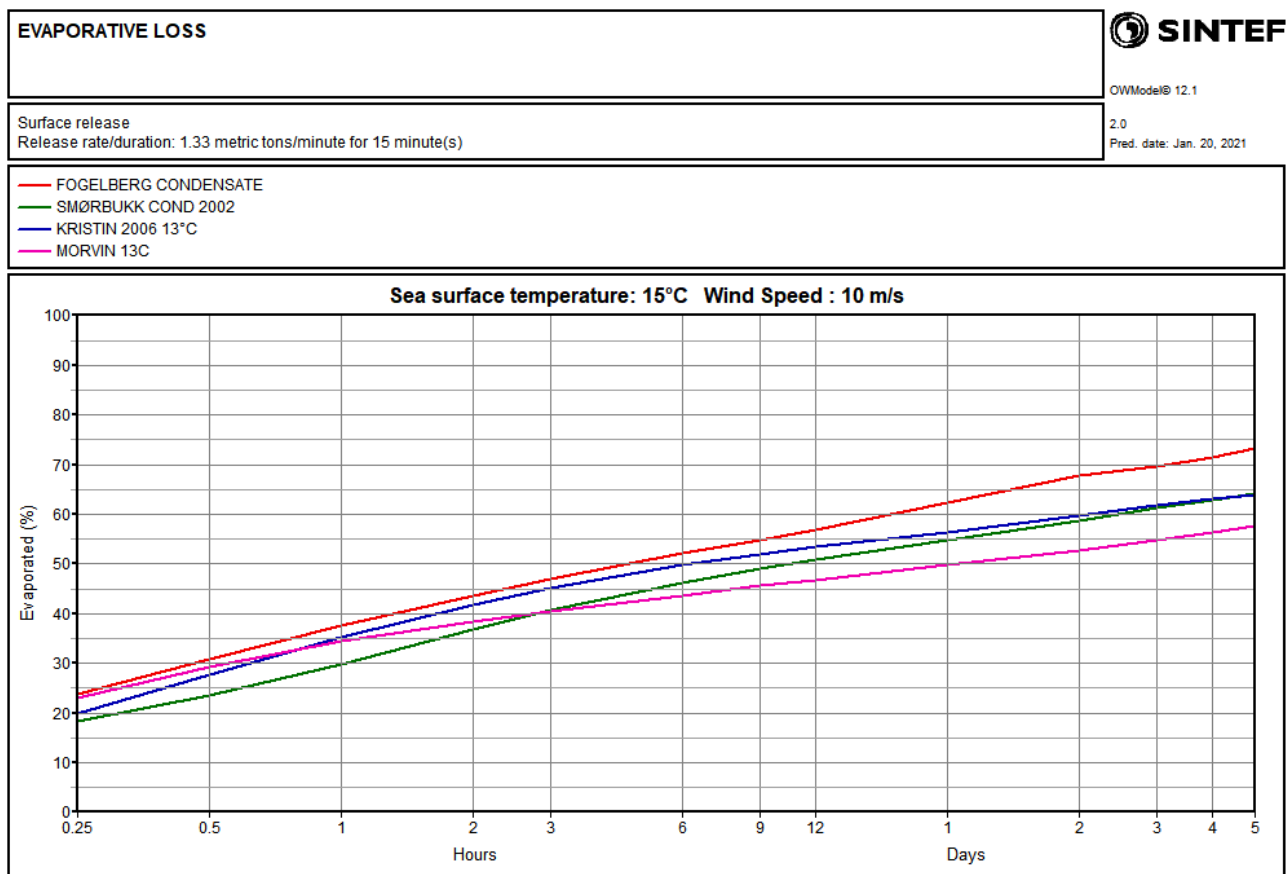


Figure 3-17 Predicted evaporative loss at 15 °C and 10 m/s for Fogelberg compared with other oils

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 3-18. Fogelberg has flash point similarities with Smørbukk condensate and Kristin. The predictions show that 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 at 10 m/s wind speed. Within 30 minutes, Kristin reaches flash point above the fire hazard limit, as for the other oils in comparison. Morvin exhibits the highest flashpoints among these oils.

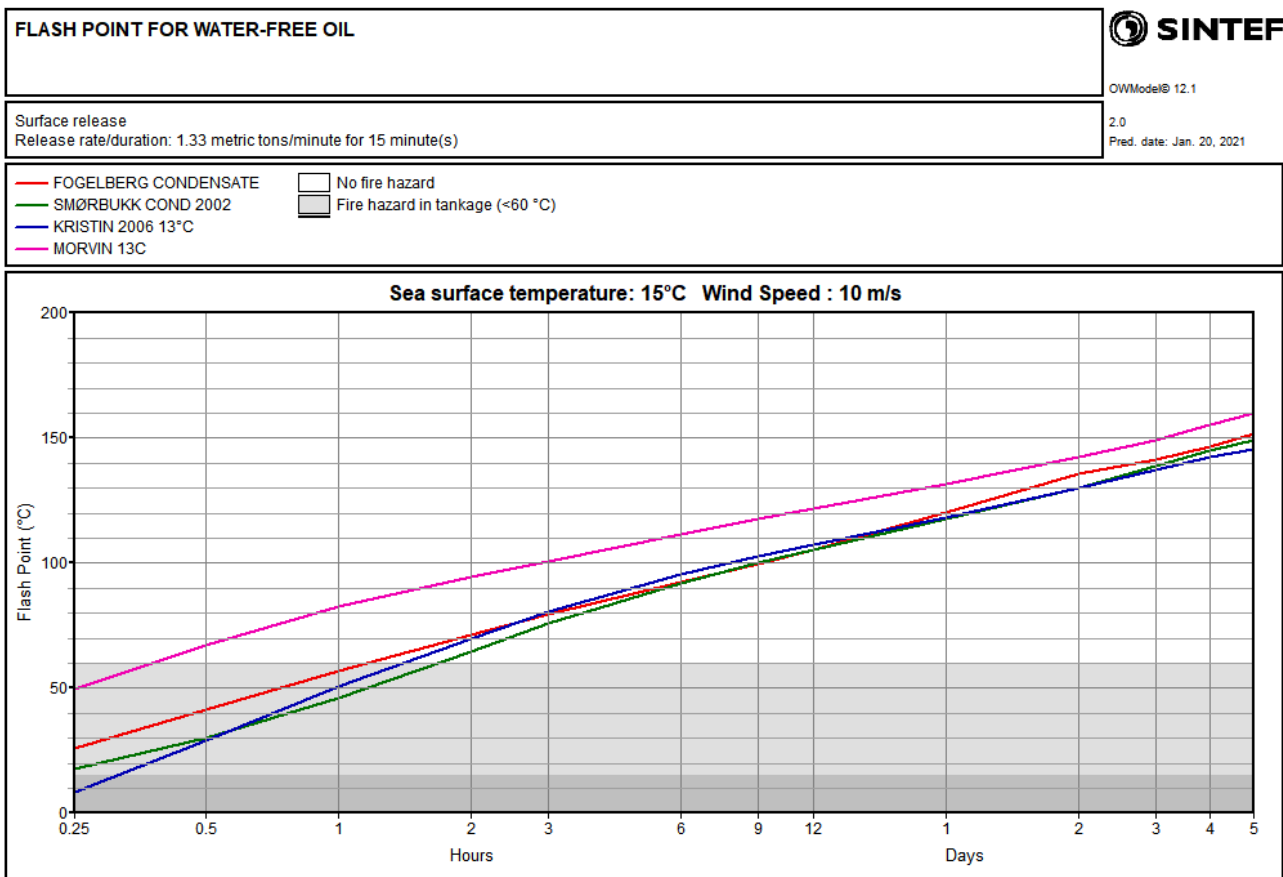


Figure 3-18 Predicted flash point at 15 °C and 10 m/s for Fogelberg compared with other oils

5.3 Pour point

The pour points of Fogelberg and the other oils in comparison are given in Figure 3-19. Fogelberg has a high pour point from the start but reaches the same level as Smørbukk condensate after 5 days of weathering. Morvin has the highest pour points among the oil in comparison. Particularly Kristin and Morvin have a potential to solidify on the sea surface by time if spilled at sea.

