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Report

Heidrun Åre – Weathering properties and behaviour at sea

In relation to oil spill response

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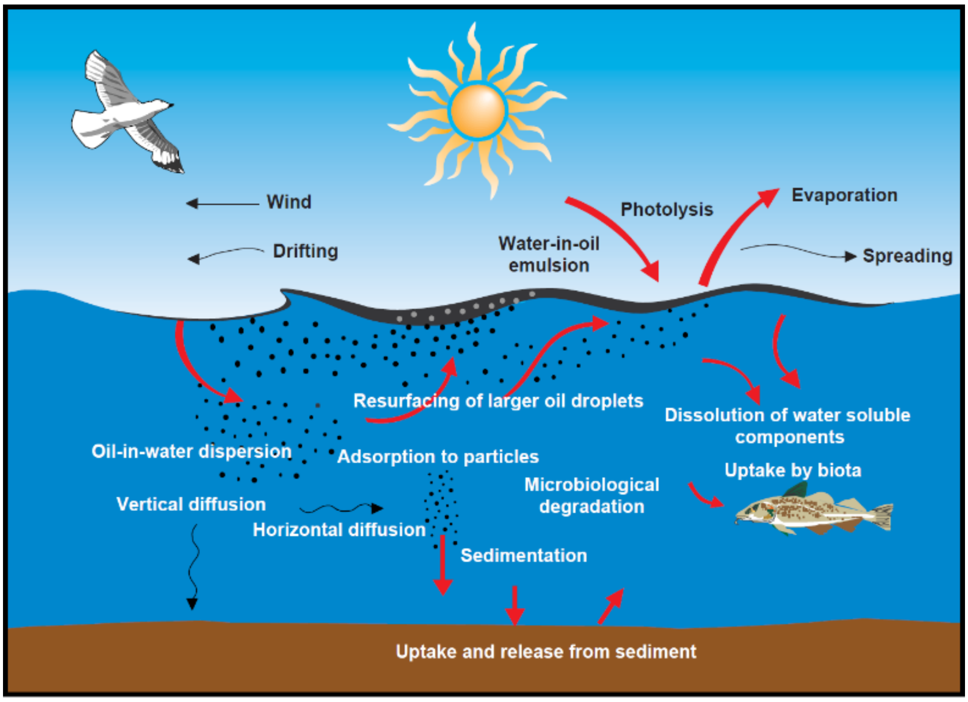

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ABSTRACT

A standardized small-scale weathering and dispersibility study has been conducted on Heidrun Åre crude oil from 2023 at 13 °C. The dispersibility testing was included to estimate the viscosity limits and time window for dispersant use. The obtained laboratory data were further used as input to the SINTEF Oil Weathering Model (OWM) for weathering and dispersibility predictions of Heidrun Åre 2023 at sea at 5 and 15 °C, reflecting winter and summer conditions. The weathering properties of Heidrun Åre are also discussed in relation to oil spill response.

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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 preparedness. Oil weathering varies over time and with different environmental conditions. The fate and behaviour, and lifetime of an oil spill at sea depends on the oil's properties, emulsification, release scenario, and environmental conditions (temperature, wind, waves). Natural dispersion and evaporation are the main weathering processes that reduced oil volumes of oil spills from the sea surface. Based on input from the experimental weathering data of Heidrun Åre 2023, 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 weathering properties for Heidrun Åre 2023 based on an oil spill scenario producing an initial oil film thickness > 0.1 mm.

Compared to many other Norwegian crude oils, this weathering study of Heidrun Åre 2023 shows the following properties relevant for the behaviour if spilled at sea with film thickness that is sufficient high to emulsify, i.e., typically higher than 0.1 mm.

- Heidrun Åre 2023 is a biodegraded/naphthenic relatively heavy crude oil with a density of 0.900 g/mL with a volatile loss of 21.6 vol.% for the 250°C+ residue that cause a relatively low degree of evaporation at sea. For example, after 12 hours, the evaporative loss is in the range of 10-15% at 10 m/s wind speed.
- The combination of low wax content (0.78 wt.%), and asphaltenes (0.15 wt.%) Heidrun Åre 2023 formed loose /semi-stable water-in-oil emulsions for the 150 and 200 °C+ residues and more stable emulsion of the 250 °C+ residue, with medium to high viscosities (<10 000 mPa.s), and maximum water uptake to about 68-73 vol%.
- The emulsion formed are expected to have a high persistency on the sea surface after some days at sea, e.g., the predictions indicate a lifetime of 2-3 days at 15 m/s wind speed. In calmer weather conditions the lifetime is predicted to be >5 days.
- As much as 83-86 % of the oil can remain on the sea surface in very calm weather conditions (2 m/s wind speed) after 5 days.
- The overall volume of the spilled oil may increase about 1.3 times relative to the volume due to emulsification.
- Heidrun Åre 2023 exbibits low pour points of -36 to -30 °C for the fresh oil and its residues and 250°C+ residues, and a potential residue at sea is therefore not expected to form semi-solid lumps that is typically for oils with high pour point, either in summer or winter conditions.

Summary of oil spill response of Heidrun Åre 2023

Risk of fire /explosion hazard in oil spill response:
Flash point refers to the lowest temperature at which an oil can vaporize to form an ignitable mixture in the air. In case of an oil release on the sea surface, the oil rapidly will be cooled to the ambient seawater temperature within a short period of time. The fire hazard, based on the evaporated volatiles from the oil, may be high if the flash point of the free-drifting oil is below the sea temperature.

The flash points for Heidrun Åre 2023 are expected to surpass the sea temperature within a few minutes at 5 and 15 °C, predicted with the standardized surface release (80 m^3/h). However, for larger instantaneous surface release rates, e.g., spill from a tanker loading, the time for the flash point to exceed the seawater 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. Heidrun Åre 2023, the tank storage limit is predicted to be surpassed within 3-9 hours in summer temperatures at low wind speeds (2-5 m/s) and within shorter time for higher wind speeds. At winter temperature, it takes longer time (>12 hours) to reach the limit of 60 °C at 2 m/s wind speed (very calm condition), and within shorter time at higher wind speeds.

For oil recovery vessels (e.g., NOFO's ORO vessels) with A class certification for transport of liquids (Class I/II, flash point <60 °C), there should not be any risks in storing the recovered emulsion in such tanks. In general, 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 always be utilized to measure concentrations of free gas to minimize the risk for fire and explosion hazard at the spill site.

Effect of adding emulsion breaker:
Use of emulsion breaker can be beneficial during an oil spill operation to remove or reduce water from the recovered oil/emulsion which minimizes the storage volume. Emulsion breakers are normally injected at the skimmer head prior to transferring the collected oil/water to storage tanks. Based on the laboratory studies, the use of emulsion breaker (Aerosol OT-SE) was efficient on the weathered oil (250°C+ residue) and limited effect on the least weathered oil (150-200°C+ residue) due to the semi-stability of the emulsion (loose emulsions). Minor difference in efficiencies for adding concentrations of 500 ppm (82-94 %) vs. 2000 ppm (87-99 %) of the emulsion breaker on Heidrun Åre 2023. Emulsion breaker is considered as not necessary for the loose and unstable emulsions during the first day but is recommended for the more weathered and stable emulsions after some days of weathering at sea.

Solidification of residue at sea:
Increased weathering may potentially increase the pour points to the point of solidification at the sea surface and typically reduces the dispersibility. Solidification typically arises in calm sea conditions (i.e. non-breaking waves) when the pour point of the oil is 5-15 °C above the seawater temperature. For Heidrun Åre 2023, the formation of solidified lumps is not likely due to its very low pour points of the fresh oils and its residues.

Mechanical recovery :
The risk for boom leakage in a mechanical recovery operation is more of a concern for low viscous emulsions (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. The predictions indicate that the emulsion viscosities of Heidrun Åre surpass 1000 mPa.s between 6 hour at 10 m/s wind speed at 5 and 15 °C, but the time may be stretched up to about 2-3 days for very low wind speed (2 m/s). Moreover, viscosities larger than 20 000 mPa.s are known to reduce the flowability of the oil/emulsion when using traditional weir skimmers. The predicted emulsion viscosities of Heidrun Åre are well below 20 000 mPa.s for 5 days weathering at sea. Overall, Heidrun Åre 2023 is therefore expected to have a wide window of opportunity for use of traditional weir-skimmer head.

Chemical dispersion (viscosity limits):
Heidrun Åre 2023 is expected to have a good potential and a long time-window (several days) for chemical dispersion compared with other crude oil. The oil was dispersible with use of Dasic Slickgone NS (DOR; dispersant-to-oil ratio 1:25) for viscosities up to 4000 mPa.s based on the low-energy test (IFP), and poorly or not dispersible for viscosities above 10 000 mPa.s based on the high-energy test (MNS). In the field, if the oil is reduced dispersible i.e., viscosities between 4000-10 000 mPa.s, additional energy e.g., thrusters, Fire Fighting (Fi-Fi) systems, higher DOR by repeated dispersant application may increase the efficiency of the dispersant treatment.

High-capacity water flushing (mechanical dispersion):
The oil emulsion viscosity and oil film thickness are the limiting factors as a stand-alone method. The predicted film thicknesses are >0.2-0.3 mm which is the estimated upper limit for effective use of water flushing. Water flushing (e.g. from Fi-Fi monitors, spray booms) could be a supplementary method if there are areas on the sea surface with thin oil films e.g., metallic /rainbow appearance in very calm weather conditions.

Monitoring and remote sensing: Monitoring and remote sensing should always be used a support in a response operations for Heidrun Åre 2023.

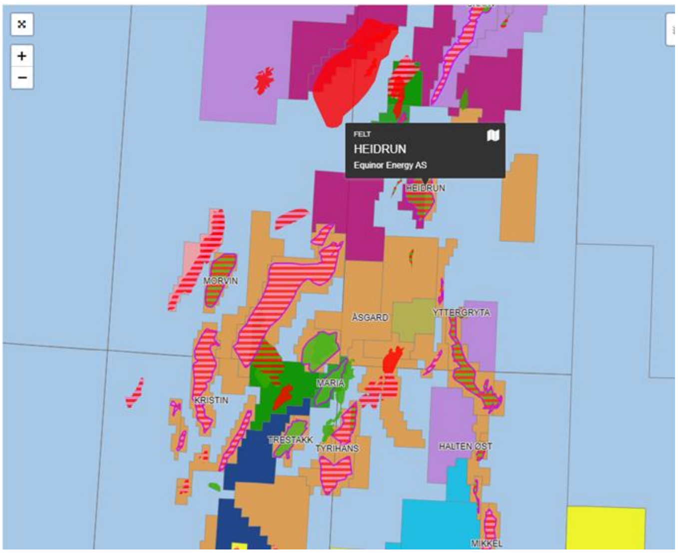
Subsurface release (blowout): An evaluation of oil spill response from a potential subsea blowout has not been evaluated for Heidrun Åre 2023. However, certain scenarios from underwater releases depending on the water depth, gas to oil ratio (GOR), release rate, release rupture diameter etc. may also produce initial film thicknesses >0.1 mm of surfaced oil, otherwise thinner initial oil films can be expected for sub-surface gas/oil releases of e.g., high GORs in shallow waters. In such cases of formation of thin oil films (<0.05-0.1 mm), the traditional response options can be limited for effective dispersant treatment or confinement in a booming operation. Water-flushing could then be a relevant method to enhance the natural dispersion.

2 Introduction

New oil types, from heavy crude oil to light crude oils and condensates, are continuously coming into production worldwide, as well as on the Norwegian continental shelf. 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 oil spilled on the sea surface.

According to the Norwegian Environment Agency (NEA) and the Norwegian Ocean Industry Authority (Havtil[1] 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 oils coming into production.

SINTEF Ocean has performed a standardized small-scale and dispersibility testing on Heidrun Åre crude oil at 13 °C. A supplementary meso-scale flume testing was considered as not necessary for Heidrun Åre due to its properties, as agreed upon with the client. The obtained laboratory data have been used to predict the weathering properties of Heidrun Åre crude oil at 5 and 15 °C, reflecting winter and summer seawater temperatures in the Norwegian Sea, by use of the SINTEF Oil Weathering Model (OWM). Such documentation gives an important basis for oil spill contingency planning and decision making during an oil spill operation. Information about the Heidrun Åre field is given, below (Figure 2-1).



Heidrun is a field on Haltenbanken in the Norwegian Sea, 30 kilometres northeast of the Åsgard field in Norwegian Sea.
The water depth is 350 meters.

Heidrun was discovered in 1985, and the plan for development and operation (PDO) was approved in 1991.

The field has been developed with the world's first floating concrete tension-leg platform (TLP), installed over a large subsea template with 56 well slots.

Production started in 1995. Heidrun produces oil and gas from Lower and Middle Jurassic sandstone in the Åre, Tilje, Ile and Garn Formations. The reservoir lies at a depth of 2,300 metres and is heavily faulted and segmented.

The oil is exported via the Heidrun B FSU onto tankers and shipped to the market. The gas is transported by pipeline to the terminal at Tjeldbergodden and/or via the Åsgard Transport System (ÅTS) to the Kårstø terminal.

Figure 2-1 *https://www.norskpetroleum.no/en/facts/field/heidrun/*

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[1] Former Petroleum Safety Authority Norway (Ptil). Changed name to the Norwegian Ocean Industry Authority (Havtil) from 1 January 2024.

3 Small-scale laboratory testing of Heidrun Åre crude oil

Description of the oil sample of Heidrun Åre for testing and the experimental setup for the small-scale and dispersibility methods are described in Appendix B. Physico-chemical parameters and weathering properties of Heidrun Åre are also compared with previous weathering studies of Heidrun Åre 2003 and Heidrun Blend 2003. The oils for comparison were selected in agreement with Equinor (Table 3-1).

Table 3-1 Crude oils compared with Heidrun Åre (SINTEF Id 2023-4732) in this report.

Oil name	SINTEF Id	SINTEF report no	Reference
Heidrun Åre 2003	2003-0348	STF80 A04009	Leirvik et al., 2004
Heidrun Blend 2003	2003-0349	STF80 A04009	Leirvik et al., 2004

3.1 Gas chromatographic (GC-FID) characterization

The hydrocarbon profile of Heidrun Åre 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 Heidrun Åre and the corresponding evaporated residues at three different degrees of evaporative loss of residues with initial boiling points 150, 200 and 250°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) corresponding to approximately 0.5-1-hour, 0.5-1 day and 0.5-1 week of weathering on the sea surface, respectively.

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 ($>nC_{40}$) are not possible to analyze with this technique.

Heidrun Åre 2023 is a biodegraded/naphtenic crude oil (Figure 3-1). The GC-FID profiles of Heidrun Åre 2023 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003 are shown in Figure 3-2. Heidrun Åre 2023 and Heidrun Åre 2003 have a high degree of UCM that indicated non-chromatographic compounds like resins. However, Heidrun Åre 2023 has become slightly less biodegraded than Heidrun Åre 2003, that is a very biodegraded oil completely lack *n*-alkanes (paraffins). Heidrun Blend 2003 on the other hand expresses a more paraffinic character with distinct peaks of *n*-alkanes, but this oil also has a relatively high abundance of UCM. 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 nC_{17}/Pristane and nC_{18}/Phytane ratios. Table 3-2 shows the ratios of Heidrun Åre 2023 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003.