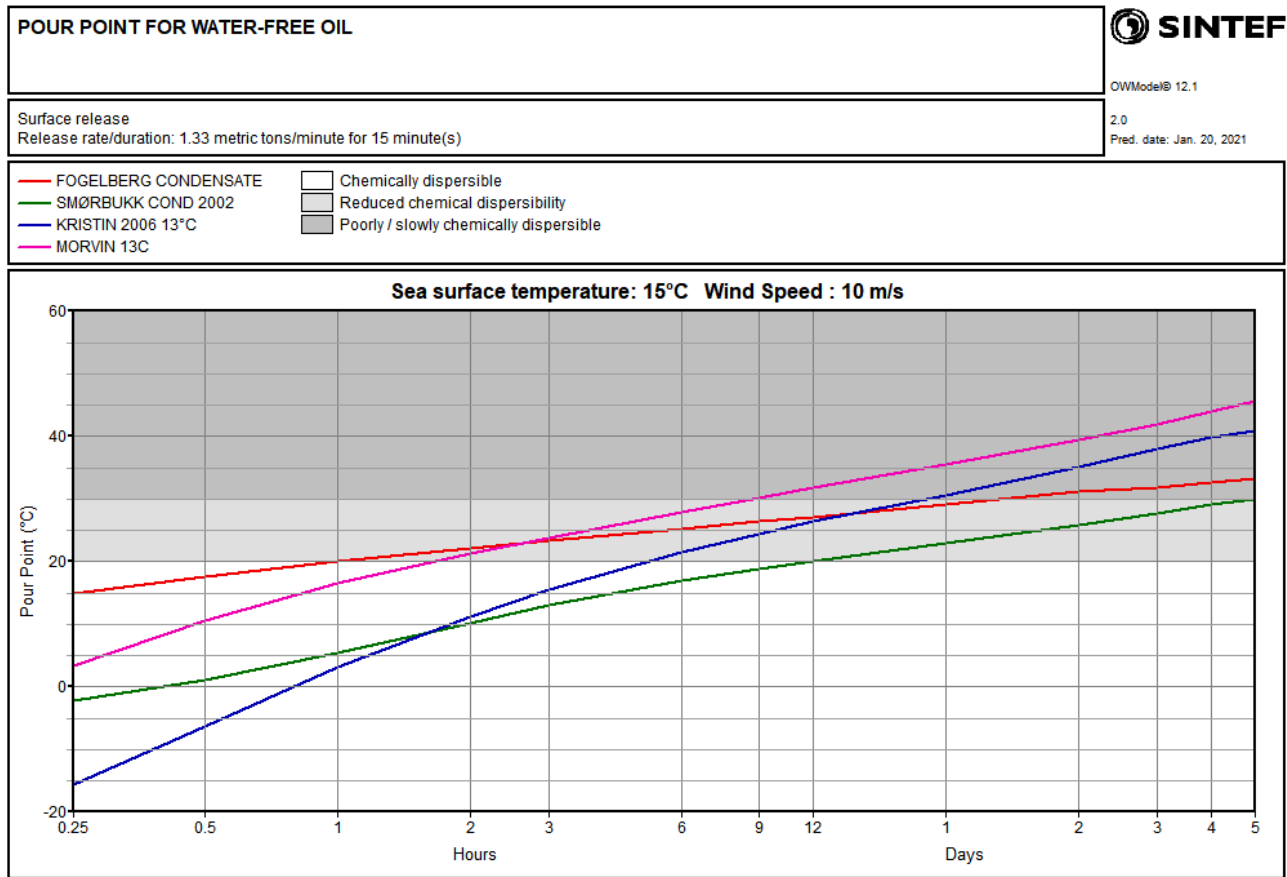


Figure 3-19 Predicted pour point at 15 °C and 10 m/s for Fogelberg compared with other oils.

5.4 Water content

The water content of Fogelberg in comparison with the other oils are shown in Figure 3-20. The predictions show that Morvin exhibits the most rapid emulsification rate and reaches the highest water uptake of 80 vol. %. Fogelberg has also a potential to reach a relatively high-water uptake by time 75 vol. % after 2 day of weathering at sea (unstable emulsions) but has a low water-uptake rate. Kristin and Smørbukk cond. reach lower water uptake among these oils.

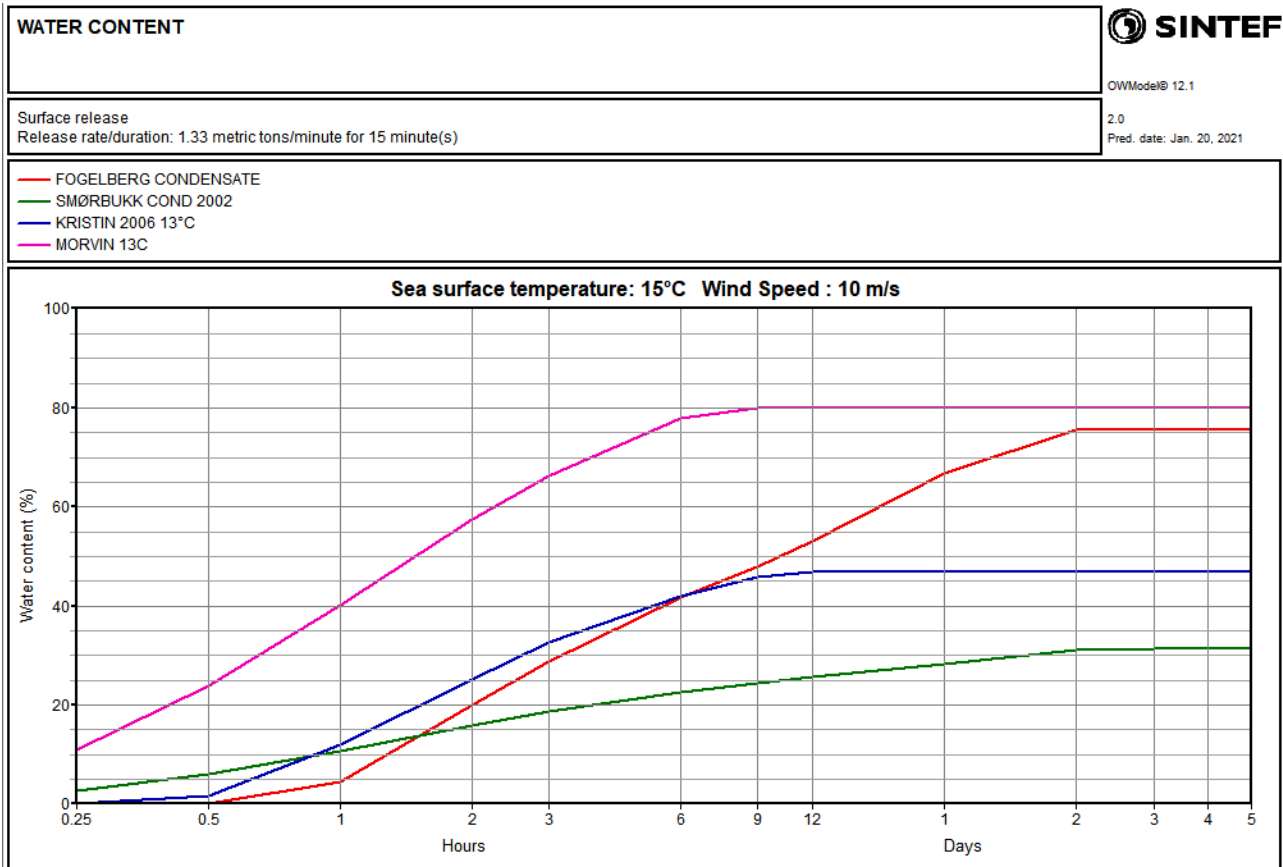


Figure 3-20 Predicted water content at 15 °C and 10 m/s for Fogelberg compared with other oils.

5.5 Viscosity

Figure 3-21 shows the predicted (emulsion) viscosities of the oils in comparison. Fogelberg has the lowest viscosity followed by Smørbukkk condensate (range of < 100-1000 mPa.s). Kristin and Morvin reach similar viscosities around 4000 mPa.s. after 5 days of weathering. In general, crude oils exhibit significantly higher viscosities than the condensates or light (crude) oils.

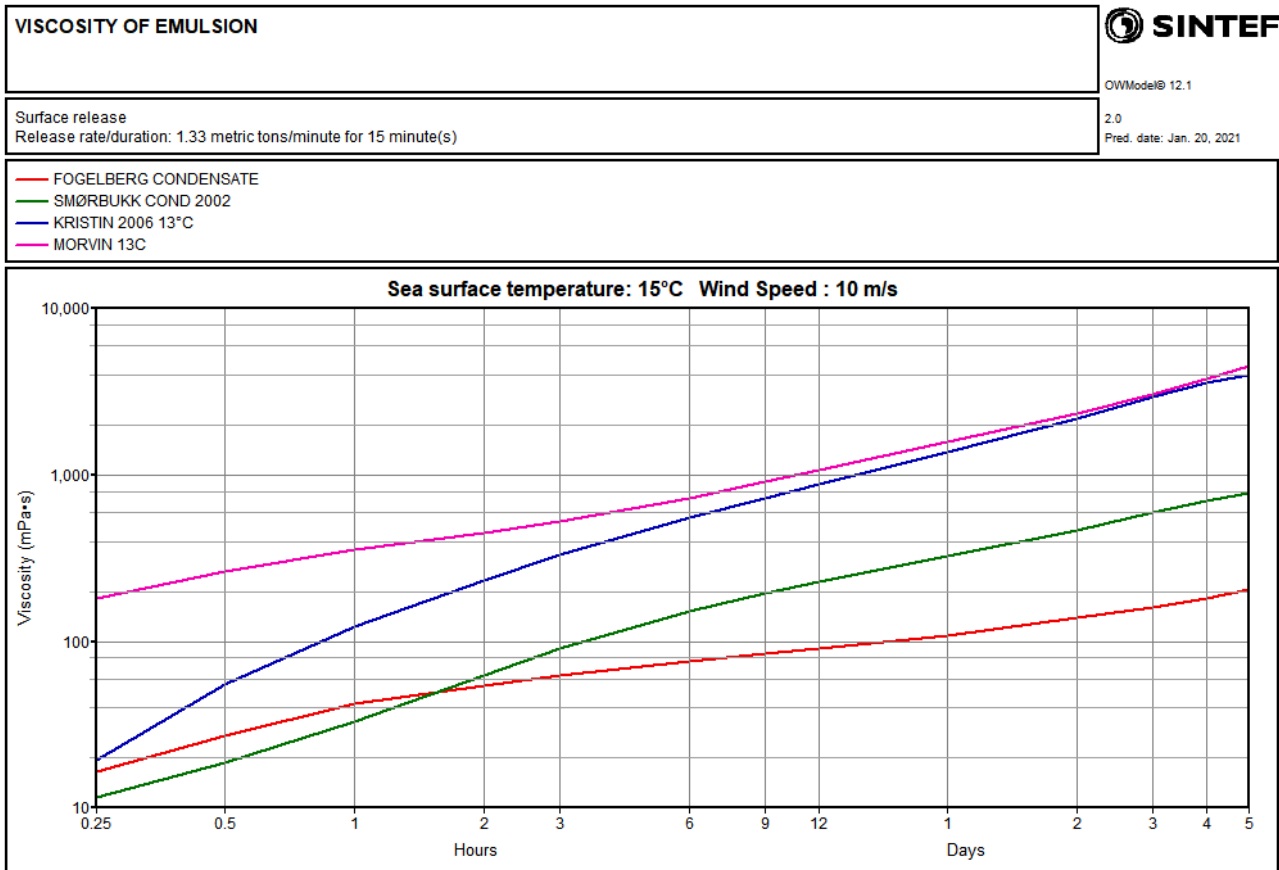


Figure 3-21 Predicted (emulsion) viscosity at 15 °C and 10 m/s for Fogelberg compared with other oils

5.6 Surface oil emulsion

The predicted surface oil emulsion is based on the evaporative loss, natural dispersion/entrainment, and emulsification. Figure 3-22 shows the predicted mass balance of remaining surface emulsion as a function of weathering. Fogelberg, Smørbukk condensate and Kristin are predicted to be removed from the sea surface due to evaporation and natural dispersion after 12 hours-2 days, whilst Morvin is more persistent on the sea surface with longer predicted lifetime.

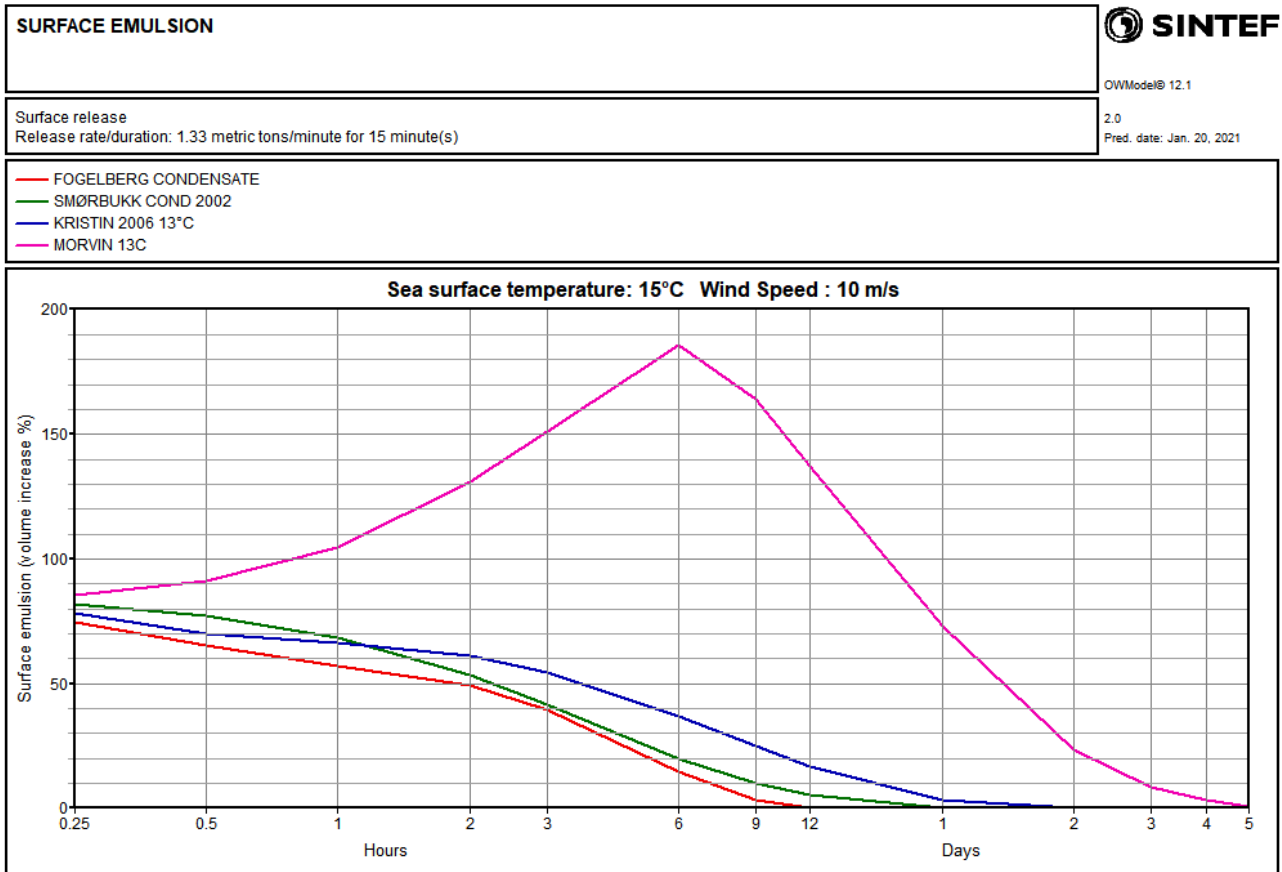


Figure 3-22 Predicted remaining surface oil at 15 °C and 10 m/s for Fogelberg compared with other oils

6 Weathering properties and response of Fogelberg

The relative content of heavy oil components within a spilled oil increases due to evaporation, 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 (artificial energy) to disperse thin oil films and low viscous oils is also discussed in this report.

6.1 Oil properties

The specific physico-chemical parameters are input to SINTEF OWM. The physico-chemical analysis of the fresh and topped residues show that Fogelberg is a paraffinic condensate with a density of 0.799 g/mL with a low content of asphaltenes (<0.01 wt. %) and a relatively low wax content of 2.8 wt. %. Fogelberg has an evaporate loss of 62 vol. % of the 250°C+ residue. The fresh oil has a viscosity of 8 mPa.s at shear rate 10s⁻¹ (13 °C) and increases by evaporation to 627 mPa.s (10s⁻¹) for the waterfree 250°C+ residue. The fresh oil has a pour point of +6 °C, that also increases significantly from +24 to +27 °C upon evaporation (200 to 250 °C+). Moreover, Fogelberg lacks the ability to form stable water-in-oil emulsions and rather forms loose low-viscous emulsions that easily break with applied mechanical stress.

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 below the seawater temperature.

The flash points for Fogelberg are 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 3-11 and Figure 6-1. In calmer weather conditions (2 and 5 m/s), care should be taken during the first hour and use of explosimeter is recommended. However, the release rate may influence on the rate of evaporation, and for considerably larger (batch) release rates e.g. 100 times higher (8000 m³/h), the rate of evaporative loss is thus reduced particularly for the first hours after the release. Such high batch release can be e.g. an incident scenario in connection to loading on vessels. For Fogelberg, 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 6-1).

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 the flash point predictions in Figure 4-5 and Figure 6-1.

As a general recommendation after an acute oil spill involving free gas (e.g. from a subsea release), a "safety" zone typically 1-2 km from the source should be established early on and downwind from the spill site before response actions are initiated in open seaways. Less than 1-hour waiting time can be predicted related to fire/explosion hazard related to the flash point of the drifting oil itself. 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.

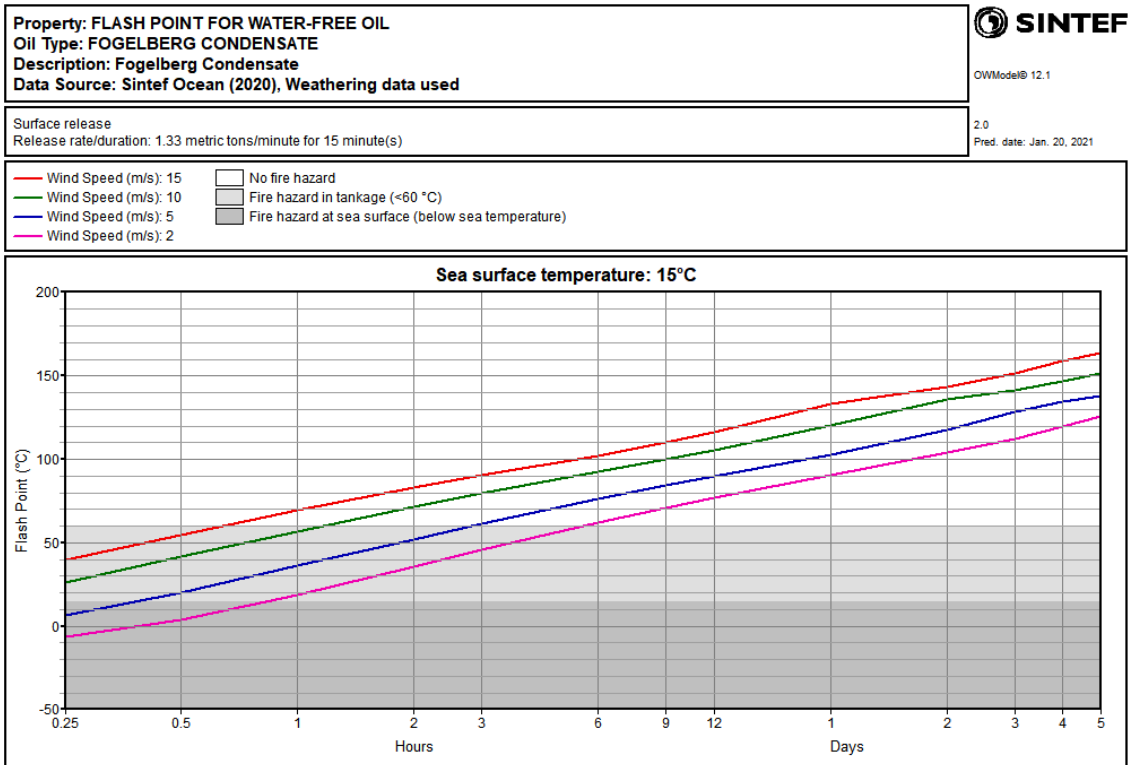


Figure 6-1 Predicted flash points for Fogelberg at 15 °C (80 m³/h)

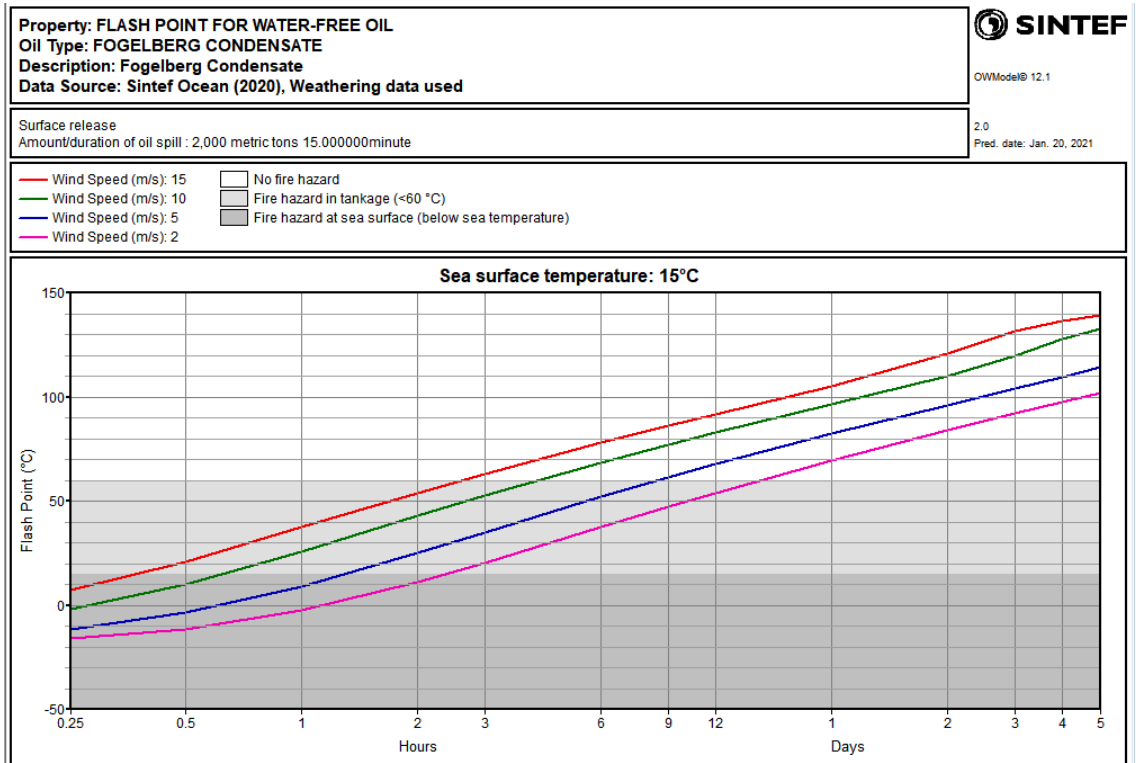


Figure 6-2 Predicted flash points for Fogelberg at 15 °C (8000 m³/h)

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.