Table 3-2 Ratios from GC-FID (nC_{17}/Pristane and nC_{18}/Phytane)

Oil name	nC_{17}/Pristane	nC_{18}/Phytane
Heidrun Åre 2023	1.2	2.3
Heidrun Åre 2003	ND	ND
Heidrun Blend 2003	1.4	1.9

ND: Not detected due to lack of n-alkanes

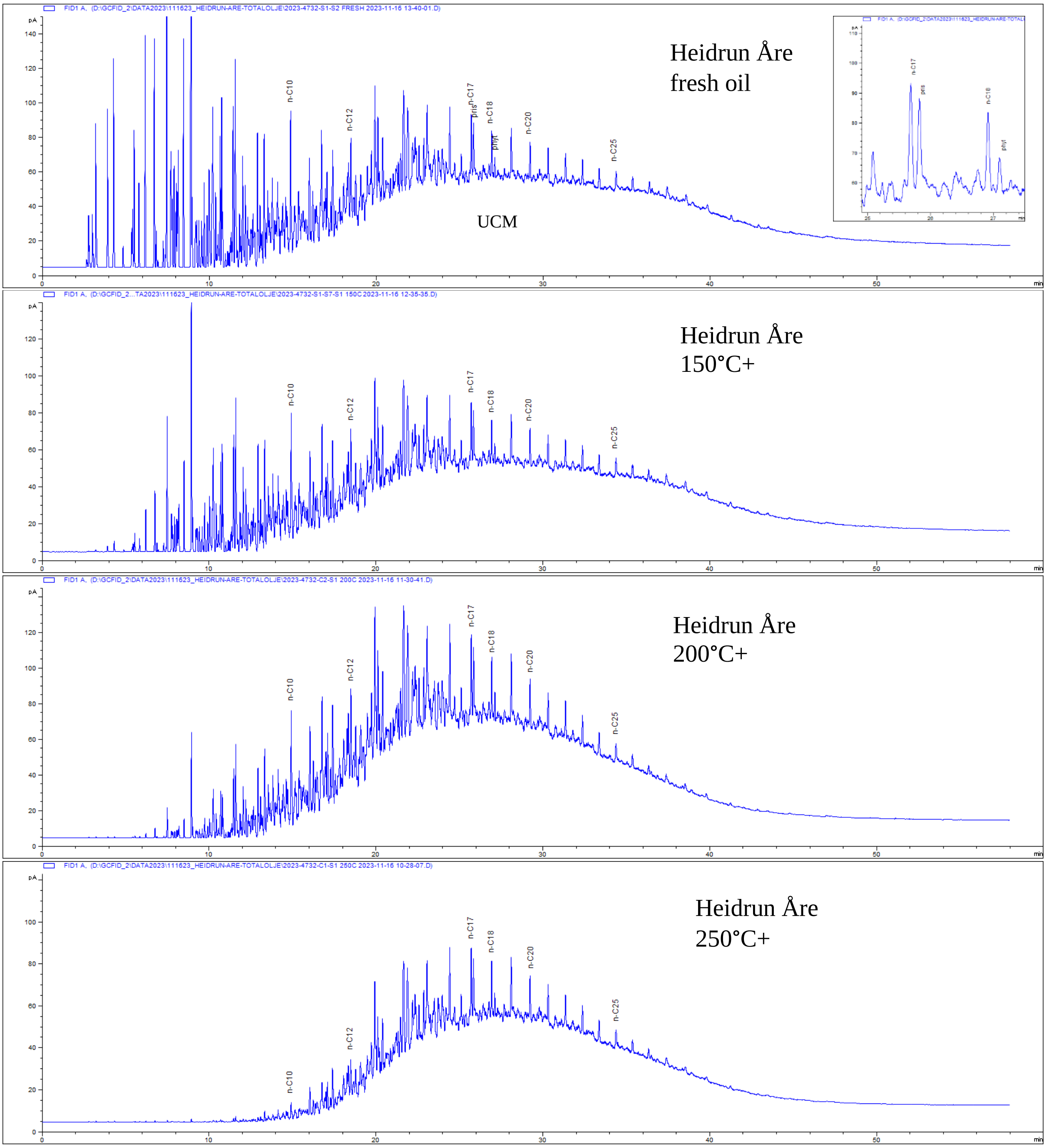


Figure 3-1 *GC-FID chromatograms of fresh oil and evaporated residues of Heidrun Åre. Normalized chromatograms based on peak nC25.*

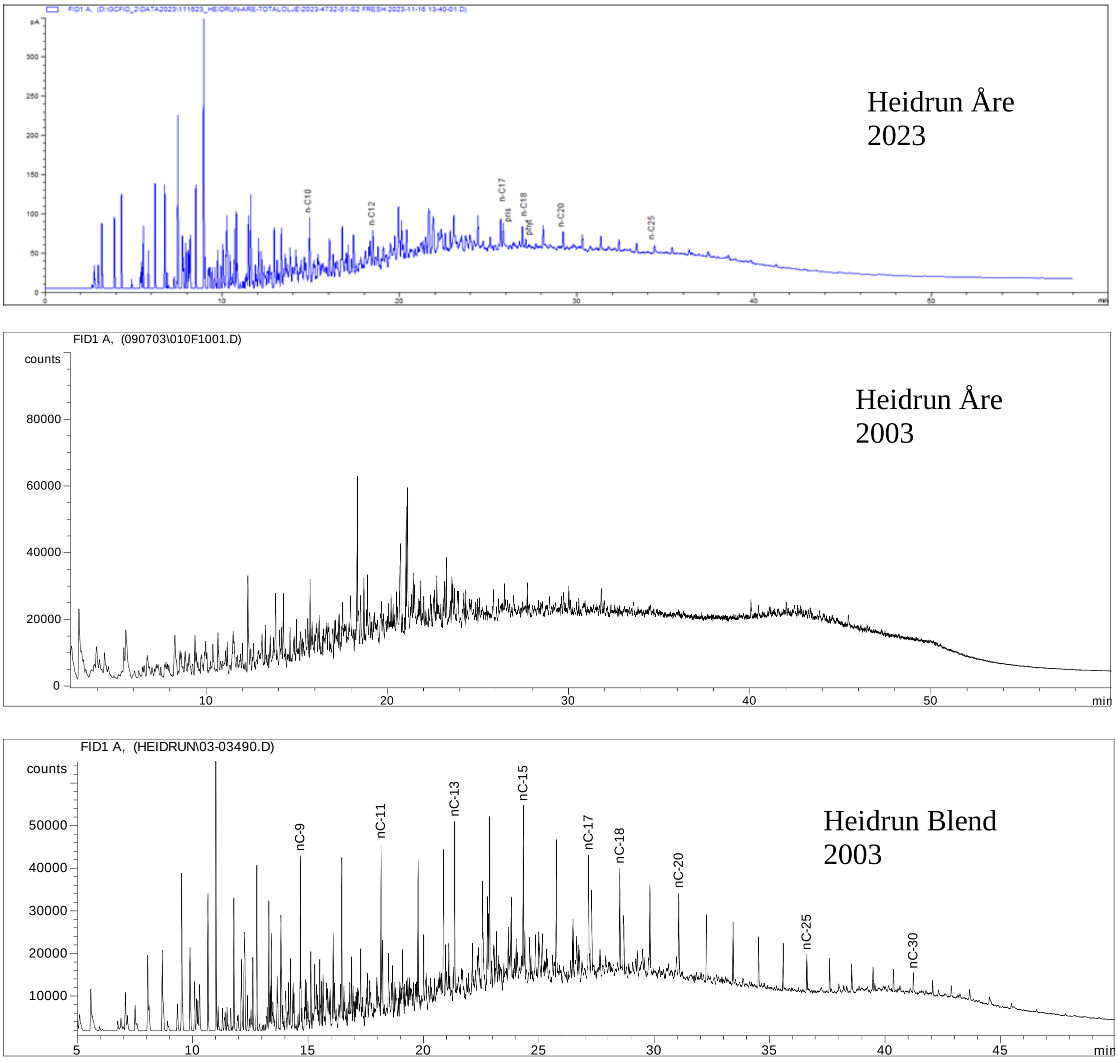


Figure 3-2 GC-FID chromatograms for fresh oils of Heidrun Åre 2023 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003. The retention times may differ between the chromatograms due to different temperature programs (relative comparison).

3.2 Asphaltenes and wax content

The content of asphaltenes and wax of Heidrun Åre 2023 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003 are shown in Table 3-3. The wax content is relatively low and has however increased for Heidrun Åre 2023 (0.78 wt.%) than in 2003 (0.3 wt.%). This is due to the slight presence of paraffinic compounds.

Table 3-3 Asphaltene ("hard") and wax content of Heidrun Åre 2023 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003.

Oil type	Residue	Asph[1) (wt. %)	Wax (wt. %)
Heidrun Åre 2023	Fresh	0.15	0.78
	150°C+	0.15	0.82
	200°C+	0.16	0.87
	250°C+	0.18	0.97
Heidrun Åre 2003	Fresh	0.30	0.30
	150°C+	-	0.31
	200°C+	-	0.32
	250°C+	-	0.35
Heidrun Blend 2003	Fresh	0.08	1.03
	150°C+	0.08	1.09
	200°C+	0.09	1.17
	250°C+	0.10	1.30

1) n-heptane (nC_7) precipitation

3.3 Physical properties of the fresh and weathered residues

The physical properties of Heidrun Åre 2023 are shown in Table 3-4 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003.

The fresh Heidrun crude oils have densities in the range of 0.892-0.926 g/mL, where Heidrun Åre 2003 has the highest density (0.926 g/mL) followed by Heidrun Åre 2023 (0.900 g/mL). The evaporative loss of Heidrun Åre 2023 is 22 vol% for the 250°C+ residue and most similar to Heidrun Blend (24 vol.%), whilst Heidrun Åre 2003 has a significantly lower evaporative loss of 15 vol. % of the same residue.

The Heidrun crude oils have all very low pour point of the fresh oils (<-36 °C) and their residues in the range of -30 °C to -24 °C for the 250°C+ residues.

The viscosities of Heidrun Åre 2023 at 13 °C, shear rate $10s^{-1}$ are 43 mPa.s of the fresh oil and in the range 66-295 mPa.s for its residues. These viscosities are most similar with Heidrun Blend 2003, whilst the viscosities of Heidrun Åre 2003 are higher (165 mPa.s of the fresh oil). The viscosities measured at 5 °C for Heidrun Åre 2023 are somewhat higher than 13 °C.

The interfacial tensions of the Heidrun crude oils are also relatively low in the range of 10-14 mN/m for the fresh oils and their residues.

Table 3-4 Physical properties of Heidrun Åre 2023, Heidrun Åre 2003, and Heidrun Blend 2003.

Oil type	Residue	Evap. (vol. %)	Residue (wt. %)	Density (g/mL)	Flash point (°C)	Pour point (°C)	Visc. (mPa.s) 5°C (10 s^{-1})	Visc. (mPa.s) 13°C (10 s^{-1})	IFT (mN/m), init.5 min)
Heidrun Åre 2023	Fresh	0	100	0.900	-	<-36	73	43	12
	150°C+	6	96	0.909	44	<-36	128	66	11
	200°C+	12	90	0.917	74	<-36	217	169	11
	250°C+	22	81	0.927	111	-30	558	295	11
Heidrun Åre 2003	Fresh	0	100	0.926	19	-39	-	165	14*
	150°C+	5	96	0.932	86	-39	-	268	12*
	200°C+	7	94	0.935	103	-30	-	338	12*
	250°C+	15	86	0.943	135	-24	-	747	12*
Heidrun Blend 2003	Fresh	0	100	0.892	-	-48	-	37	11*
	150°C+	7	94	0.905	46	-42	-	63	10*
	200°C+	14	88	0.914	89	-39	-	119	10*
	250°C+	24	79	0.924	130	-24	-	226	11*

-:No data
Measured with ASTM-method 971-82 (Du Noüy ring method)

The True Boiling Point curves (TBPs) of the Heidrun oils are shown in Figure 3-3. Heidrun Åre 2003 has the lowest distillation fraction followed by Heidrun Åre 2023 and Heidrun blend batch from 2003 and 2023. The TBPs from Heidrun Åre and Heidrun Blend 2023 are from the Equinor report FORV-22-05-30-002, 2022.

The TBPs reflect the evaporative loss of the 150, 200 and 250°C+ residues (Table 3-3), indicating a relatively low evaporative loss at sea for the oils in comparison.

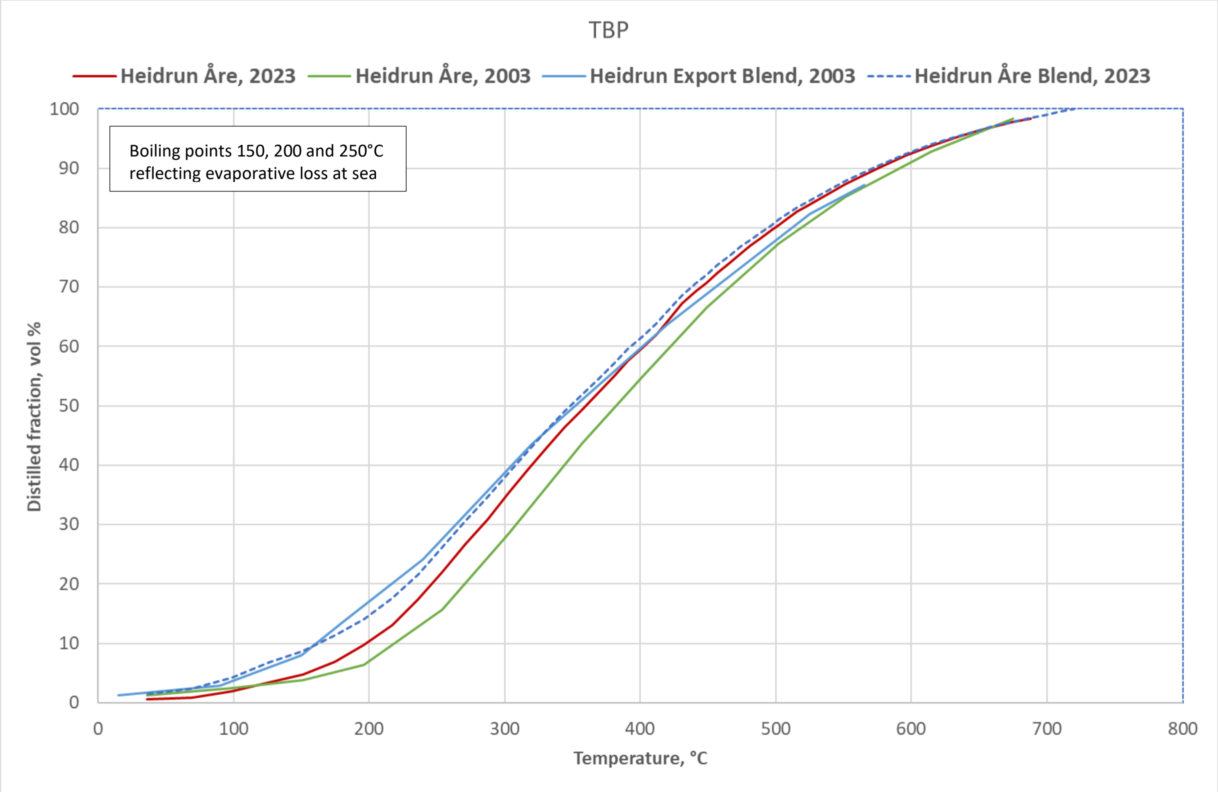


Figure 3-3 True boiling point curves of Heidrun Åre 2023 compared with other Heidrun crude oils.

3.4 Emulsifying properties

In general, oil-in water (o/w) emulsification is the mixing of seawater droplets into spilled oil at the sea surface (water-in-oil emulsion). The rotating cylinder method (Mackay and Zagroski, 1982) was used to study the emulsifying properties of Heidrun Åre 2023, and the procedure for maximum water uptake is described in Hokstad et al. 1993 (Appendix B).

3.4.1 Emulsification

Emulsification testing of Heidrun Åre were conducted on the residues of 150°C+, 200°C+ and 250°C+ to produce data for stability, viscosity, maximum water uptake, kinetics of water uptake, and the effectiveness of the emulsion breaker application. Emulsions of the maximum water content after 24 hours rotation are shown in Figure 3-4 at 13 °C, below. The figures show from left to right four emulsions prepared from the residues of 150°C+, 200°C+ and 250°C+, respectively.

Figure 3-4 Rotating cylinders of water-in-oil (w/o) emulsions of Heidrun Åre 2023 after 24 hours at 13 °C.

3.4.2 Kinetics of water uptake

The rate (kinetics) of water content in the water-in-oil (w/o) emulsions as a function of time is tabulated in Table 3-5. 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).

Table 3-5 Kinetics ($t_{1/2}$) for the emulsified residues of Heidrun Åre 2023 at 13 °C.

Mixing time	**150°C+ * (vol. % water)**	**200°C+ * (vol. % water)**	**250°C+ * (vol. % water)**
Start	0	0	0
5 min	14	12	8
10 min	17	16	14
15 min	18	20	18
30 min	27	33	35
1 hour	34	45	46
2 hours	37	56	56
4 hours	42	59	64
6 hours	49	59	68
24 hours	53	60	70
$t_{½}$	**0.61**	**0.43**	**0.63**

** Depending on weather situation and release rate, the residues are corresponding to approximately 0.5-1-hour, 0.5-1 day and 0.5-1 week of weathering on the sea surface.*

3.4.3 Efficiency of emulsion breaker and stability of emulsions

In mechanical recovery operations, separating oil from water enables optimal use of available storage (i.e., facilities/tankers), and the efficiency of this separation can be enhanced by applying emulsion breakers. The effectiveness of the emulsion breaker Aerosol OT-SE (surfactant similar fluid NOFOs stock) was evaluated on different residues of emulsified Heidrun Åre at 13 °C.

The results show that the emulsified oil volume decreased after treatment with the emulsion breaker, as water was efficiently released from the emulsion as shown in Table 3-6. Overall, there were only minor differences in the efficiency of adding 500 ppm (0.05 wt.%) vs. 2000 ppm (0.2 wt.%) of the emulsion breaker relative to the oil. Use of emulsion breaker is most recommended on the weathered oil after some days at sea, and limited effect on the least weathered oil due to the semi-stability of the emulsion (loose emulsions).

The emulsion stability was studied by quantifying the amount of volume fraction of water released from the emulsion after 24 hours settling time. Overall, Heidrun Åre 2023 formed relatively loose (semi-stable) w/o-emulsions particularly for the 150 and 200°C+ residues as shown in the first main row of Table 3-6. The emulsions released water after settling time (24 hours), with stability ratios in the range of 0.13-0.65 at 13 °C, where a stability ratio of 1.0 implies stable emulsion without release of water after settling time of 24 hours.