If the oil is mixed with the seawater by waves, the wax lattice in the oil will likely be weakened and may break up. This is accordance with the emulsifying properties of the condensate from the laboratory experiments. Fogelberg has a potential form loose low-viscous emulsion, and solidifying lumps was not observed in the laboratory testing. However, due to the high pour point, a remaining residue at sea may have a potential to solidify, particularly in winter condition as shown for the pour point prediction in Figure 3-12.

6.4 Submerged oil 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). Submerged oil (natural dispersion) and evaporation are the main weathering processes that remove an oil spill from the sea 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.

Figure 6-3 shows the predicted remaining surface oil over time for different wind speeds and temperatures for Fogelberg. Only minor difference in lifetime between 5 and 15 °C for this condensate. At high wind speeds of 10-15 m/s, no oil remains on the sea surface after 12 hours of weathering at 10 m/s, and similar 3 hours at 15 m/s wind speed.

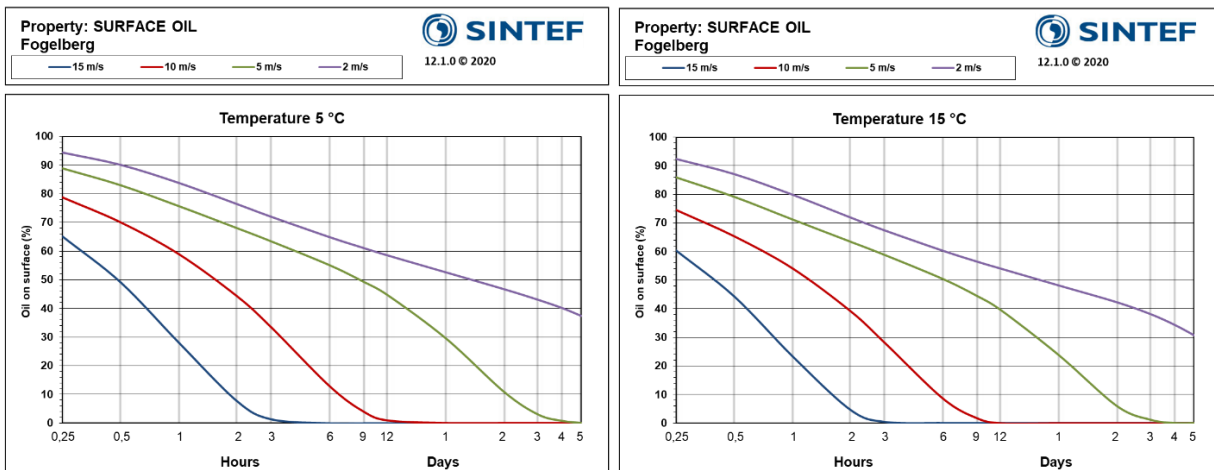


Figure 6-3 Predicted remaining surface oil for Fogelberg at 5 and 15 °C

6.5 Film thickness from surface release

In general, 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. Lower film thicknesses are likely to disperse naturally under breaking waves conditions and can be enhanced in non-breaking waves by mechanical dispersion (chapter 6.8). However, other factors than film thickness should be considered when evaluate response options, as described in the next chapters.

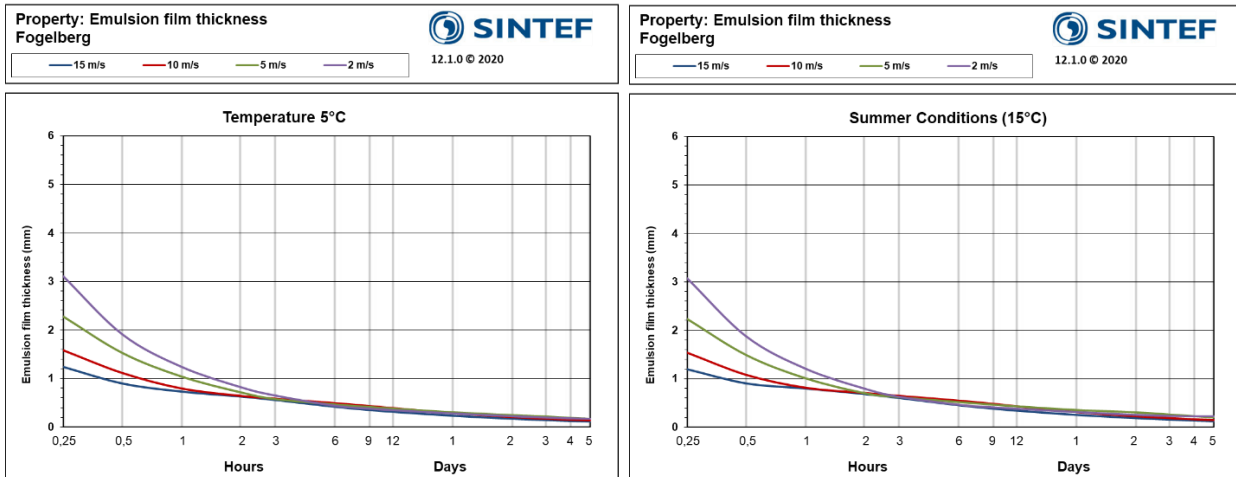


Figure 6-4 Predicted emulsion film thickness of Fogelberg after 5 days of weathering (surface batch release) at 5 and 15 °C

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.

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). 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).

For Fogelberg, the emulsion viscosities of are very low, and the risk for boom leakage is highly present during several days at sea, and should be considered in a recovery operation e.g. reducing the towing speed (Figure 6-5).

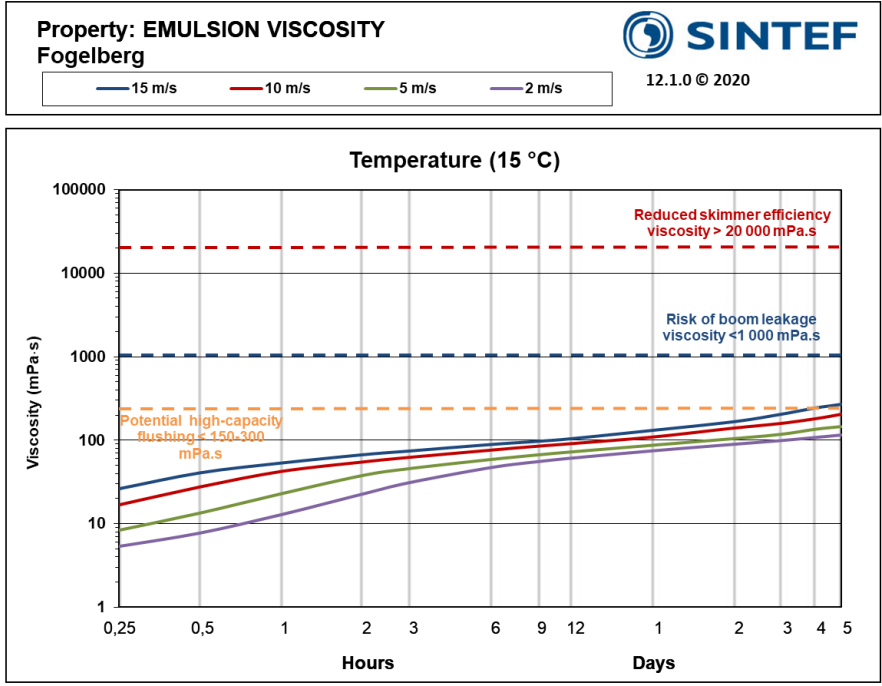
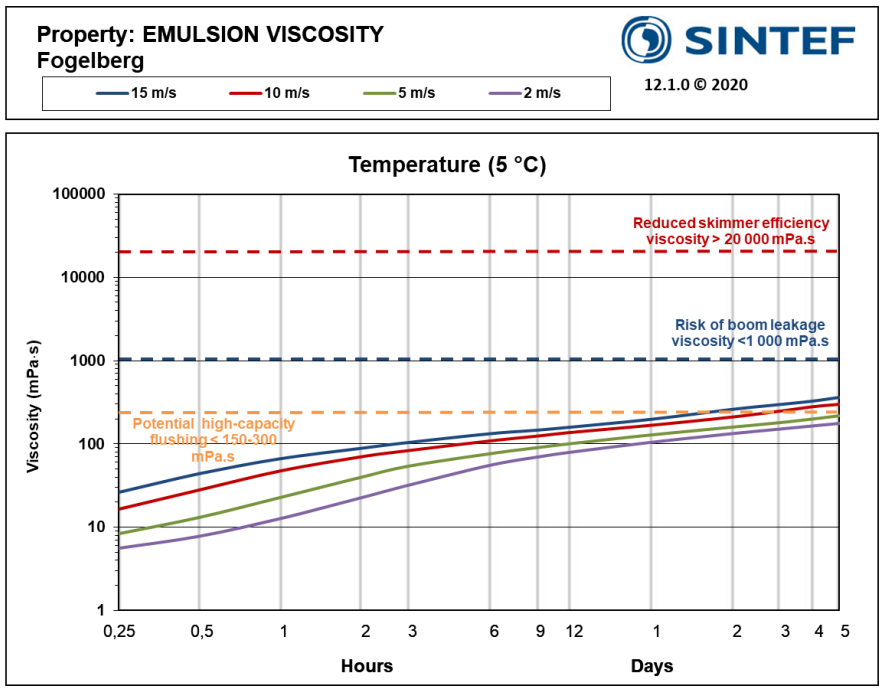


Figure 6-5 Expected time window for effective use of booms and skimmers and high-capacity water flushing (see chapter 6.8) as a function of emulsion viscosity of Fogelberg at 5 and 15 °C

6.7 Mechanical dispersion by high-capacity water flushing

In general, mechanical dispersion by high-capacity water flushing without using dispersants 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 some minutes after the dispersant treatment. 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 (NOFO), today.