Table 3-6 Stability of emulsion and the effectiveness of emulsion breaker at 13 °C of Heidrun Åre 2023.

Residue Heidrun Åre 2023	Emulsion breaker	Water-in-oil emulsion (vol. %) at 13 °C		Stability ratio**	% Effect. (Released water)
		Reference	**24 hours settling ***		
150ºC+	None	53	17	0.17	83
200ºC+	None	60	17	0.13	87
250ºC+	None	70	61	0.65	35
150ºC+	Aerosol OT-SE 500 ppm	53	14	0.14	86
200ºC+	Aerosol OT-SE 500 ppm	60	21	0.18	82
250ºC+	Aerosol OT-SE 500 ppm	70	12	0.06	94
150ºC+	Aerosol OT-SE 2000 ppm	53	9	0.09	91
200ºC+	Aerosol OT-SE 2000 ppm	60	17	0.13	87
250ºC+	Aerosol OT-SE 2000 ppm	70	3	0.01	99

** Reference: w/o emulsion after 24 hours rotation*

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

*** Stability ratio of 0 implies a totally unstable emulsion after 24 hours settling; all the water is settled out for 24 hours settling. Stability ratio of 1 implies a totally stable emulsion.*

*** Stability ratio of 0 implies a totally unstable emulsion after 24 hours settling; all the water is settled out for 24 hours settling. Stability ratio of 1 implies a totally stable emulsion.*

3.5 Emulsion viscosities and yield stress

The viscosities of emulsified residues of Heidrun Åre 2023 at 13 °C are given in Table 3-7 (including fresh oil and waterfree residues). The emulsions behave as *non-Newtonian* fluids due to the increasing degree of weathering (evaporation and water uptake), with higher viscosities at a lower shear rate (10 s^{-1}) compared to the viscosities measured at higher shear rate (100 s^{-1}). This decrease in viscosity with increasing shear rate is due to the shear thinning property of emulsion with increased mechanical force.

Yield stress is defined as the force that must be overcome so that an oil can spread or flow like a liquid on the sea (also known as the flow limit). This force is called the fluids "yield stress" or flow limit and is given the unit Pascal (Pa). Yield stress is measured with Physica MRC 300 rheometer. Many crude oils (particularly weathered residues and emulsions) are so-called *Bingham-plastic* fluids at sea temperature. This means that applied force must be exerted to the fluid to make it flow and spread and is mainly pronounced for *non-*

Newtonian oils where the viscosities vary with the shear rate. The oil /emulsions of Heidrun Åre 2023 have low yield stress (Table 3-7), compared with typically paraffinic waxy crude oils with higher pour points.

Table 3-7 Viscosities waterfree residues and emulsions of Heidrun Åre 2023 at 13 °C.

Heidrun Åre 2023	**Water content (vol. %)**	**Viscosity 13 °C (mPa.s) 10 s^{-1}**	**Viscosity 13 °C (mPa.s) 100 s^{-1}**	**Yield stress Pa**
Fresh	0	43	42	n.d
150°C+	0	66	65	n.d
200°C+	0	169	111	n.d
250°C+	0	295	284	n.d
150°C+	50	471	274	n.d
200°C+	50	804	451	n.d
250°C+	50	1853	1052	n.d
150°C+	75	1295	550	2
200°C+	75	1514	613	5
250°C+	75	3896	1702	12
150°C+	56	691	364	n.d
200°C+	62	1254	583	7
250°C+	72	4288	1687	15

n.d: Not detected.

3.6 Chemical dispersibility

The dispersibility testing of Heidrun Åre 2023 included:

- Screening of dispersant effectiveness.
- Dosage testing of a relevant dispersant.
- Systematic testing on weathered /emulsified samples as a basis to predict the time-window for effective application of dispersant.

3.6.1 Screening testing of dispersants

The screening testing was performed using the low-energy IFP test (Institute Français du Pétrole), reflecting non-breaking waves (<2-5 m/s wind speed), in combination with the high-energy MNS test (Mackay-Nadeau-Szeto), reflecting breaking waves conditions (>5-10 m/s wind speeds). Dispersants tested were Dasic Slickgone NS, Corexit 9500A, Finasol OSR-52, and Gamlen OD 4000. The screening testing was performed 13 °C using the 200°C+ residue emulsified with 50 vol. % seawater with a dispersant of oil ratio (DOR) 1:25. DOR=Dispersant to oil ratio /DER=Dispersant to emulsion ratio. The results are presented in Table 3-8 and in *Figure* ***3-5***.

The IFP test showed dispersant effectiveness in the range 63-75%, where Dasic Slickgone NS (71%) and Corexit 9500A (75%) were the most efficient dispersants. Dispersant efficiency >50% for the low-energy test (IFP) is considered as good dispersion. Dispersant efficiency >75% for the high-energy MNS test is considered as good dispersion, and all the Dasic Slickgone NS and Corexit 9500A showed both dispersibility of 100%.

Table 3-8 Screening testing on Heidrun Åre 2023 using the IFP-test and MNS-test at standard temperature of 13 °C.

Dispersant (DOR/DER =1:25)	Efficiency dispersant (200°C+ /50 vol. % emulsion)* IFP	Efficiency dispersant (200°C+ /50 vol. % emulsion)* MNS
Dasic NS	71	100
Corexit 9500A	75	100
Finasol OSR 52	59	-
Gamlen OD 4000	63	-

** Emulsion viscosity: 804 mPa.s (10s^{-1})*

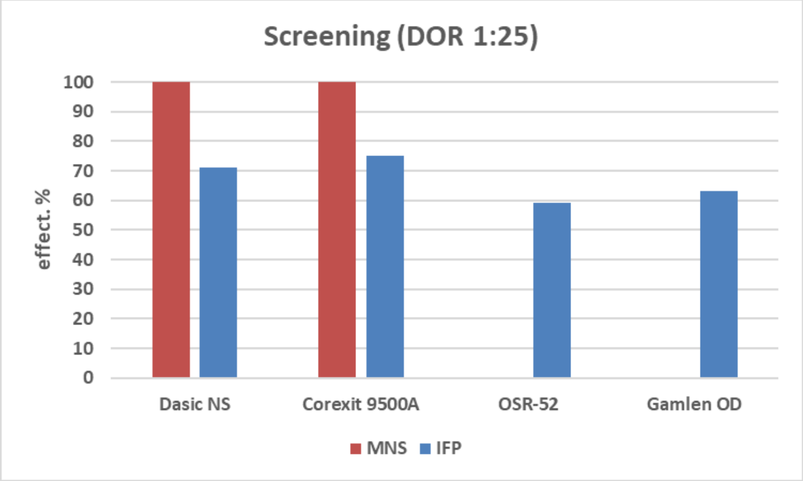


Figure 3-5 Screening of dispersants on 200°C+/ 50% w/o emulsion of Heidrun Åre 2023.

3.6.2 Dosage testing

The dosage test helps to identify optimal design conditions for dispersant use and was performed with DOR/DER of 1:25, 1:50, 1:100 and 1:200, and with no dispersant added. Dosage testing at 13 °C was performed using Dasic Slickgone NS on Heidrun Åre 2023 emulsion (200°C+/50 vol.%). Dasic Slickgone NS is the main dispersant agent in NOFO's stockpile today. Results from the dosage testing are presented in Table 3-9. Examples (images) from the dosage testing (MNS test) on Heidrun Åre 2023 are given in Figure 3-7.

The tests show a clear dosage dependant effect for the low-energy test (IFP). The DOR/DER 1:25 showed the highest effect of 71% and was reduced to 27% with DOR/DER 1:100 and showed very low effect (13%) with DOR/DER 1:200. The MNS test gave high dispersion effectiveness for alle the dosage tested, but dosage of 1:25 and 1:50 clearly produced smaller oil droplets compared to the lower dosages of 1:100 and 1:200. No dispersant added to the emulsion showed very limited effect (< 5%), only large droplet was observed then the wave broke up the emulsion, i.e. no real dispersion.

Table 3-9 Dosage testing on 200°C+/50% emulsion of Heidrun Åre 2023 at 13 °C.

Dispersant (dispersant-to-emulsion ratio)	% Effectiveness 200 °C+/ 50%* IFP	% Effectiveness 200 °C+/ 50%* MNS
Dasic Slickgone NS (1:25)	71	100
Dasic Slickgone NS (1:50)	67	83
Dasic Slickgone NS (1:100)	27	85
Dasic Slickgone NS (1:200)	13	92
No disp.	<5	<5

** Emulsion viscosity: 804-832 mPa.s (10s^{-1}).*

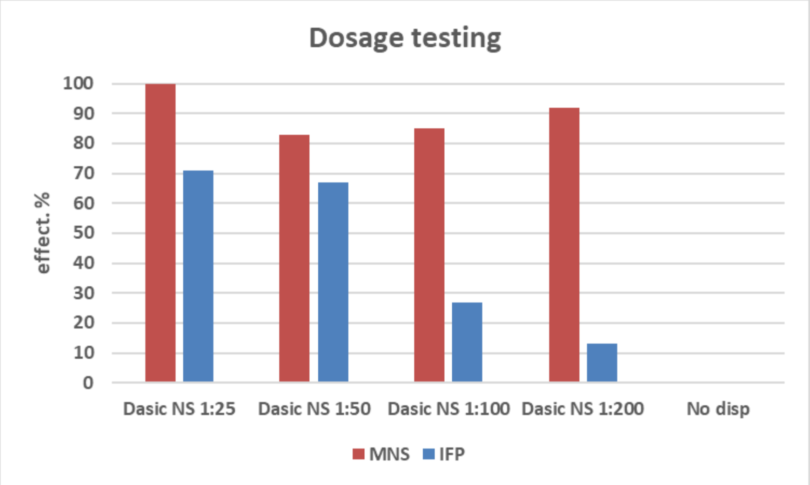
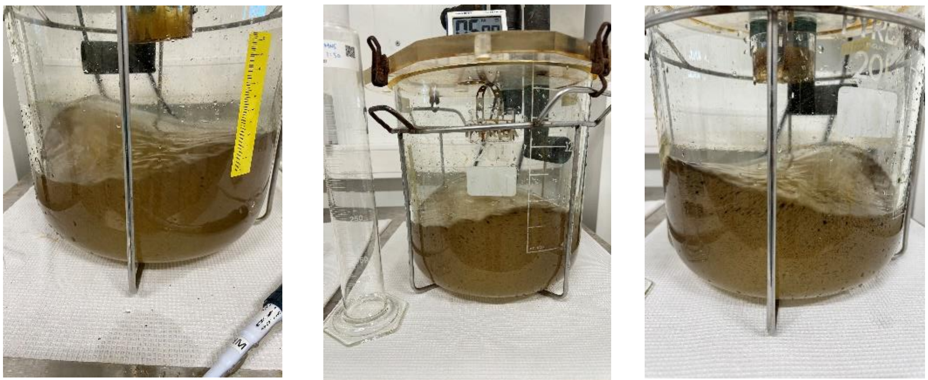


Figure 3-6 Dosage testing of Dasic Slickgone NS on 200°C+/ 50% w/o emulsion of Heidrun Åre 2023.



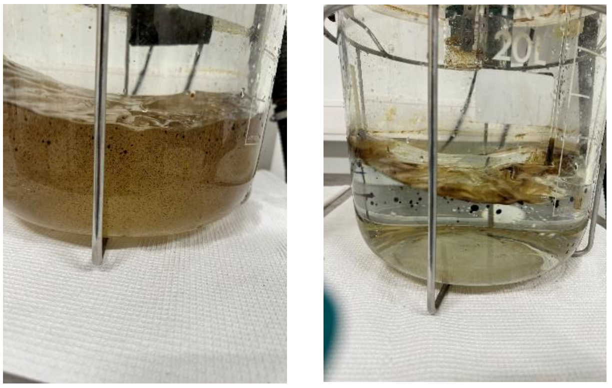


Figure 3-7

MNS high energy test on 200°C+ 50% emulsion (Heidrun Åre 2023). Upper left to right: After adding DOR/DER 1:25, 1:50 and 1:100 of Dasic Slickgone NS. Below: After adding DOR/DER 1:200 of Dasic Slickgone, and no dispersant added on the emulsion.

3.6.3 Systematic dispersant testing and dispersibility limits

A dispersant-to oil-dosage ratio of 1:25 (4 wt.%) is commonly used as the standard procedure to establish the time window for dispersant application. The results from the systematic dispersant testing at 13 °C are shown Table 3-10 and in Figure 3-8. In addition, some supplementary test on MNS at 5 °C (Table 3-11) were also performed for estimating the viscosity limits for dispersant use.

Table 3-10 Systematic testing and effectiveness of Dasic Slickgone NS on Heidrun Åre 2023 at 13 °C.

Heidrun Åre	**Water content (vol. %)**	**Viscosity 13 °C (mPa.s) 10 s^{-1}**	**Effectiveness (%) IFP**	**Effectiveness (%) MNS**
150°C+	0	66	62	100
200°C+	0	169	70	100
250°C+	0	295	65	100
150°C+	50	471	74	100
200°C+	50	804	71	100
250°C+	50	1853	68	56
150°C+	75	1295	80	30
200°C+	75	1514	55	5
250°C+	75	3896	52	-
150°C+	77	691	78	6
200°C+	73	1254	58	47
250°C+	62	4288	48	46

-:No data

Table 3-11 Additional MNS-test of Dasic Slickgone NS on Heidrun Åre at 5 °C.

Heidrun Åre	**Water content (vol. %)**	**Viscosity 5 °C (mPa.s) 10 s^{-1}**	**Effectiveness (%) MNS**
250°C+	50	3601	100
250°C+	75	9359	11
250°C+	69	7281	22

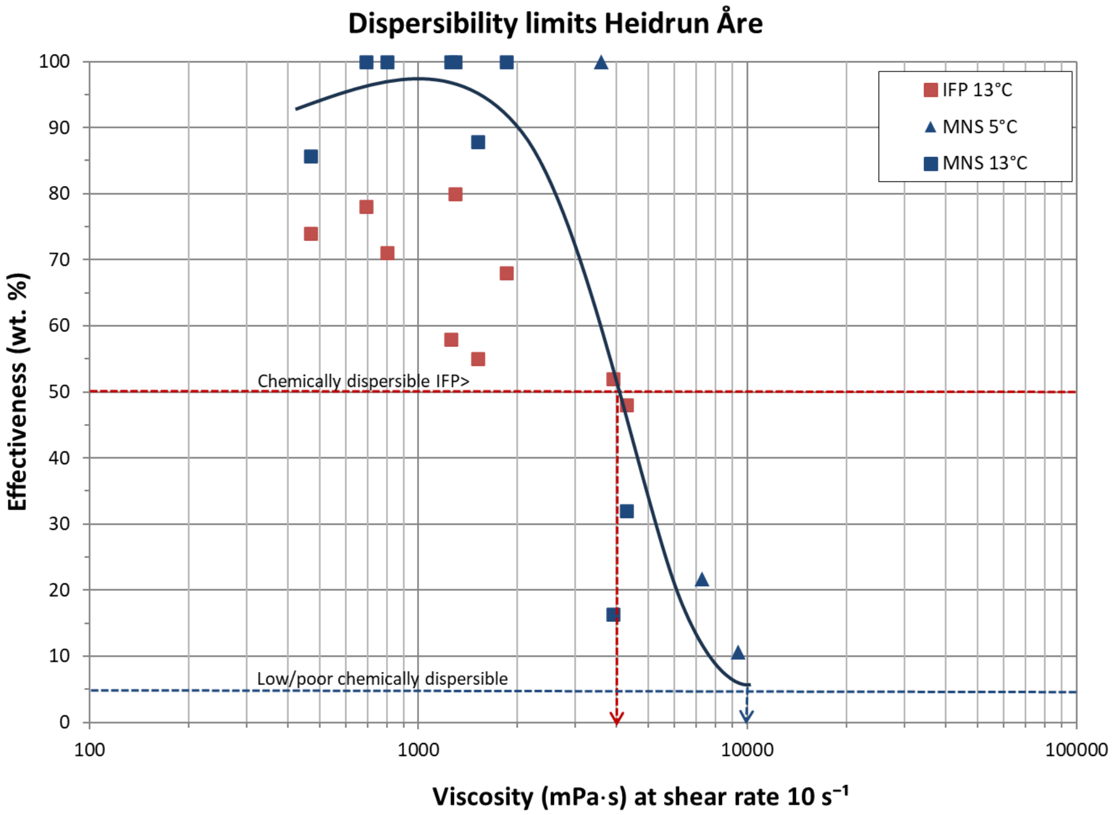


Figure 3-8 Dispersant effectiveness limits of Heidrun Åre 2023.

Heidrun Åre 2023 was estimated to be good chemically dispersible for viscosities lower than 4000 mPa.s (IFP test) and found not or poor chemically dispersible >10 000 mPa.s based on the high energy MNS-test, reflecting breaking waves conditions (>5-10 m/s wind speeds). Heidrun Åre 2023 is expected to be reduced dispersible with viscosities between 4000 and 10 000 mPa.s, this means that the oil is still dispersible but may require additional energy and/or higher dispersant dosage or multiple applications to enhance effective dispersion. The dispersibility limits are also summarised in Table 3-12.