For Fogelberg, mechanical dispersion by high-capacity water flushing can be considered as a possible strategy in calm weather conditions from a surface release due to low emulsion viscosities ($< 150\text{-}300\text{ mPa}\cdot\text{s}$) even up to some days at sea (Figure 6-5). However, the oil film thickness in the early stage from a surface release can be $> 0.2\text{-}0.3\text{ mm}$ (Figure 6-4) that may limit the efficiency of mechanical dispersion. In such cases a combined response strategy with use of chemical dispersant application followed by water-flushing could be beneficial particularly in non-breaking waves ($< 2\text{-}5\text{ m/s}$ wind speed).

7 Summary of response options

Surface release

For a surface release of Fogelberg with oil film thickness $> 0.1\text{ mm}$, this condensate has a potential to form (loose) emulsions if spilled at sea with low emulsion viscosities. The high pour point of Fogelberg may cause a remaining residue to solidify at sea, particularly in low temperature.

Mechanical recovery:

- The low emulsion viscosity ($< 1000\text{ mPa}\cdot\text{s}$) may reduce the efficacy of mechanical response due to risk of boom leakage.
- Risk of boom leakage and reduced recovery are expected for Fogelberg, that should be considered during mechanical recovery operations.

Use of chemical dispersants:

- Use of dispersants were not tested for Fogelberg in the laboratory. It is assuming a high degree of natural dispersion in breaking waves ($> 5\text{-}10\text{ m/s}$ wind speed), but use of dispersant could be used in combination with water-flushing in an early stage after a release if the film thickness is $> 0.1\text{ mm}$.

High-capacity water flushing (mechanical dispersion):

- Water flushing may be a strategy for thin oil film $< 0.2\text{-}0.3\text{ mm}$, but could be used in combination with dispersant application in an early phase after a release if the film thickness is $> 0.2\text{-}0.3\text{ mm}$.

Monitoring and remote sensing:

- Monitoring and remote sensing should be used as support in a response operations for Fogelberg.

Subsea release

For a subsea release with combination with gas it is likely that the initial oil film thickness of the surfacing oil is thinner than from a surface release. However, this is dependent on the release conditions (gas-oil-ratio, release rate, water depth etc.). To evaluate response options from a subsea release scenario for Fogelberg, it is recommended to perform simulation with use of the 3-D plume model (OSCAR) and predictions of oil weathering properties with the SINTEF OWM.

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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

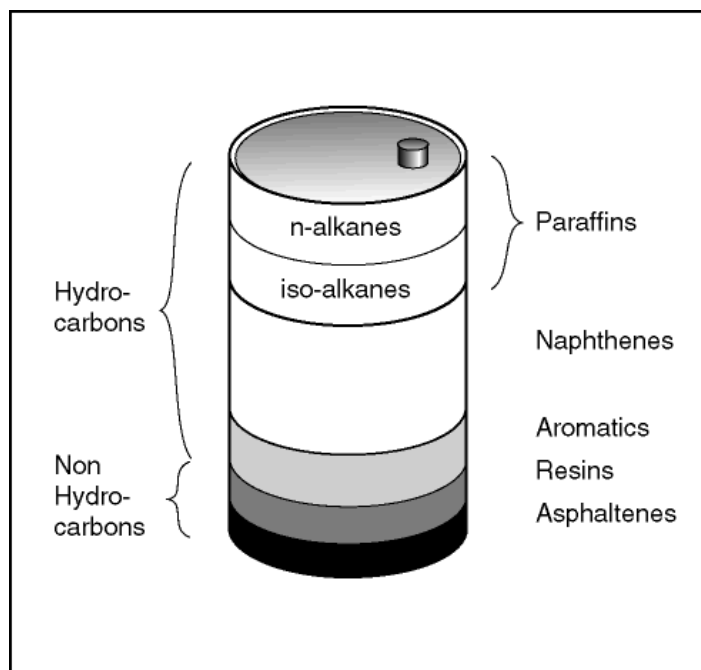


Figure A-1 The chemical composition of crude oils

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 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:

$$^{\circ}\text{API} = \frac{141.5}{\text{Specific gravity}} - 131.5$$

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/m², Pa s or kg/(m s), where 1 Pa s = 1 N s/m² = 1 kg/(m s). Absolute viscosity can also be expressed in the metric CGS (centimeter-gram-second) system as g/(cm s), dyne s/cm² or Poise, where 1 Poise = 1 dyne s/cm² = 1 g/(cm s) = 1/10 Pa s = 1/10 N s/m². https://www.engineeringtoolbox.com/dynamic-absolute-kinematic-viscosity-d_412.html The industry often uses centipoise, as the *Poise* is normally too large, 1 Poise = 100 cP and 1 cP = 0.001 N s/m². 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 exhibit 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.

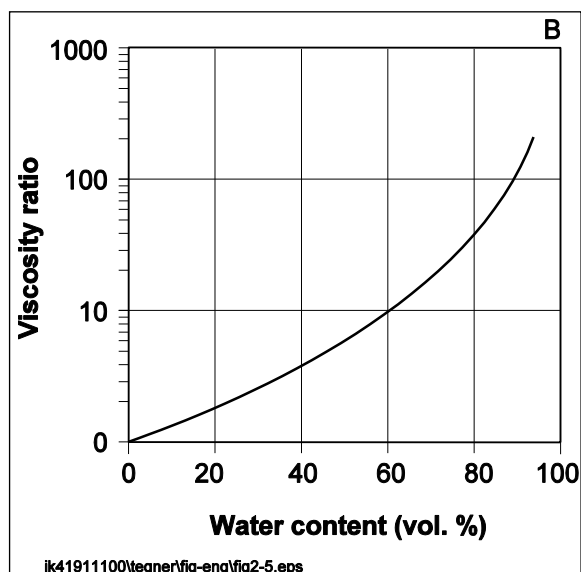


Figure A-2 Example of viscosity ratio as a function of water content

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 15°C 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.

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 that 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-3 illustrates the various weathering processes, and Figure A-4 shows their relative importance over time.

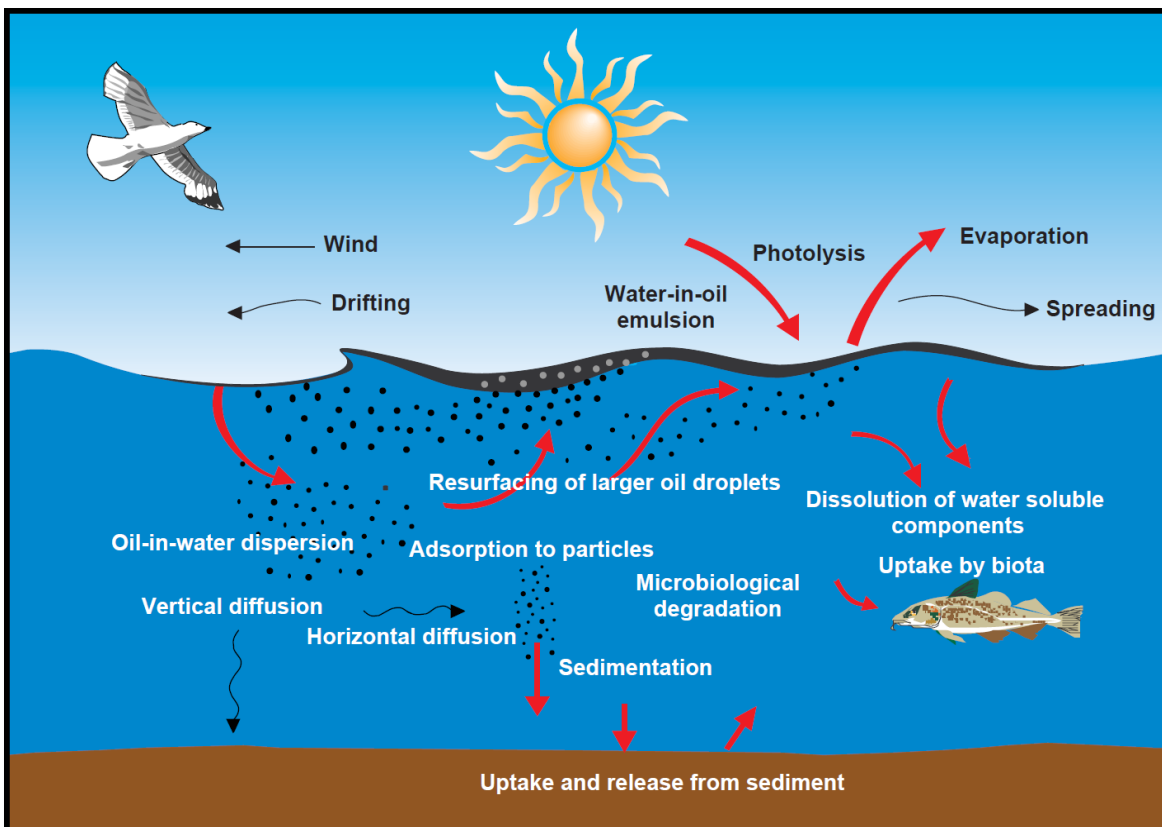


Figure A-3 Illustrating the weathering processes that take place when oil is spilled on the sea surface

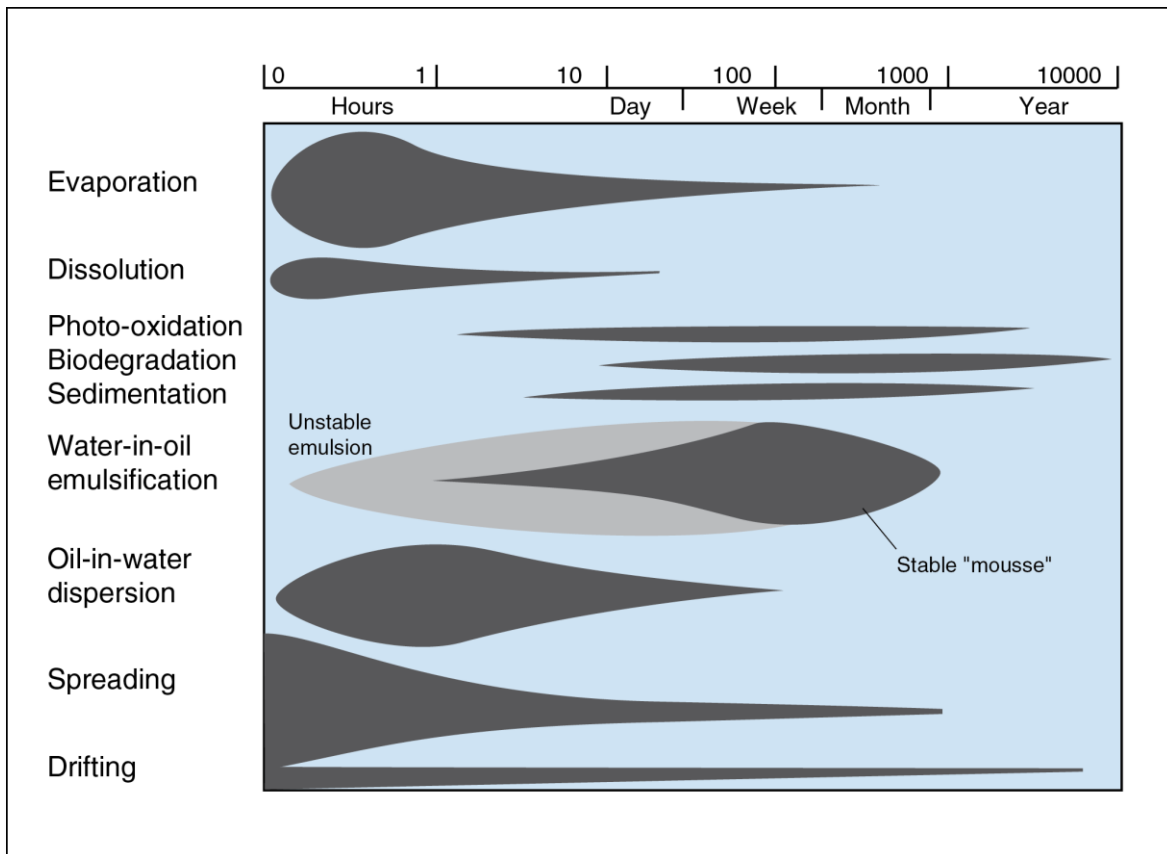


Figure A-4 Weathering processes' relative importance over time. Note: logarithmic scale

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

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.

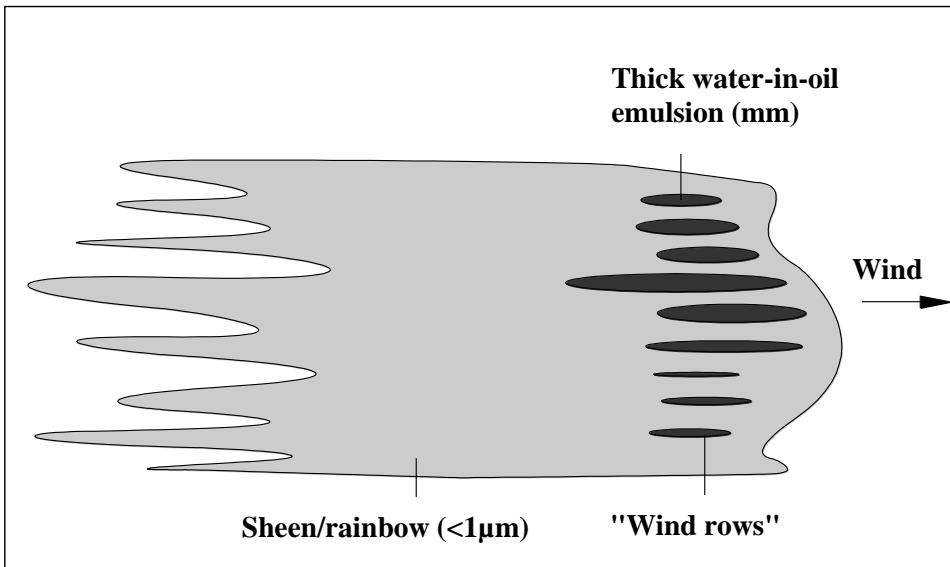


Figure A-5 The spreading of oil spilled on the sea surface and the distribution within the oil slick

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.

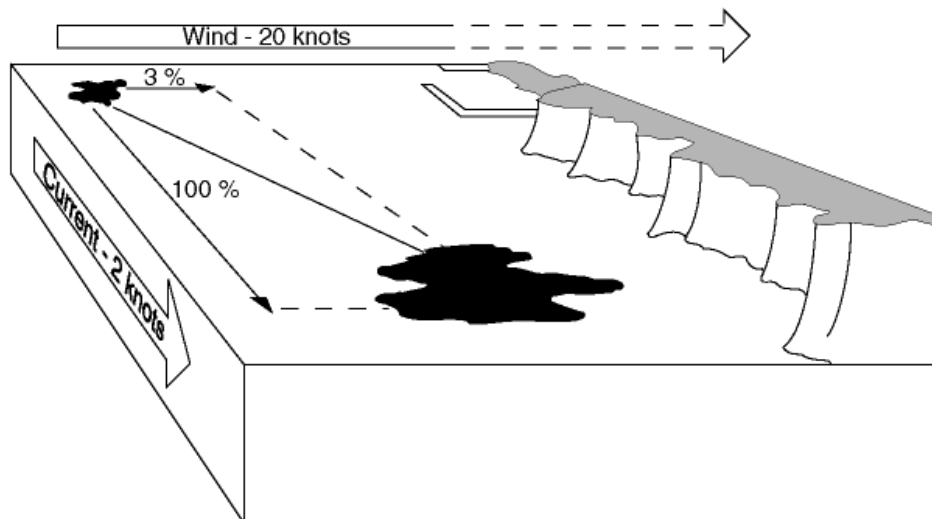


Figure A-6 An illustration showing how wind and current can influence the drifting of an oil slick

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.

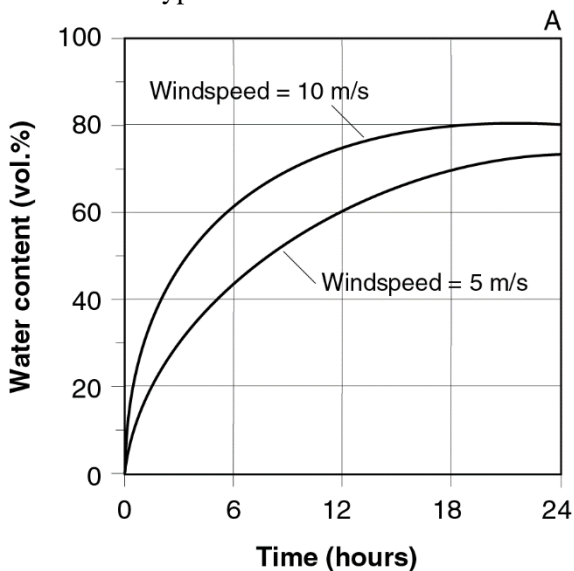


Figure A-7 Example of how weather conditions influence the w/o emulsion formation for typical oils

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.

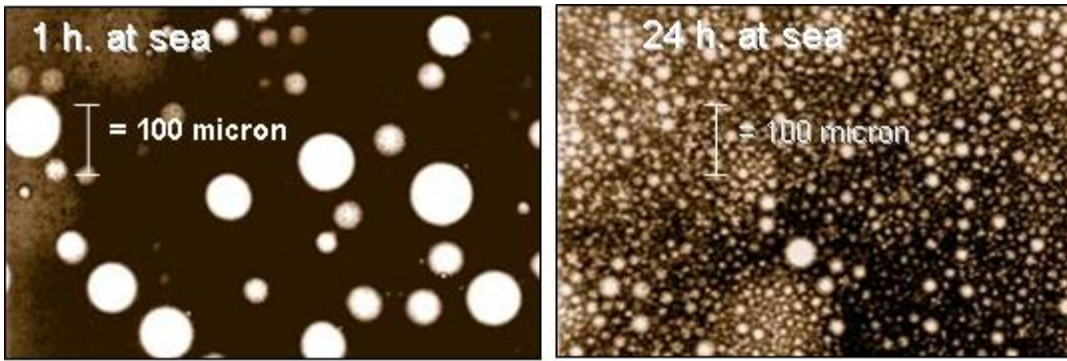


Figure A-8 Microscope pictures of w/o emulsion after (A) 1 h. and (B) 24 h. in a rotating cylinder

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.