Table 3-12 Estimated viscosity limits for Heidrun Åre 2023 for use of dispersant and definition of time window.

Dispersibility	**Criteria for effectiveness (wt. %)**	**Dispersibility limits based on emulsion viscosity (mPa.s)**
Good chemically dispersible	IPF >50%	4000
Not/poor chemically dispersible	MNS <5 %	10 000

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 Heidrun Åre 2023 was conducted at13 °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 Heidrun Åre 2023 to the SINTEF OWM are given in Appendix C.

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

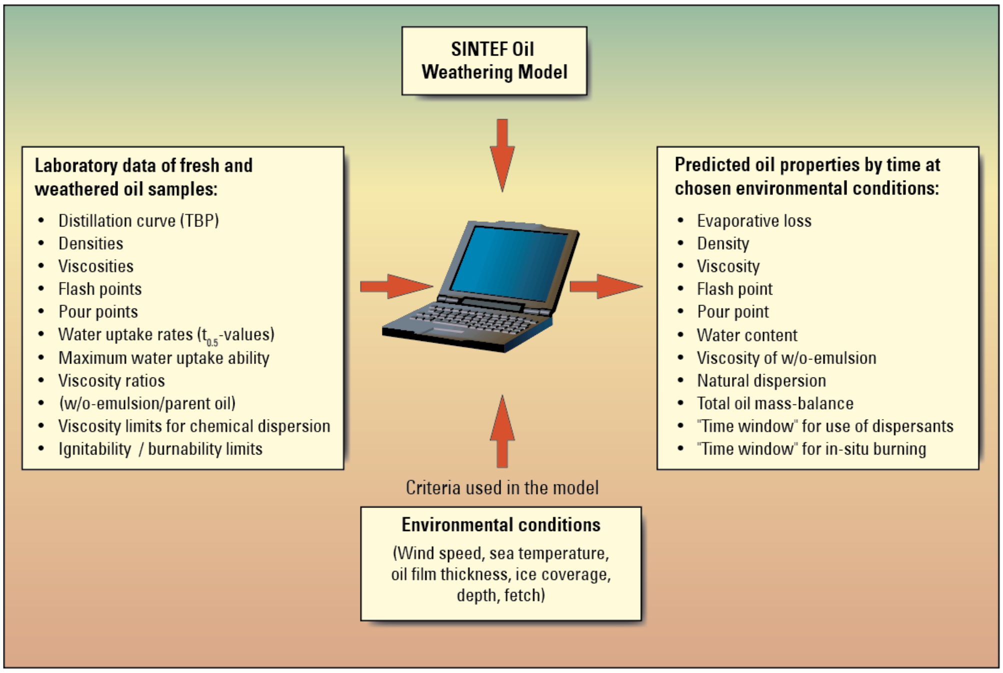


Figure 4-1 Schematic input data to the SINTEF OWM and the predicted output oil properties.

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. Heidrun Åre 2023 is categorized as an emulsifying oil in OWM with 1 mm terminal film thickness.

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 seawater temperatures chosen for predictions was 5 and 15 °C, reflecting typically winter and summer conditions.

Wind speed

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

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

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

4.2 Predictions of weathering properties of Heidrun Åre 2023

A standard surface release was used as a spill scenario. 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.

Input to SINTEF OWM

Oil type:	Crude oil
Geographical area:	Norwegian Sea
Terminal oil film thickness:	1 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 remining oil within shorter time. The predictions are shown to indicate the weathering properties in cases there are patches or oil left on the surface up to 5 days.

How to use the prediction charts: an example

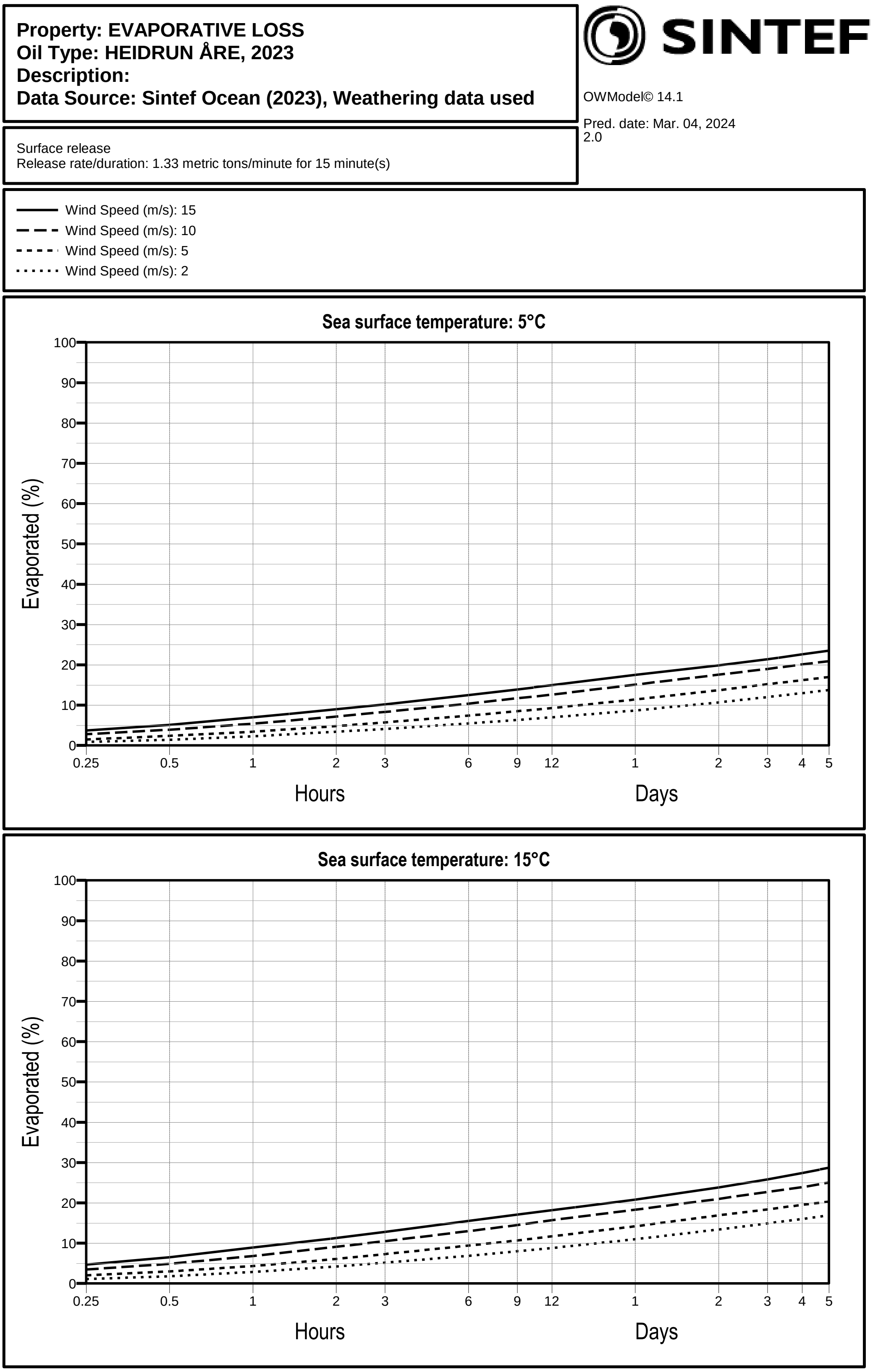
If the oil has drifted on the sea surface, the following prediction charts could be used to determine the weathering properties of the oil/emulsion. Table 4-2 gives an example of predicted weathering properties for Heidrun Åre 2023.

Table 4-2 Example of weathering properties of Heidrun Åre 2023 obtained from the OWM predictions after 12 hours of weathering at 2, 5 and 10 m/s at 15 °C.

Weathering properties	**12 hours 15 ˚C 2 m/s**	**12 hours 15 ˚C 5 m/s**	**12 hours 15 ˚C 10 m/s**	**12 hours 15 ˚C 15 m/s**
Evaporation, wt. %	9	12	16	18
Flash point, °C	65	77	96	110
Pour Point, °C	-35	-34	-32	-31
Water content, vol.%	15	36	63	71
Viscosity, mPa.s *	180	530	1930	3170
Mass balance / Oil on surface wt.%	90	85	50	10

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

4.3 Prediction of Heidrun Åre 2023



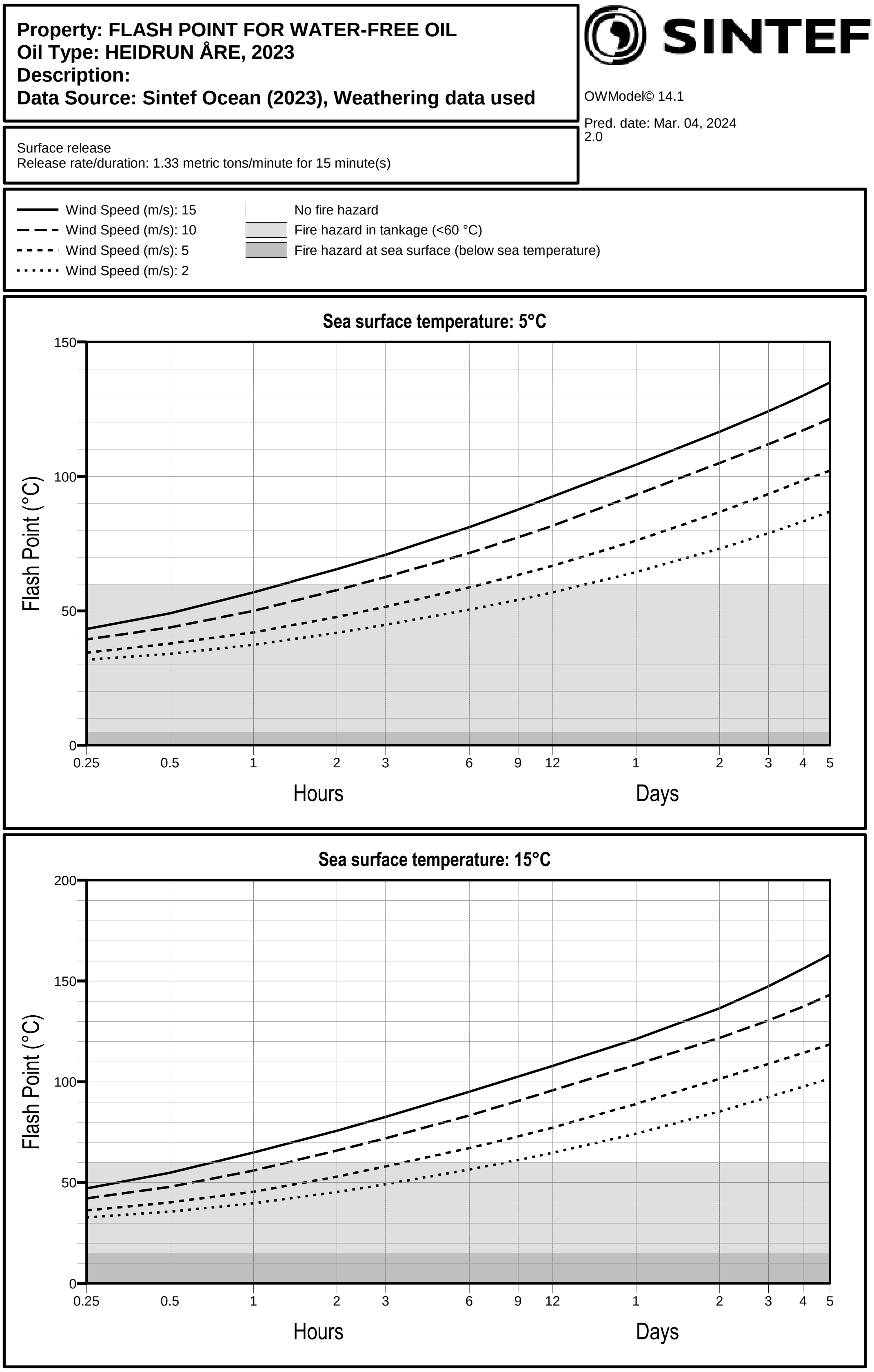
Property: EVAPORATIVE LOSS
Oil Type: HEIDRUN ÅRE, 2023
Description:
Data Source: Sintef Ocean (2023), Weathering data used

OWModel© 14.1

Pred. date: Mar. 04, 2024
2.0

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

Figure 4-2 *Evaporative loss of Heidrun Åre 2023 predicted at sea temperatures of 5 and 15 °C.*



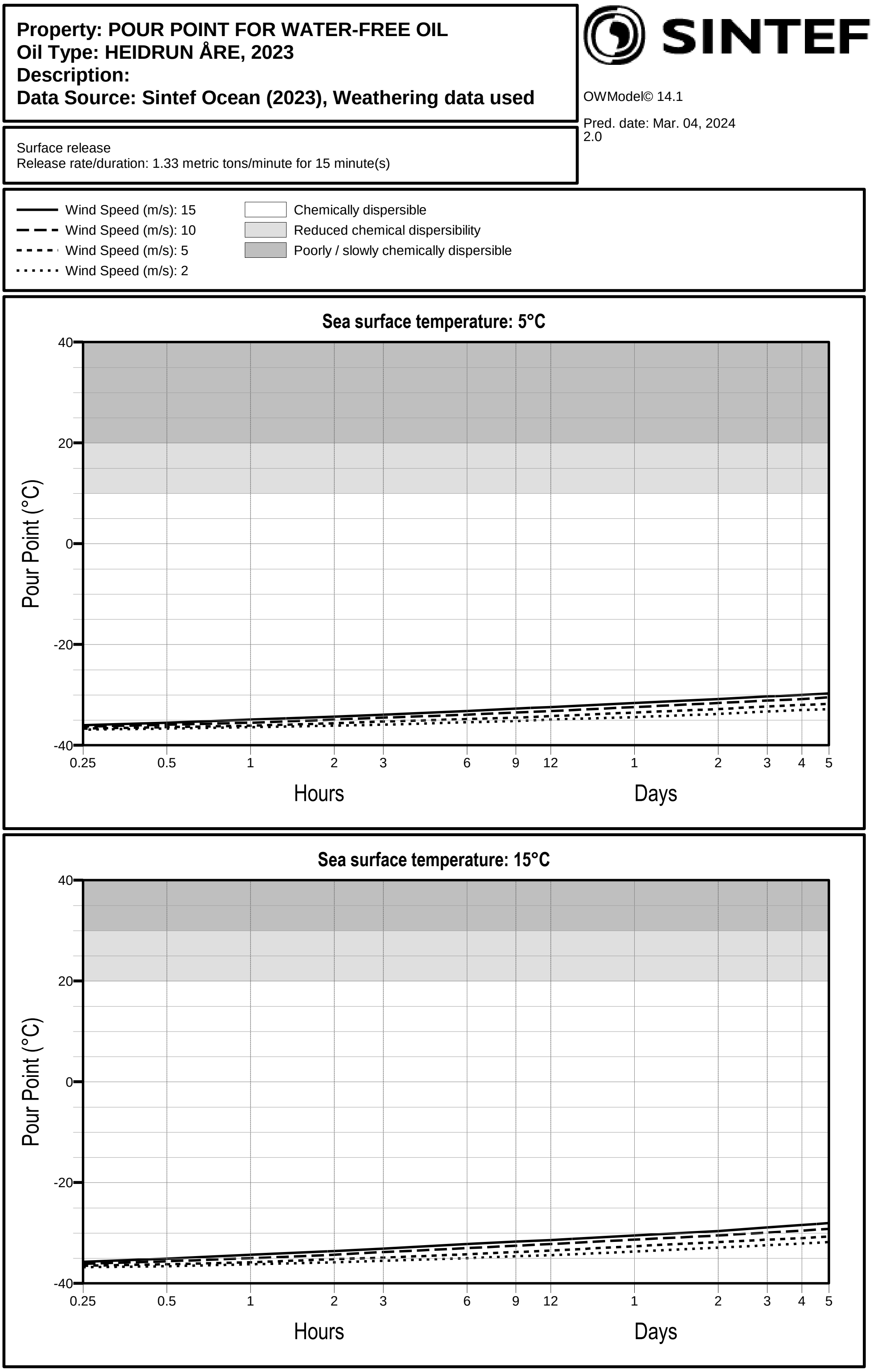
Property: FLASH POINT FOR WATER-FREE OIL
Oil Type: HEIDRUN ÅRE, 2023
Description:
Data Source: Sintef Ocean (2023), Weathering data used

OWModel© 14.1

Pred. date: Mar. 04, 2024
2.0

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

Figure 4-3 *Flash point of water-free Heidrun Åre 2023 predicted at sea temperatures of 5 and 15 °C.*



Property: POUR POINT FOR WATER-FREE OIL
Oil Type: HEIDRUN ÅRE, 2023
Description:
Data Source: Sintef Ocean (2023), Weathering data used

OWModel© 14.1

Pred. date: Mar. 04, 2024
2.0

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

Figure 4-4 Pour point of water-free Heidrun Åre predicted at sea temperatures of 5 and 15 °C.