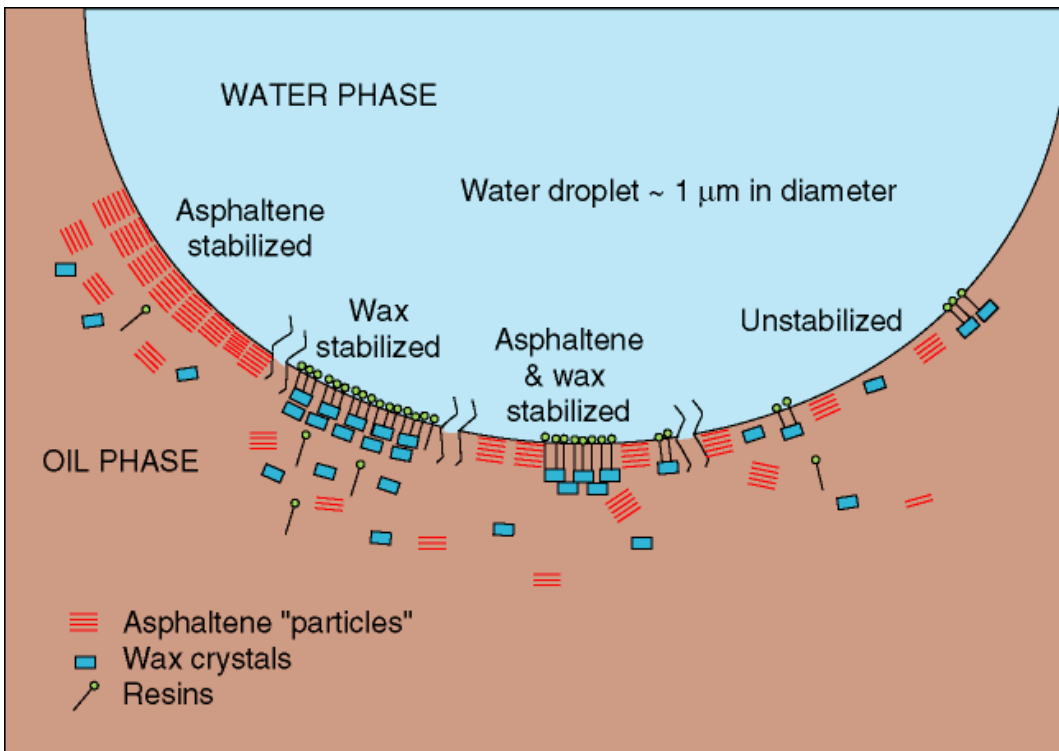


Figure A-9 Interfacial layer stabilized by wax and asphaltenes in w/o emulsion

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 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 reduce 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 C₇) 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 Lødeng, 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.

Thick surface oil slick

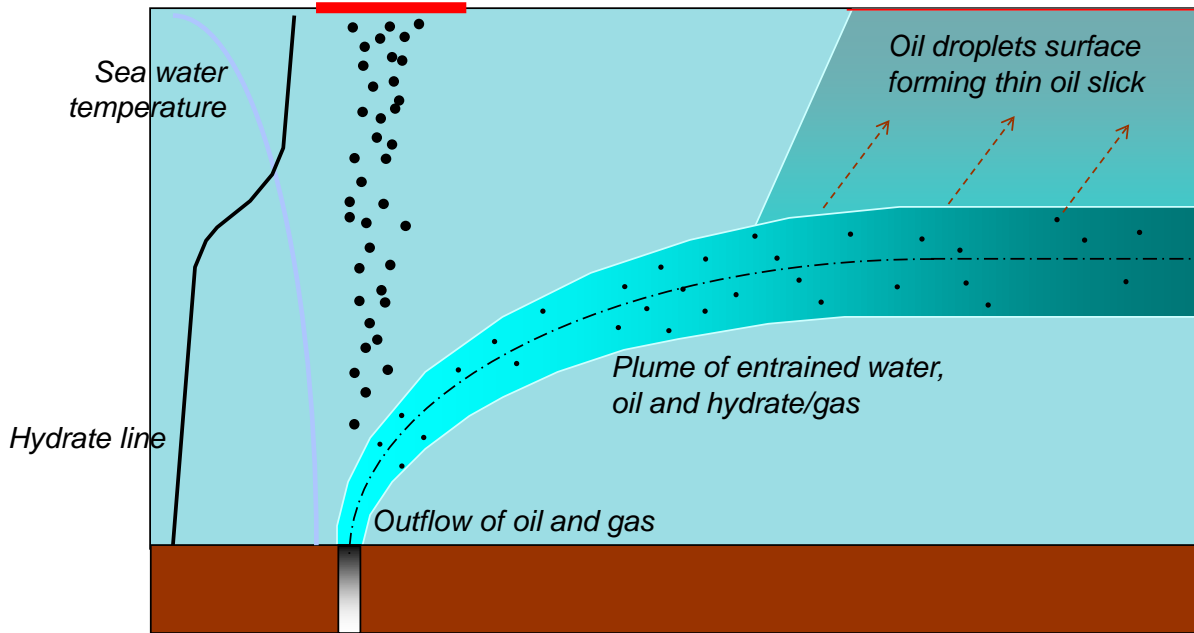


Figure A-10 Illustration of possible creation of thick surface oil slick (> 200 μm) from deep-water release of oil

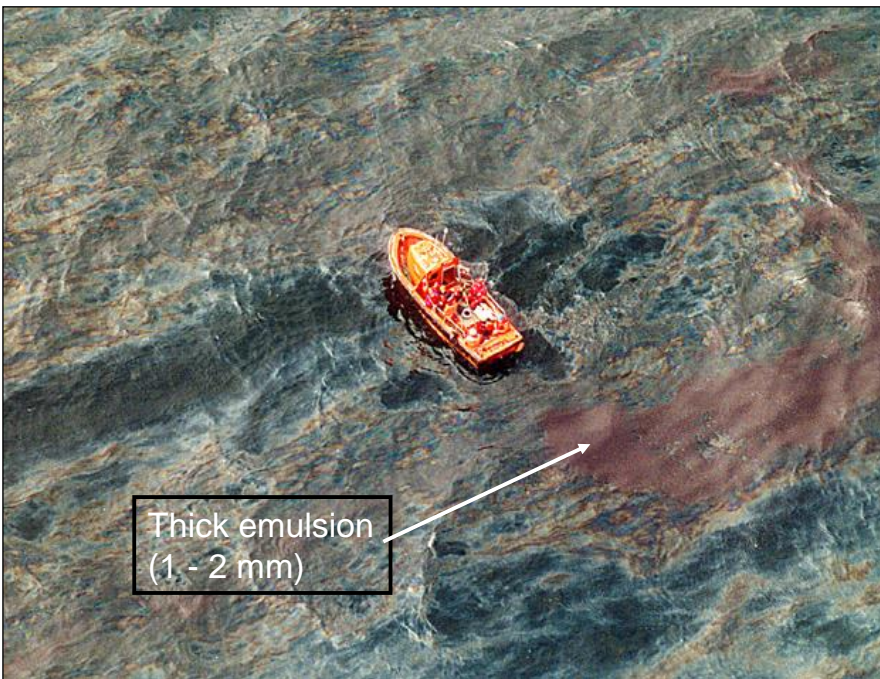


Figure A-11 Surface oil slick (initial thickness > 200 μm) from the experimental deep-water release "DeepSpill" in 2000. Surface oil is emulsifying like an oil slick from a surface batch release (from Leirvik et al., 2011)

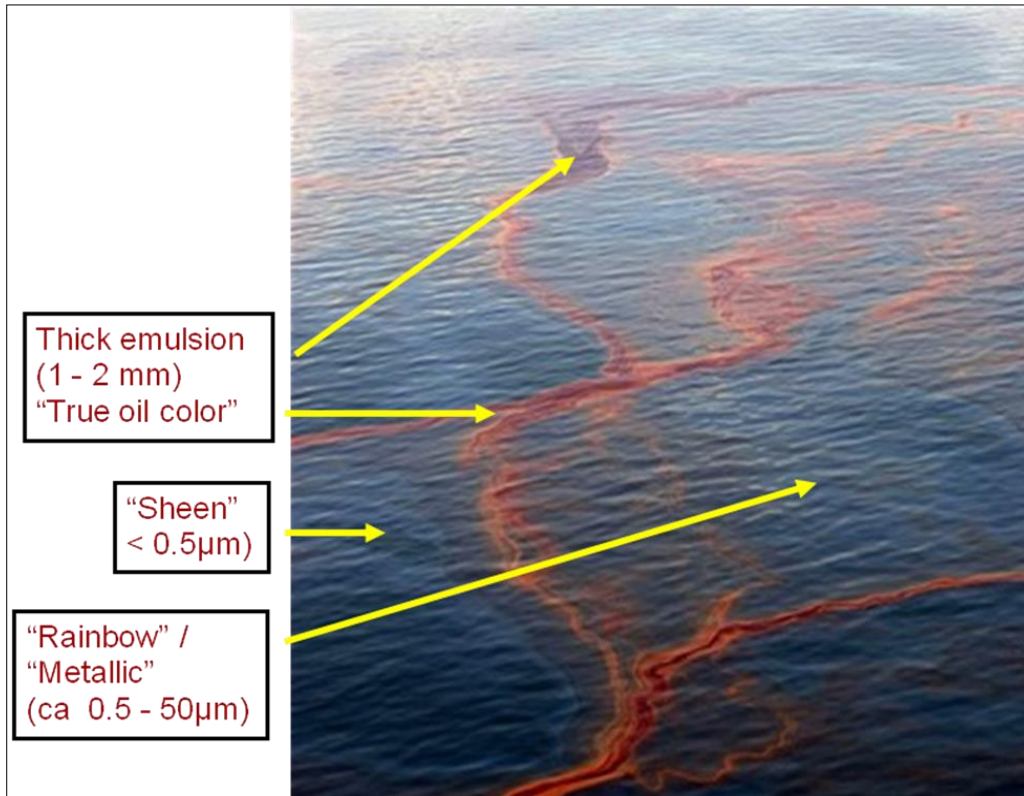


Figure A-12 Surface oil slick (initial thickness > 200 µm) from the DWH deep-water release. Surface oil is emulsifying like an oil slick from a surface batch release

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.