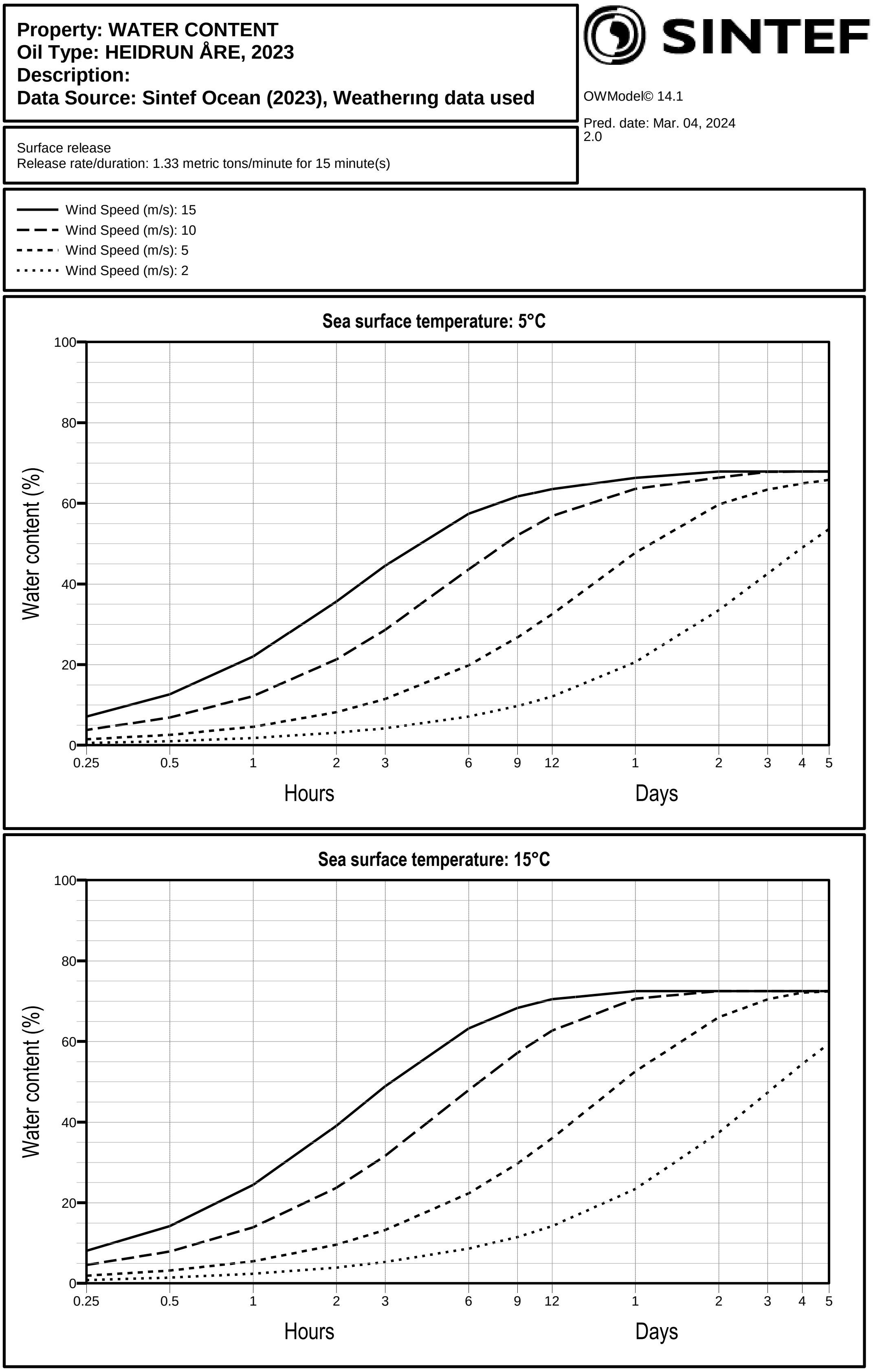
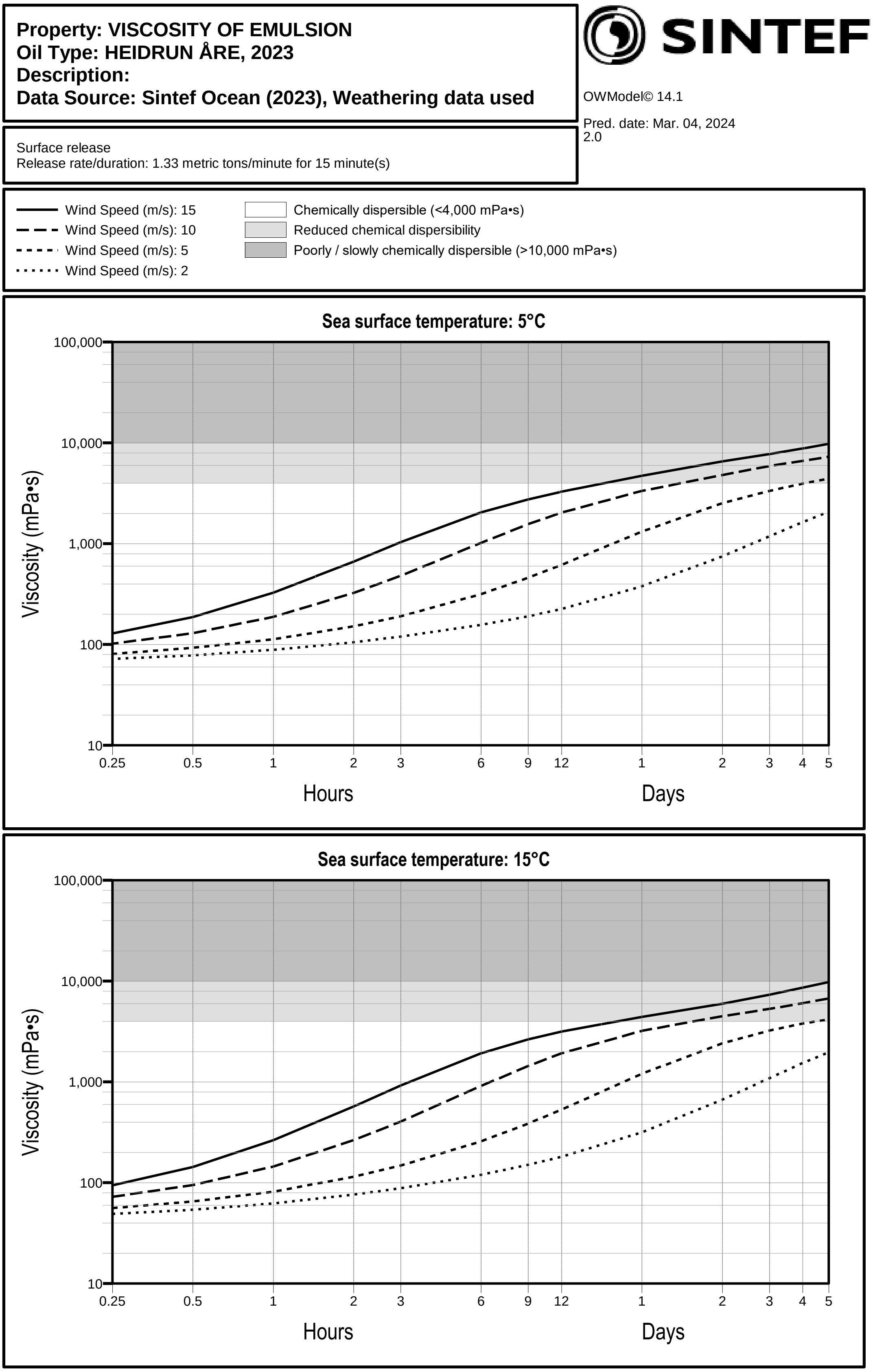


Figure 4-5 *Water content of Heidun Åre predicted at sea temperatures of 5 and 15 °C.*



Property: VISCOSITY OF EMULSION
Oil Type: HEIDRUN ÅRE, 2023
Description:
Data Source: Sintef Ocean (2023), Weathering data used

OWModel© 14.1

Pred. date: Mar. 04, 2024
2.0

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

Figure 4-6 Viscosity of Heidrun Åre predicted at sea temperatures of 5 and 15 °C.

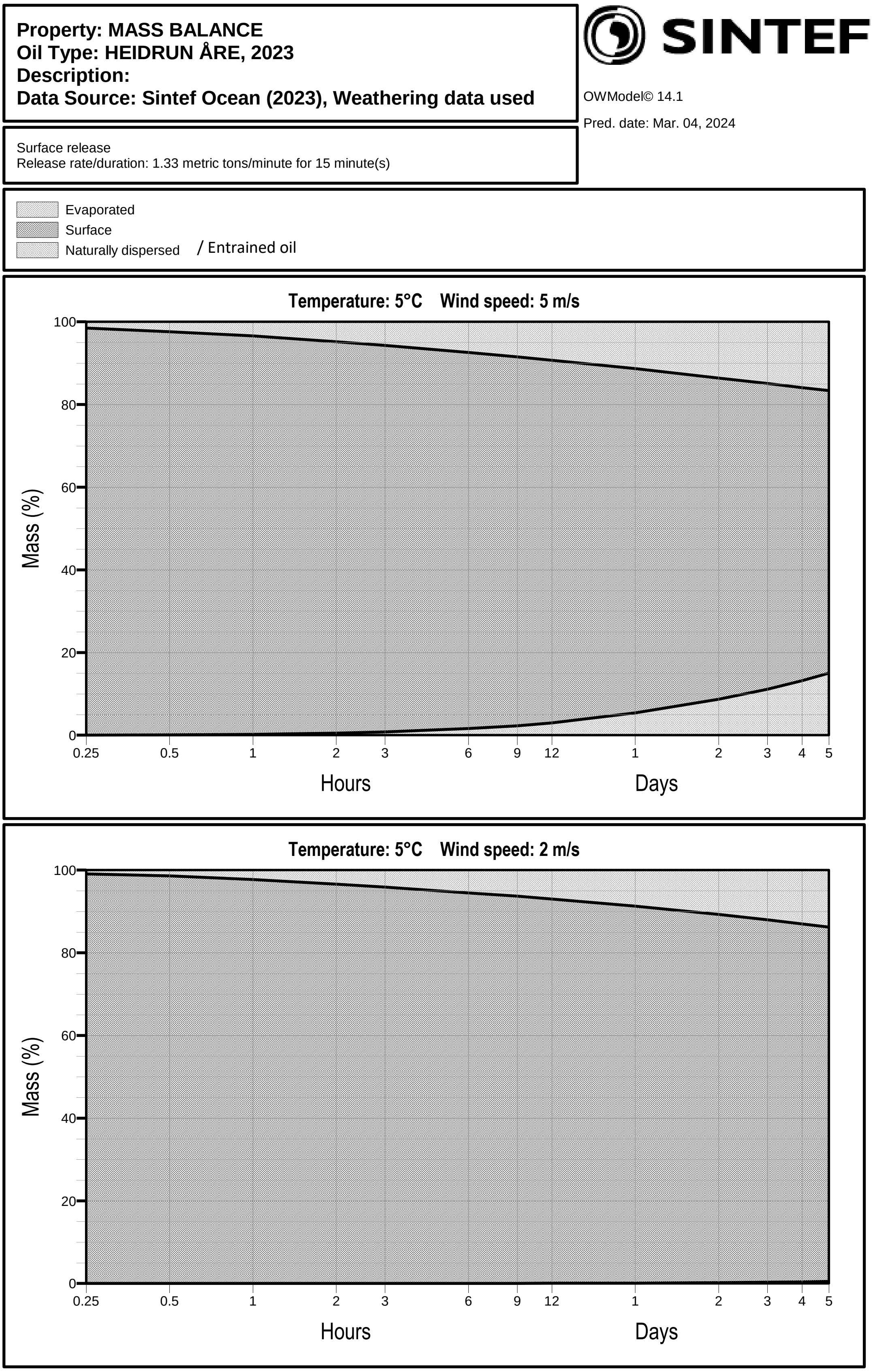
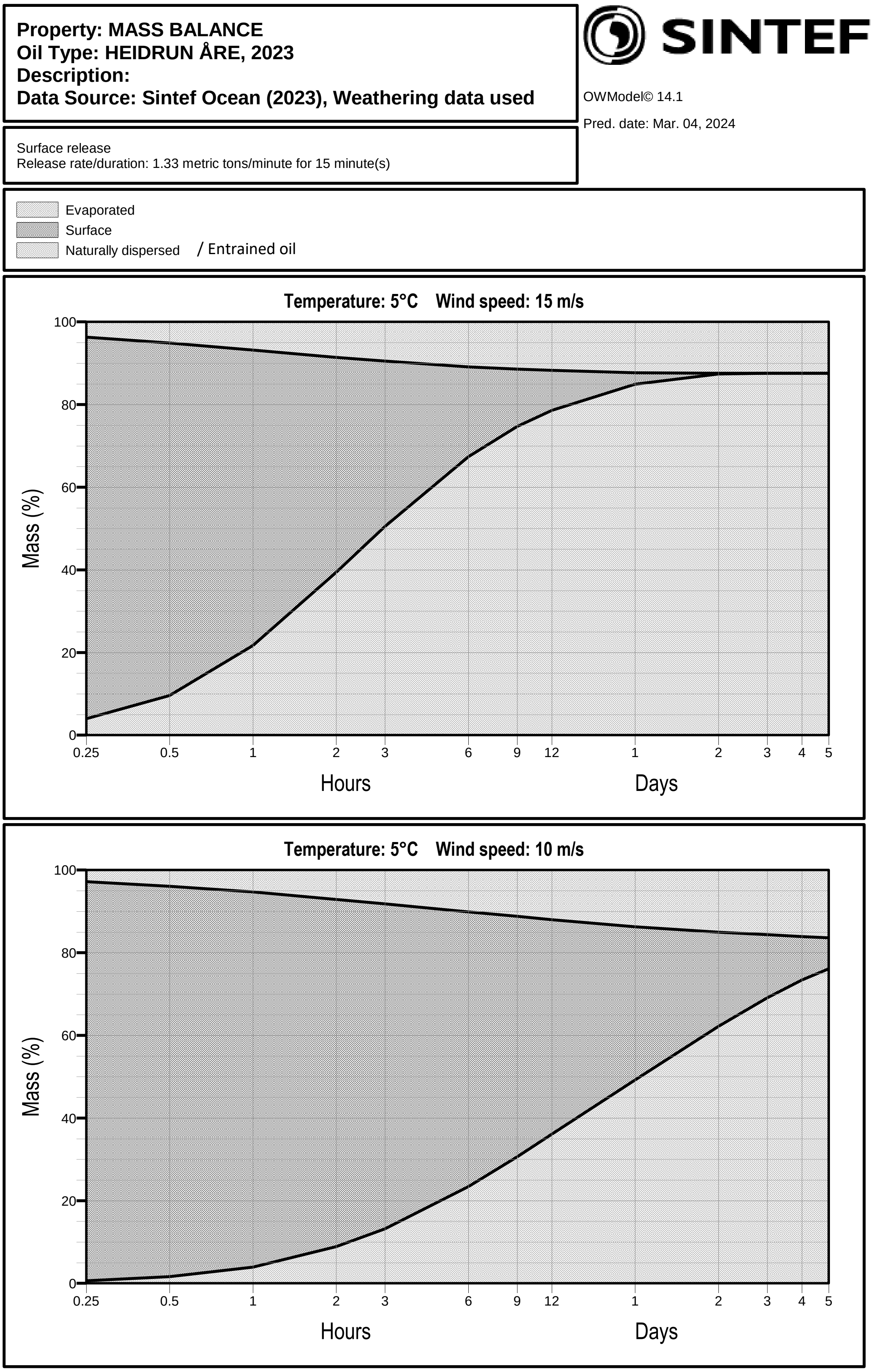


Figure 4-7 Predicted mass balance of Heidrun Åre predicted 5 °C, wind speeds of 2 and 5 m/s.