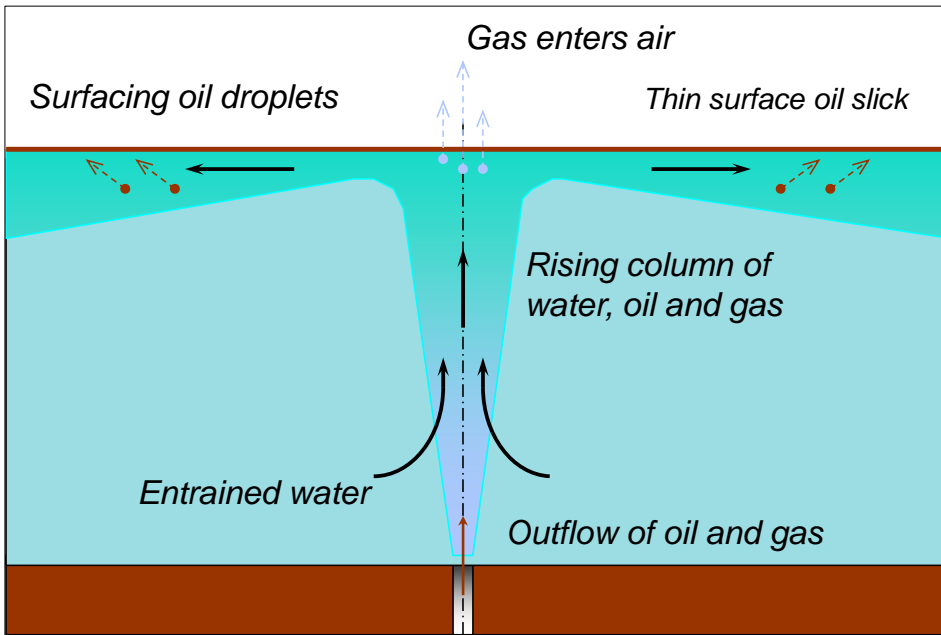


Figure A-13 Illustration of possible creation of thin surface oil slick ($< 200 \mu\text{m}$) from a shallow subsurface release ($< 500 \text{ m}$)

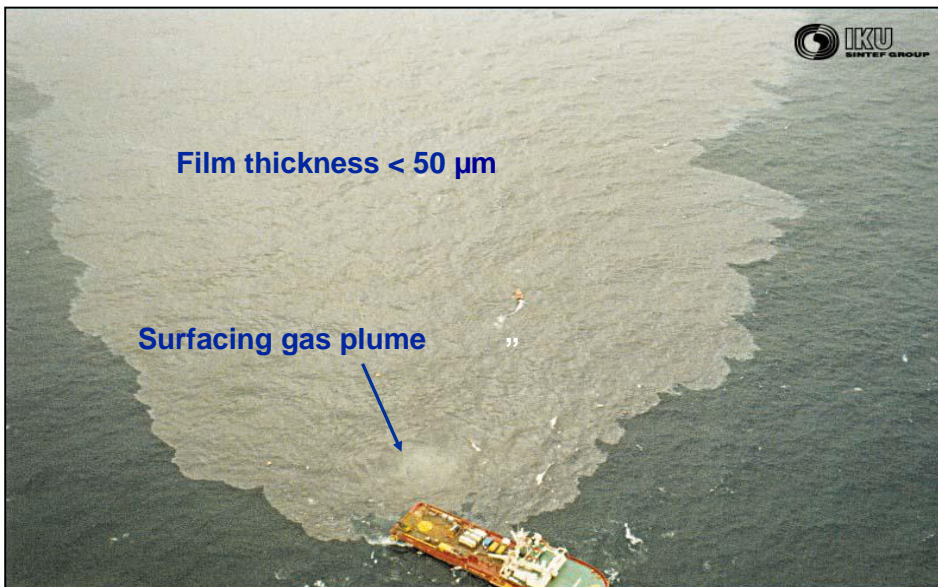


Figure A-14 Surface oil slick ($< 50 \mu\text{m}$) from experimental subsurface release at 106 m in 1996. The surface oil did not emulsify and had a very limited lifetime (hours) due to the low film thickness and high rate of natural dispersion (even at $< 10 \text{ m/s}$ wind)

B.3 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.4 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 (nC₅-nC₄₀) 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 (C₀-C₄) 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 nC₅-nC₁₀ 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).

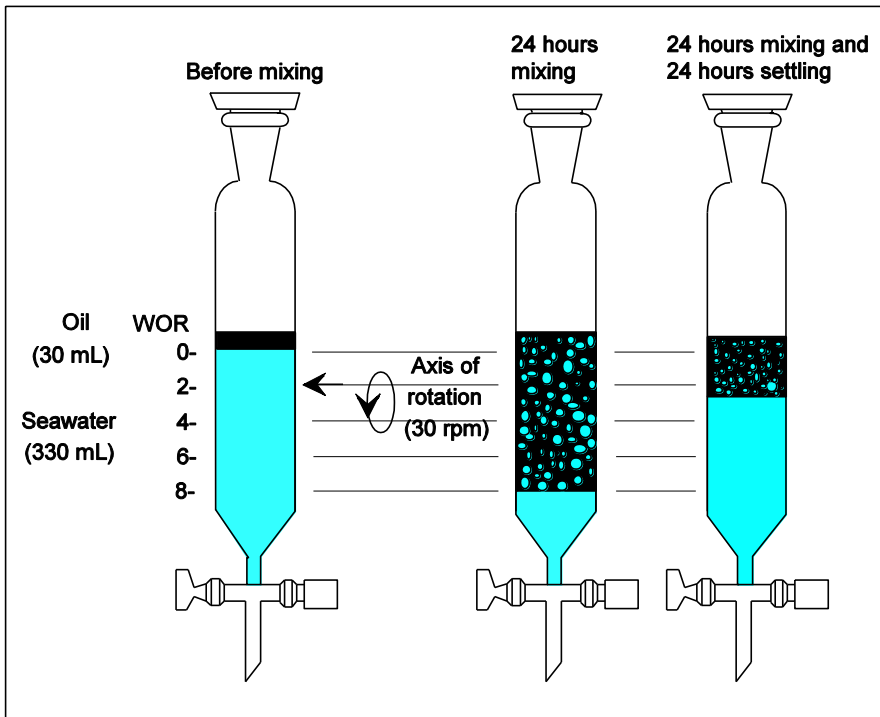
B.5 Emulsification properties

The w/o emulsification studies were performed by the rotating cylinders method developed by Mackay and Zagorski (1982), which is described in detail by Hokstad et al.,1993. The method includes the measuring of the following parameters:

- Relative water uptake (kinetics)
- Maximum water uptake
- Stability of the emulsion
- Effectiveness of emulsion breaker (Alcopol 60%)

The principle of the rotating cylinders method is illustrated in Figure B-3. Oil (30 mL) and seawater (300 mL) are mixed and rotated with a rotation speed of 30 rpm in separating funnels (0.5 L). The emulsification kinetics

is mapped by measuring the water content at fixed rotation times. The maximum water content is determined after 24 hours of rotation.



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Figure B-3 Principle of the rotating cylinder method

C Input data to SINTEF Oil Weathering Model (OWM)

The laboratory data used as input to the SINTEF OWM for Fogelberg are given in Table C-1 to Table C-3. The oil weathering predictions were based on the laboratory data at 13 °C.

Table C-1 Physical and chemical properties Fogelberg

Properties of fresh oil	Fogelberg condensate
Density (g/mL)	0.799
Pour point (°C)	6
Reference temperature (°C)	13
Viscosity at ref. temp. (mPa·s = cP) *	3
Flash point (°C)	-
Asphaltenes (wt. %)	0.01
Wax Content (wt. %)	2.8
Dispersible for visc. <	-
Not dispersible for visc. >	-

* Measured at shear rate 100 s⁻¹

** Conservative estimate

-: Not analyzed or tested

Table C-2 True boiling point (TBP) curve of Fogelberg condensate

*TBP based on crude assay Intertek West Lab AS, 2018-06050, 16.okt.2018

Temp. °C	Fogelberg Vol. %
0.01	1.1
50	4
100	16
150	32
200	46
250	58
300	70
350	80
400	87
450	94

Table C-3 Lab weathering data for Fogelberg, 13 °C

Properties	Fresh	150°C+	200°C+	250°C+
Boiling Point Temp. (°C)	-	186.4	243.7	298.6
Vol. Topped (%)	0	32	48.1	62.3
Weight Residue (wt. %)	100	70.2	54.5	40.1
Density (g/mL)	0.799	0.825	0.837	0.849
Pour point (°C)	6	18	24	27
Flash Point (°C)	-	39	77	113
*Viscosity of water-free residue (mPa.s = cP)	3	33	77	234
Viscosity of 50% emulsion (mPa.s = cP)	-	-	-	-
Viscosity of 75% emulsion (mPa.s = cP)	-	-	-	-
Viscosity of max water (mPa.s = cP)	-	46	153	89
Max. water cont. (vol. %)	-	0	0	75
(T1/2) Halftime for water uptake (hrs)	-	0.01	0.01	0.05
Stability ratio	-	0	0	0.01

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

- No data – not measured

D Chemical characterization – OSCAR composition file

The method for generating oil profile as input for OSCAR 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 of Fogelberg (fresh oil) from GC-MS analysis and TBP oil fraction

Wt.%	Comp. group no.	Fogelberg SINTEF ID 2020-8436
1.500	1	C1-C4 gasses (dissolved in oil)
4.000	2	C5-saturates (n-/iso-/cyclo)
3.003	3	C6-saturates (n-/iso-/cyclo)
1.497	4	Benzene
4.000	5	C7-saturates (n-/iso-/cyclo)
3.095	6	C1-Benzene (Toluene) et. B
9.705	7	C8-saturates (n-/iso-/cyclo)
3.351	8	C2-Benzene (xylenes; using O-xylene)
3.620	9	C9-saturates (n-/iso-/cyclo)
1.529	10	C3-Benzene
5.700	11	C10-saturates (n-/iso-/cyclo)
0.062	12	C4 and C4 Benzenes
6.938	13	C11-C12 (total sat + aro)
0.000	14	Phenols (C0-C4 alkylated)
0.298	15	Naphthalenes 1 (C0-C1-alkylated)
8.702	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
0.402	18	Naphthalenes 2 (C2-C3-alkylated)
7.598	19	C15-C16 (total sat + aro)
0.380	20	PAH 1 (Medium soluble Polyaromatic hydrocarbons (3 rings-non-alkylated;<4 rings)
6.620	21	C17-C18 (total sat + aro)
6.000	22	C19-C20 (total sat + aro)
7.712	23	C21-C25 (total sat + aro)
0.288	24	PAH 2 (Low soluble polyaromatic hydrocarbons (3 rings-alkylated; 4-5+ rings)
14.000	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.