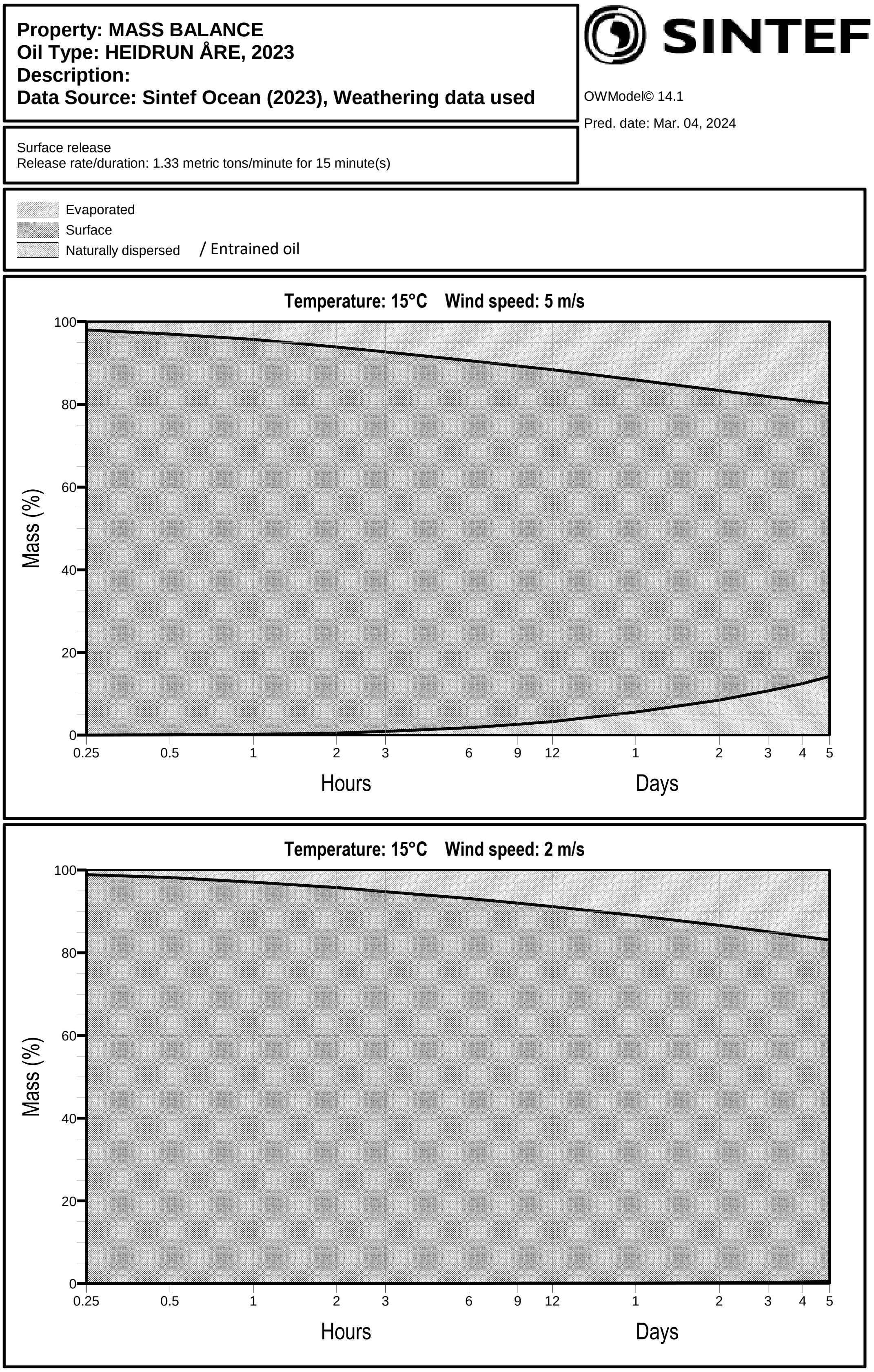


Property: MASS BALANCE
Oil Type: HEIDRUN ÅRE, 2023
Description:
Data Source: Sintef Ocean (2023), Weathering data used

OWModel© 14.1
Pred. date: Mar. 04, 2024

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

Figure 4-8 Predicted mass balance of Heidrun Åre predicted 5 °C, wind speeds of 10 and 15 m/s.



Property: MASS BALANCE
Oil Type: HEIDRUN ÅRE, 2023
Description:
Data Source: Sintef Ocean (2023), Weathering data used

OWModel© 14.1
Pred. date: Mar. 04, 2024

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

Figure 4-9 Predicted mass balance of Heidrun Åre predicted 15 °C, wind speeds of 2 and 5 m/s.

Property: MASS BALANCE
Oil Type: HEIDRUN ÅRE, 2023
Description:
Data Source: Sintef Ocean (2023), Weathering data used

SINTEF
OWModel© 14.1
Pred. date: Mar. 04, 2024

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

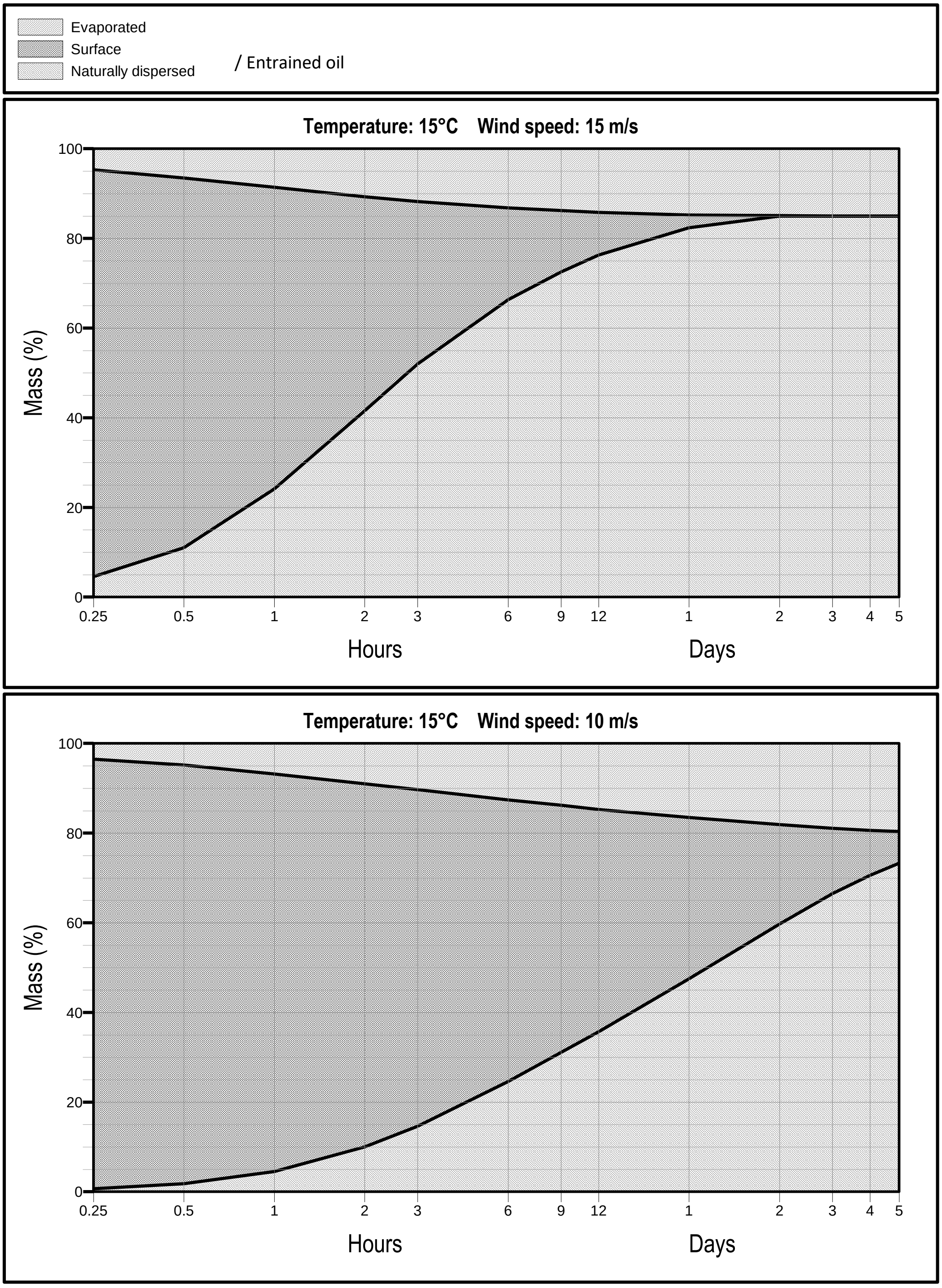


Figure 4-10 Predicted mass balance of Heidrun Åre predicted 15 °C, wind speeds of 10 and 15 m/s.

5 Comparison of OWM predictions

Weathering predictions from surface release of Heidrun Åre 2023 were compared with predictions of previous studies of Heidrun Åre 2003 and Heidrun Blend 2003. The prediction scenario for comparison is based on sea temperature of 15 °C and wind speed of 10 m/s.

5.1 Evaporative loss

Evaporation is one of the natural processes that helps reducing the surface oil volume if the oil is spilled at sea. The evaporative loss of Heidrun Åre 2023 lays in between Heidrun Åre 2003 (lowest) and Heidrun Blend 2003 (highest) as shown on Figure 5-1.

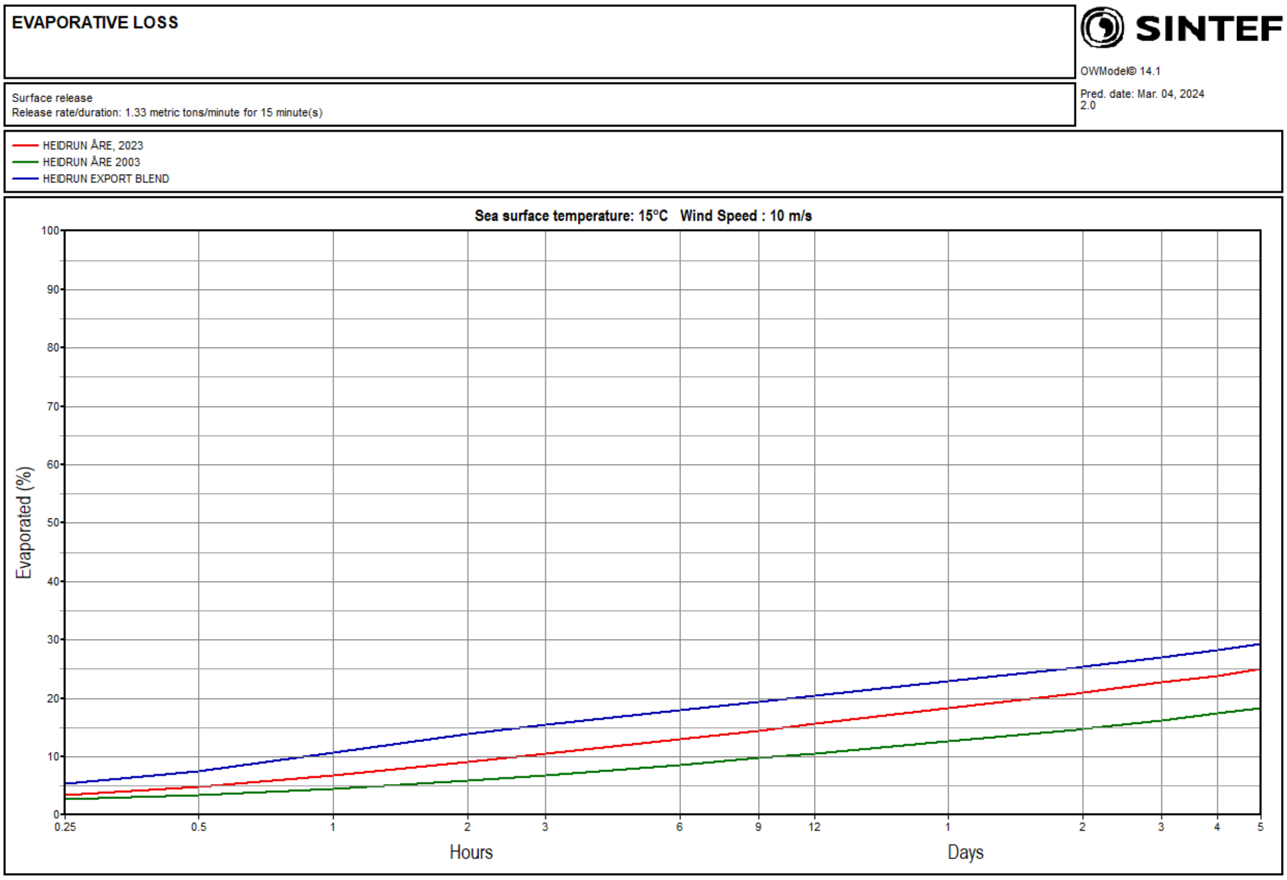


Figure 5-1 Predicted evaporative loss at 15 °C and 10 m/s for Heidrun Åre 2023 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003.

5.2 Flash point

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

The flash points of Heidrun Åre 2023 compared with Heidrun Åre 2003 and Heidrun Blend 2003 are shown in Figure 5-2. Heidrun Åre 2023 has lower flash point compared with the other oils. However, none of the oils indicate no fire or explosion hazard 15 minutes after release at 10 m/s wind speed for this scenario, where flash points are above the sea temperature of 15 °C.

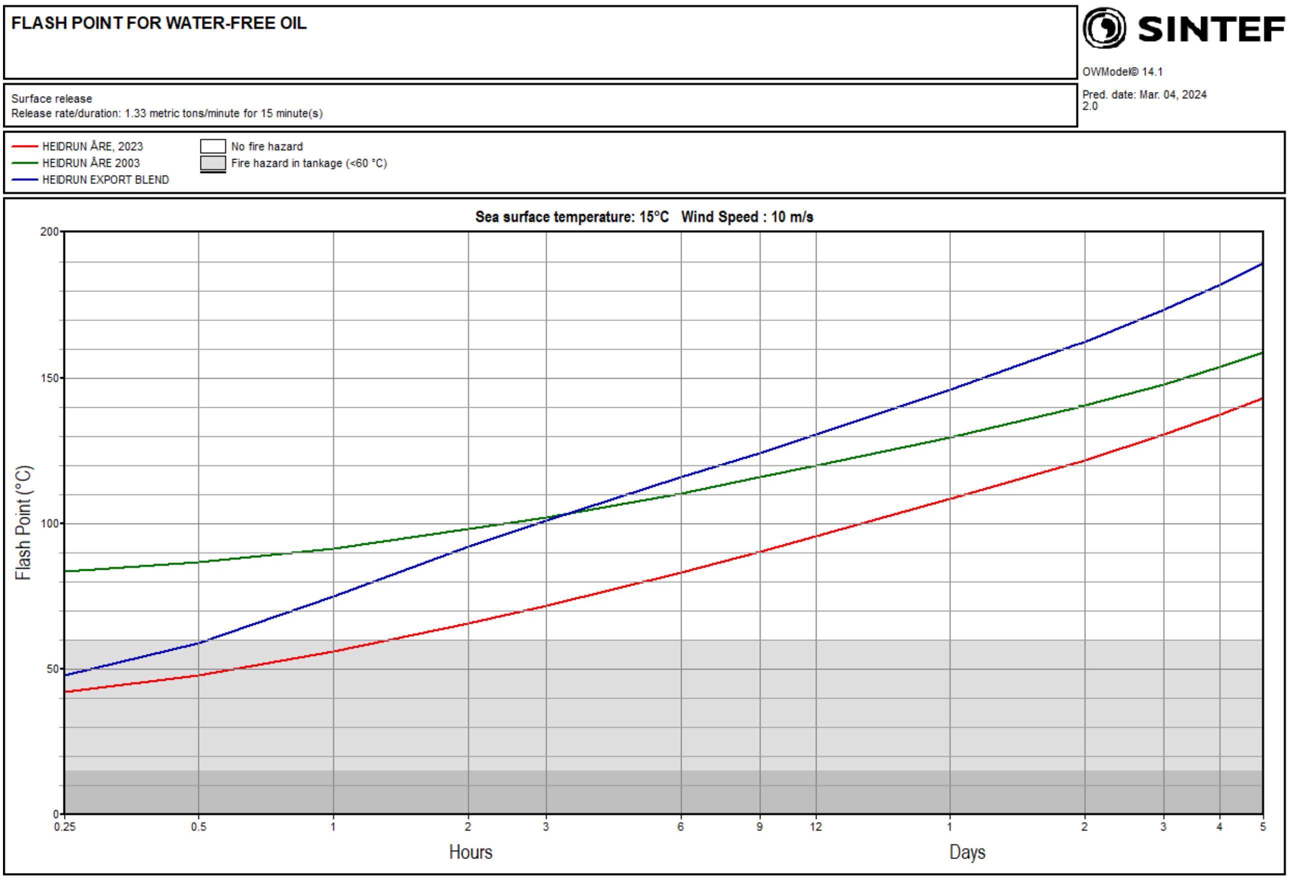


Figure 5-2 Predicted flash point at 15 °C and 10 m/s for Heidrun Åre 2023 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003.

5.3 Pour point

The pour points of these Heidrun crude oils show very low values of the waterfree residues (Figure 5-3). Heidrun Åre 2023 ends up with somewhat lower pour points after some days weathering at sea compared Heidrun Åre 2003 and Heidrun Blend 2003. Solidification at sea is not likely for these crude oils if spilled at sea.

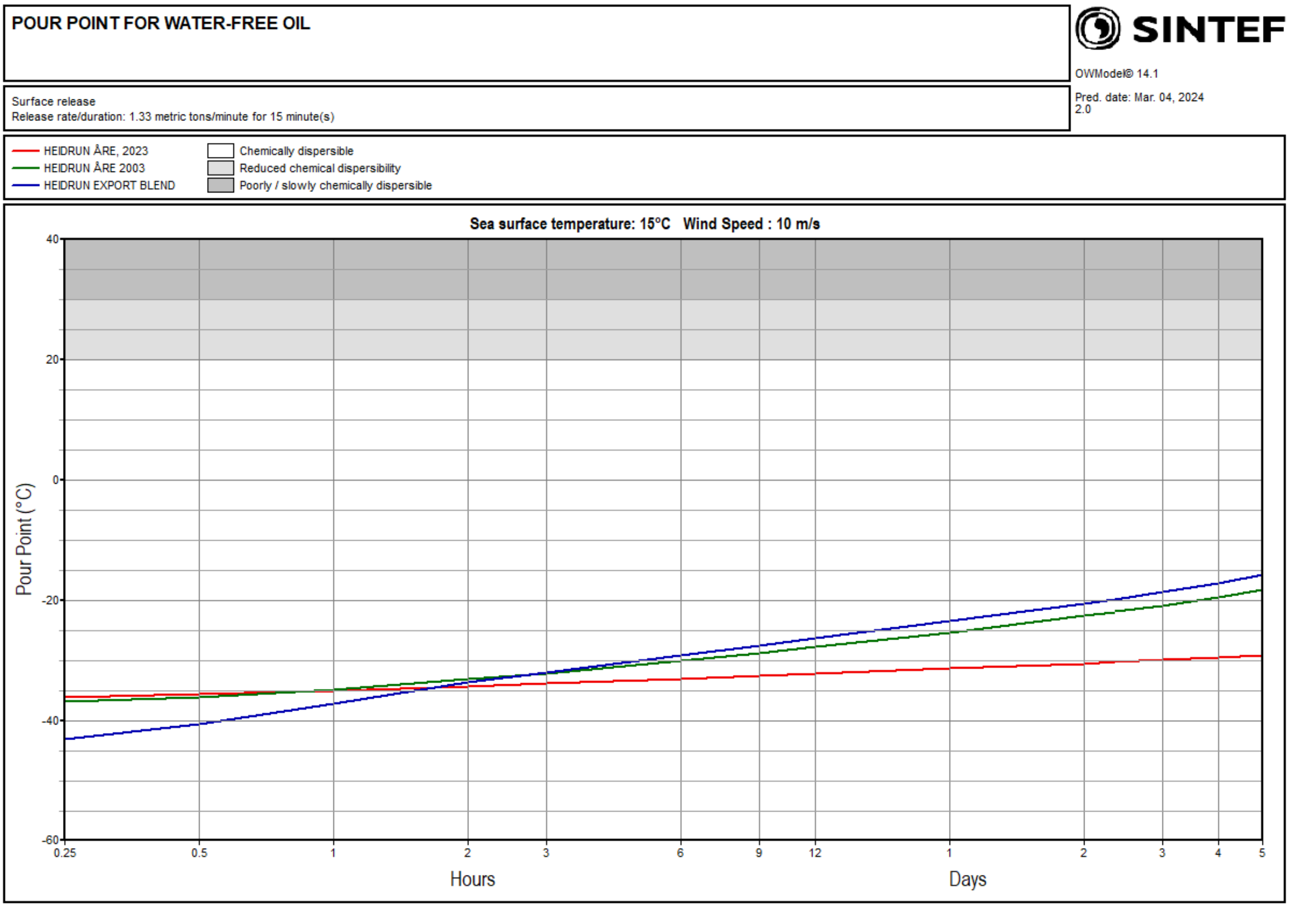


Figure 5-3 *Predicted pour point at 15 °C and 10 m/s for Heidrun Åre 2023 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003.*

5.4 Water uptake

The water uptake of Heidrun Åre compared with Heidrun Åre 2003 and Heidrun Blend 2003 is shown in Figure 5-4. The Heidrun Åre oils reach a maximum water uptake of about 73-75vol.% and follow very similar kinetics (rate of the water uptake). Heidrun Blend 2003 reaches a lower maximum water uptake of 60 vol.% and has also a faster kinetics compared to the Heidrun Åre crude oils.

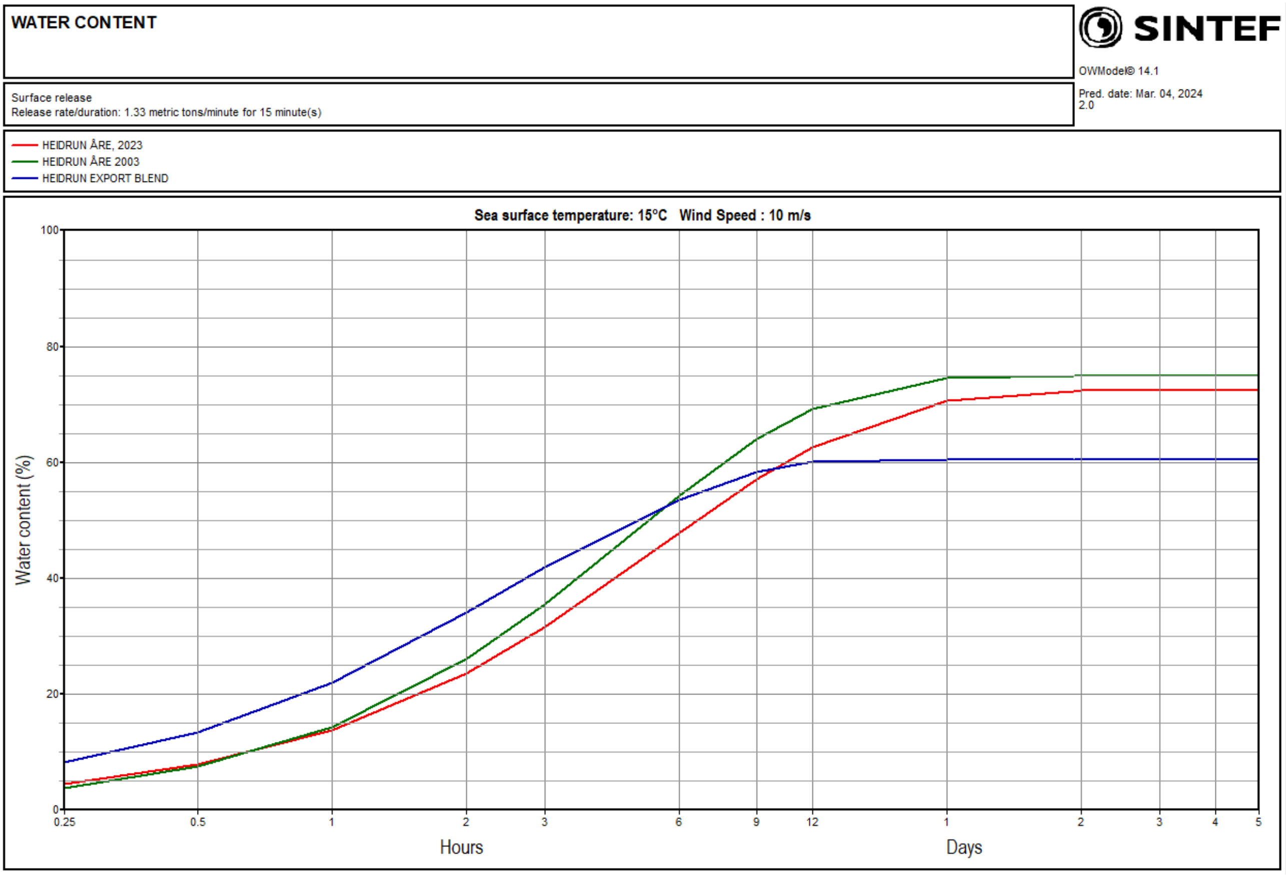


Figure 5-4 *Predicted water uptake at 15 °C and 10 m/s for Heidrun Åre 2023 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003.*

5.5 Emulsion viscosity

Figure 5-5 shows the predicted (emulsion) viscosities of Heidrun Åre 2023, Heidrun Åre 2003, and Heidrun Blend 2003. The viscosity of Heidrun Åre 2023 is most similar with Heidrun Blend 2003, whilst Heidrun Åre 2003 exhibits the highest viscosity predicted within 5 days of weathering at sea.

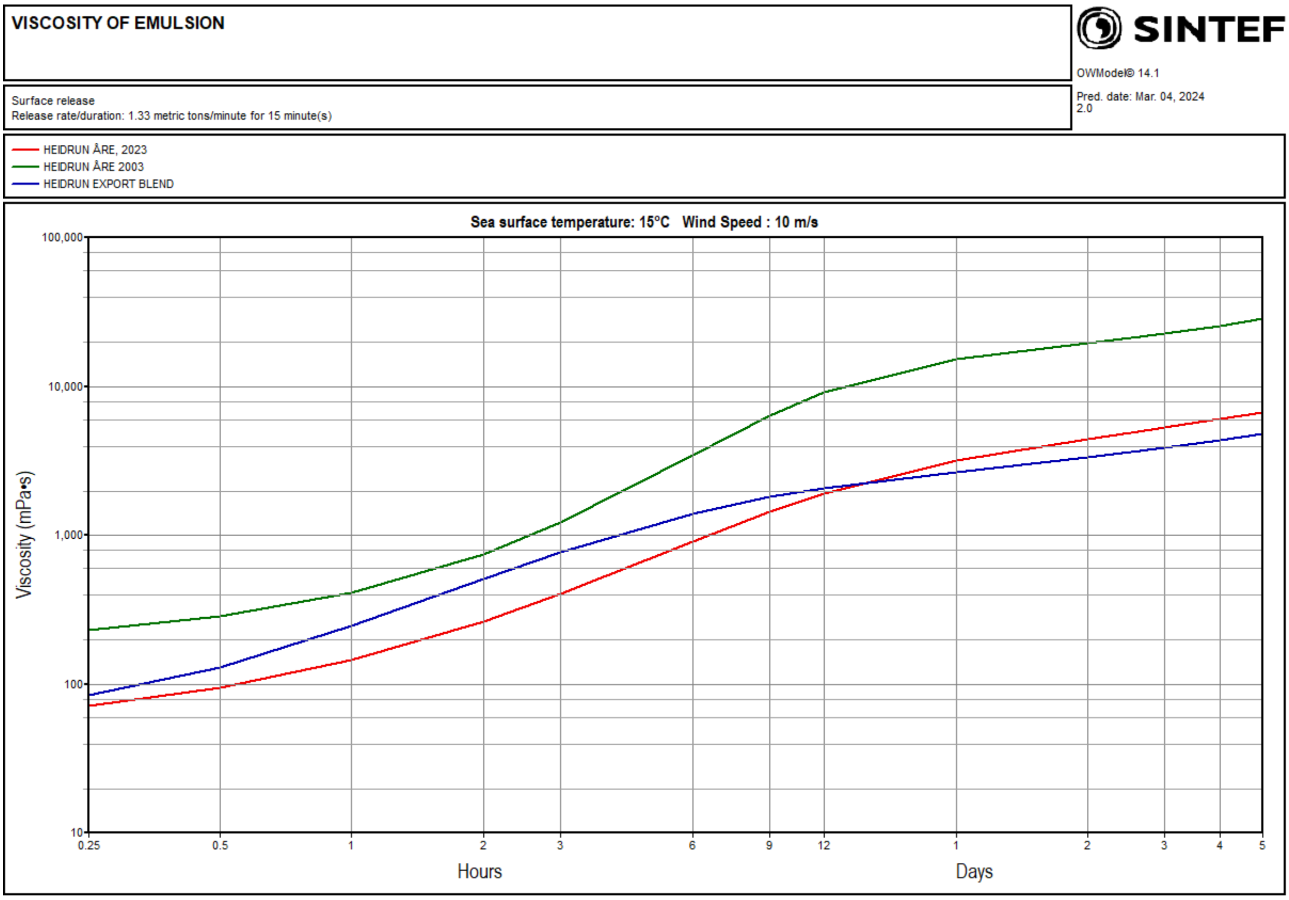


Figure 5-5 Predicted (emulsion) viscosity at 15 °C and 10 m/s for Heidrun Åre 2023 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003.

5.6 Surface oil and emulsion

The predicted surface oil volume is based on the evaporative loss, natural dispersion/entrainment, whilst surface emulsion also includes emulsification that may increase the oil volume subsequently. Figure 6-6 shows the predicted mass balance of remaining surface oil and surface emulsion as a function of weathering of the oils in comparison. The mass balance (surface oil) of Heidrun Åre 2023 is most similar to Heidrun Blend 2003, similar for surface emulsion due to emulsification (water uptake). Moreover, the oils in comparison are all persistent on the sea surface with a predicted lifetime >5 days.

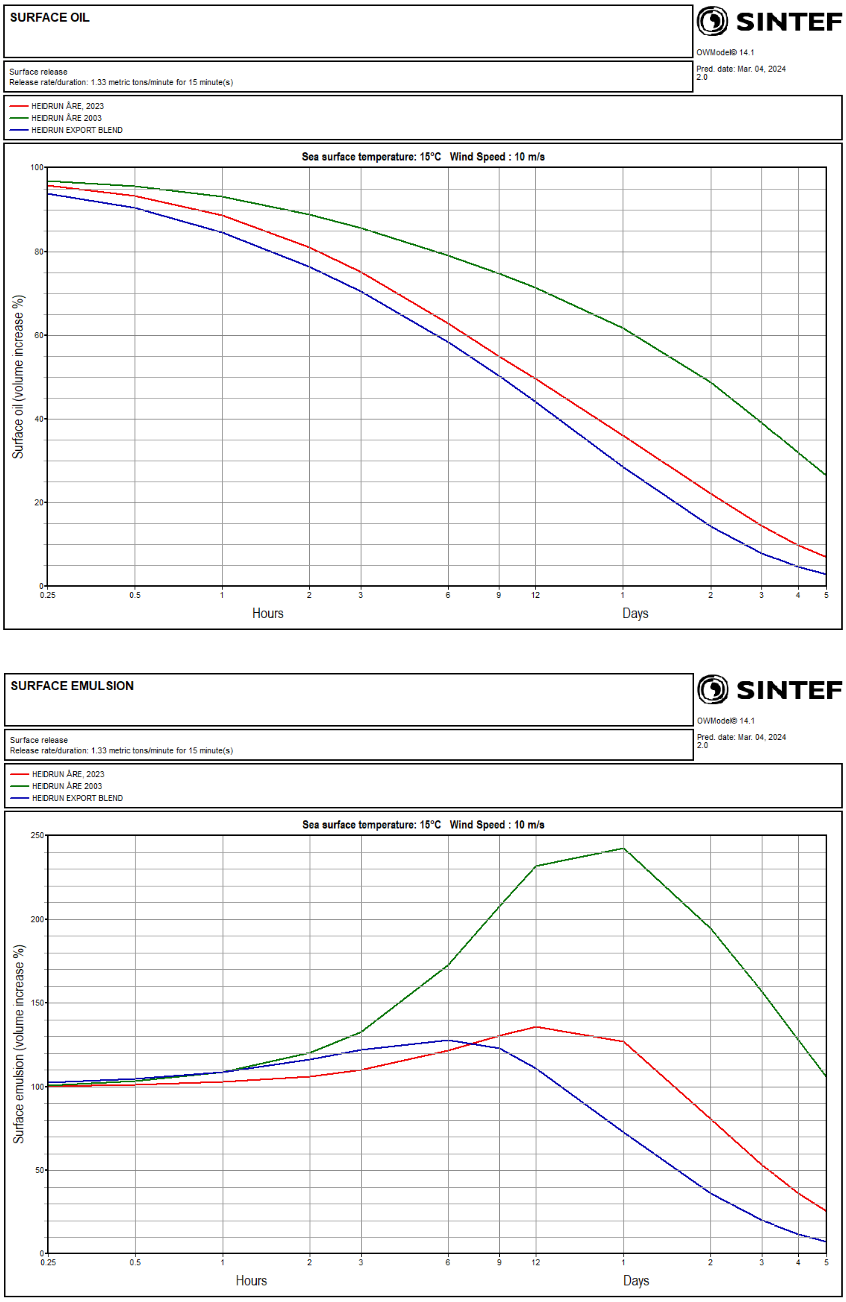


Figure 5-6 Predicted remaining surface oil (above) and surface emulsion (below) at 15 °C and 10 m/s for Heidrun Åre 2023 in comparison with Heidrun Åre 2003 and Heidrun Blend 2003.

6 Weathering properties and response of Heidrun Åre 2023

The evaluation of the weathering properties related to response assumes that the initial film thicknesses >0.1 mm, i.e. that the rheological properties of the oil itself is important for response options. The relative content of the oil components increases by evaporation at sea, and the physical and chemical properties of the oil will change over time due the weathering processes. Knowledge about how the oils properties change during weathering is therefore important in the management of oil spill response. This chapter includes an assessment of mechanical recovery and the use of oil spill dispersants on Heidrun Åre 2023. The potential of using water-flushing (artificial energy) to disperse thin oil films is also discussed in this chapter.

6.1 Oil properties

The specific physico-chemical parameters of Heidrun Åre are used as input to SINTEF OWM for oil weathering predictions. The physico-chemical analysis of the fresh and topped residues shows that Heidrun Åre 2023 is a biodegradated (naphthenic) crude oil with a density of 0.8998 g/mL, with a low contents of wax (0.78 wt.%) and a low to medium content of asphaltenes (0.15 wt. %). Heidrun Åre 2023 has a relatively low evaporative loss of 21.6 vol.% for the 250°C+ residue. The fresh oil has a viscosity of 43 mPa.s at 13°C ($10s^{-1}$) that increases by evaporation to 295 mPa.s for the 250°C+ residue. The fresh oil and its residues have very low pour points of -36 to -30 °C. Moreover, Heidrun Åre 2023 formed loose or semi-stable emulsions particularly for the 150 and 200 °C+ residues when tested in the laboratory. The water uptake was shown to be in the range of 56-72 vol. %.

6.2 Flash point – Fire/explosion hazard

Flash point refers to the lowest temperature at which an oil can vaporize to form an ignitable mixture in the air. In case of an oil release on the sea surface, the 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 predicted flash point of Heidrun Åre 2023 for the standardized batch release (80 m^3/ h) is shown in Figure 4-3. The flash points are expected to surpass the sea temperature within short time, approximately 15 minutes at 5 and 15 °C, at wind speeds of 2-15 m/s, e.g. less than 1-hour delay time (safety zone) related to fire/explosion hazard related to the flash point of the drifting oil itself. However, care should be taken during the first hours, and use of an explosimeter is recommended. The release rate may influence the rate of evaporation. For a considerably larger (batch) release rates e.g.,100 times higher (8000 m^3/h), the rate of evaporative loss can be reduced particularly for the first hours after the release due to thicker oil layer, and such high batch releases could be for example incident scenarios in connection to e.g. tanker loadings.

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 an emergency. However, for oil recovery vessels (e.g., NOFO's ORO vessels) with A class certification for transport of liquids (Class I/II, flash point <60 °C), there should not be any risks in storing the recovered emulsion in such tanks. According to NOFO's "ORO-manual" the aeration tubes should be place minimum 2.4 m above deck-levels, and aeration Zones (ex-zones) will be established onboard, that will be manually controlled with explosimeters during a response operation. For Heidrun Åre 2023, the tank storage limit is predicted to be surpassed within 3-9 hours in summer temperatures at low wind speeds (2-5 m/s) and within shorter time for higher wind speeds. At winter temperature, it takes longer time (>12 hours) to reach the limit of 60 °C at 2 m/s wind speed (very calm condition), and within shorter time at higher wind speeds.

As a general recommendation after an acute oil spill involving free gas (e.g., from an oil/gas blowout), 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 seawaters. Prior to the initiation of spill response operations, an evaluation of fire/explosion hazard must always be conducted at the site. Explosimeters should anyway be utilized continuously for safety aspects during response operations.

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 may 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) of semi-solid patches 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 to 15 °C above sea temperature and in cold temperatures. However, Heidrun Åre 2023 has low pour points of its residues (-36 to -30 °C), and possible remaining water-free residue is therefore not likely to solidify at sea either in summer or winter conditions as shown for the pour point prediction in Figure 4-4.

6.4 Emulsion formation

The total amount of oil on the sea is reduced due to evaporation and natural dispersion in the early stages of weathering. However, as water is mixed into the oil and emulsions are formed, the total volume will increase. Figure 6-2 shows an example of the predicted mass balance of remaining surface emulsion and surface oil as a function of weathering of Heidrun Åre 2023 at 10 m/s windspeed at 5 and 15 °C. The figure shows an increase in the volume of emulsion relative to the volume og released oil with a factor of approximately 1.3.

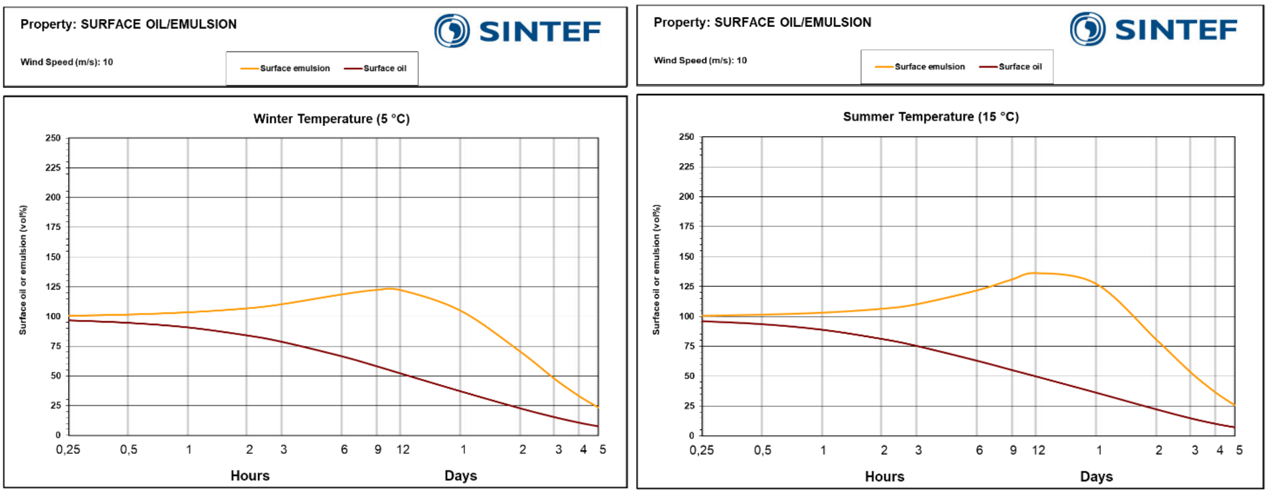


Figure 6-2 *Difference in the total slick volume due to emulsification compared to non-emulsified oil of Heidrun Åre 2023. Decrease in total volume due to evaporation and natural dispersion at 10 m/s wind speed at temperatures of 5 °C and 15 °C.*

6.5 Entrained 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). Entrained oil and evaporation are the main weathering processes that reduce the surface oil volume from a spill. The remaining surface oil after a release depends 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 at 5 and 15 °C for Heidrun Åre 2023. There is only some minor difference in lifetime between 5 and 15 °C for Heidrun Åre 2023. At high wind speeds of 15 m/s, no oil is predicted to remain on the sea surface after 2-3 days of weathering at 5 and 15 °C. Lower wind speeds will not provide sufficient energy to remove Heidrun Åre 2023 entirely from the surface within the first 5 days. For the lowest wind speed (2 m/s), the prediction indicates about 80-85 %

of the spilled oil remains on the sea surface after 5 days at summer and winter conditions. Considerably larger spills are expected to produce longer lifetimes, and specific modelling may be necessary.

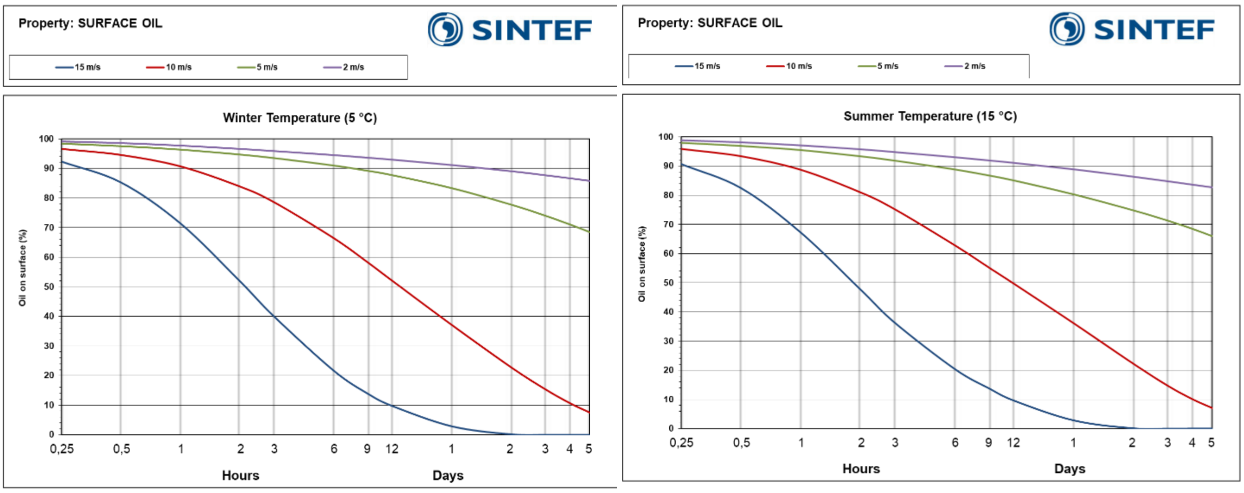


Figure 6-3 *Remaining surface oil under different sea states for Heidrun Åre 2023 at 5 °C and 15 °C. Release rate 80m^3/h.*

6.6 Film thickness from surface release

In general, mechanical recovery requires normal minimum film thickness >0.1-0.2 mm. Film thickness >0.05-0.1 mm is considered for application of oil spill dispersants. Lower film thicknesses are likely to disperse naturally under breaking waves conditions and may be enhanced in non-breaking waves by mechanical dispersion (chapter 6.8). Figure 6-4 shows the predicted film thickness of Heidrun Åre 2023 for a surface release at 5 and 15 °C with an initial surface release of 80 m^3/h, if the initial film thickens of the oil is sufficient high to emulsify, i.e., typically >0.1 mm. The increase in film thickness after few hours is due to emulsification that is most pronounced at 15 °C (summer conditions) than at 5 °C (winter conditions). Other factors than film thickness should also be considered when evaluate response options, as described in the next chapters.

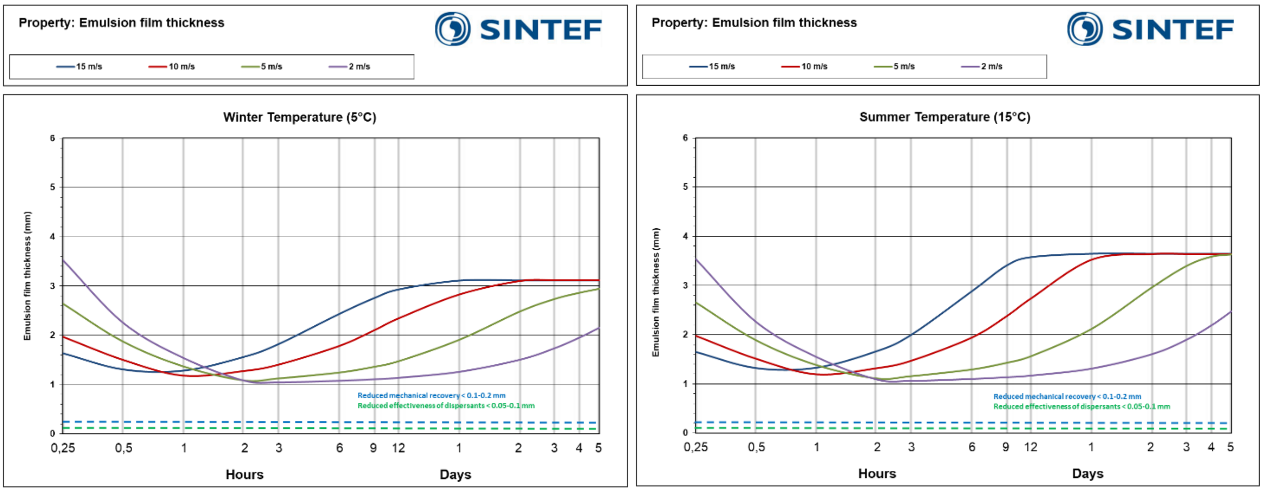


Figure 5-4 *Predicted film thickness of Heidrun Åre 2023 emulsion from a surface (batch) release at 5 and 15 °C with terminal film thickness of 1 mm water-free oil (80 m^3/h).*

6.7 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.

Generally, for many oils, weir skimmers may reduce recovery rates (m^3/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 HiVisc. skimmers (20-50 000 mPa.s), and primary HiVisc. skimmer (>50 000 mPa.s).

The emulsion viscosities of Heidrun Åre 2023 are shown in Figure 6-5 at 5 and 15 °C. For boom leakage of confined oil, the emulsion viscosity exceeds 1000 mPa.s about 6 hours at 10 m/s wind speed, but the time may be stretched up to about 2-3 days for very low wind speed (2 m/s). Overall, Heidrun Åre 2023 has a wide window of opportunity for use of traditional weir-skimmer head for viscosities lower than 20 000 mPa.s >5 days at summer and winter conditions. Moreover, Heidrun Åre forms water-in-oil emulsions with moderate to high viscosities that breaks with application of emulsion breaker (Aerosol OT-SE surfactant).

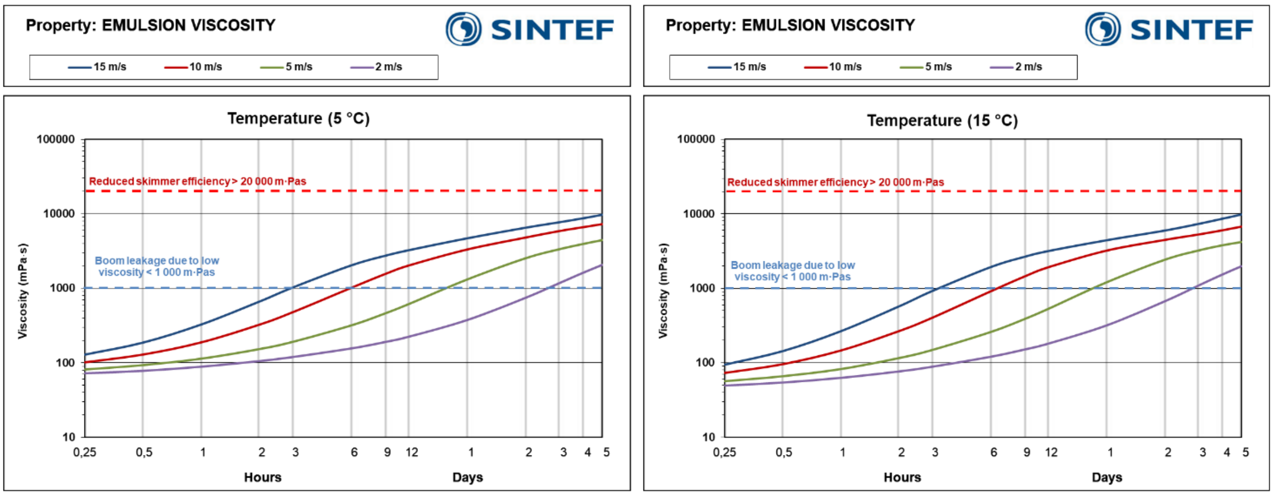


Figure 6-5 *Predicted emulsion viscosity for Heidrun Åre 2023 at 5 ° C (left) and 15 °C (right) included expected viscosity limits for boom leakage and poor flow to weir skimmers.*

Summary mechanical recovery:

- Heidrun Åre 2023 has a wide window of opportunity for mechanical recovery with use of skimmers, such as the Transrec equipped with traditional weir-skimmer head for emulsion viscosities <20 000 mPa.s.
- Boom leakage and reduced recovery is expected for viscosities <1000 mPa.s, which can be the case for Heidrun Åre 2023 the early phase after a spill.

6.8 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 (FiFi) systems could possibly break up the oil/residue into smaller droplets and enhance the dispersion into the water column. Moreover, 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.

For Heidrun Åre 2023 mechanical dispersion by water flushing only is not considered as a main strategy in oil spill response due to the formation of high emulsion film thicknesses (Figure 6-4) by emulsification, even the oil has low emulsion viscosities in the very early stage after an oil spill, as shown in Figure 6-5. The film thickness of Heidrun Åre 2023 is the main limiting factor for use of water flushing in the combatable areas. However, use of water-flushing can be a supplementary method in "peripheral" areas with thin oil films, e.g., metallic /rainbow appearance.

Summary high-capacity water flushing

- Film thickness is the limiting factor for high-capacity water flushing.
- The predicted film thickness is >0.2-0.3 mm which is the estimated upper limit for effective use of water flushing and is therefore not considered as a main response option for emulsions of Heidrun Åre 2023.
- Mechanical dispersion be used as a supplementary/secondary method on e.g., peripherical areas of thin oil films of metallic/rainbow appearances in calm weather conditions.
- Mechanical dispersion can be used after dispersant treatment under calm sea conditions.

6.9 Chemical dispersion

The viscosity limit for effective dispersant use was estimated up to 4000 mPa.s and the viscosity limit for when the emulsified oil is not or poorly dispersible was estimated above 10 000 mPa.s. In cases when the oil is expected to be reduced dispersible (4000–10 000 mPa.s), additional energy or use through use of Fi-Fi systems, thrusters or using MOB boat with water jet/propulsion to fulfil the dispersion process after dispersant application, may increase the dispersion rate in calm weather conditions.

The window of opportunity for use of dispersant Dasic Slickgone NS is presented in Figure 6-7 at 5 and 15 °C. Heidrun Åre 2023 has a good potential for use of dispersants. The oil is e.g., predicted to be good dispersible up to about 1-2 days in winter and summer conditions at wind speeds of 10-15 m/s, and longer time-windows in calmer wind speeds (2-5 m/s wind speeds). The oil is reduced dispersible for several days.

In a spill situation, the use of a simplified dispersibility testing kit is recommended to assess the potential for chemical dispersion.

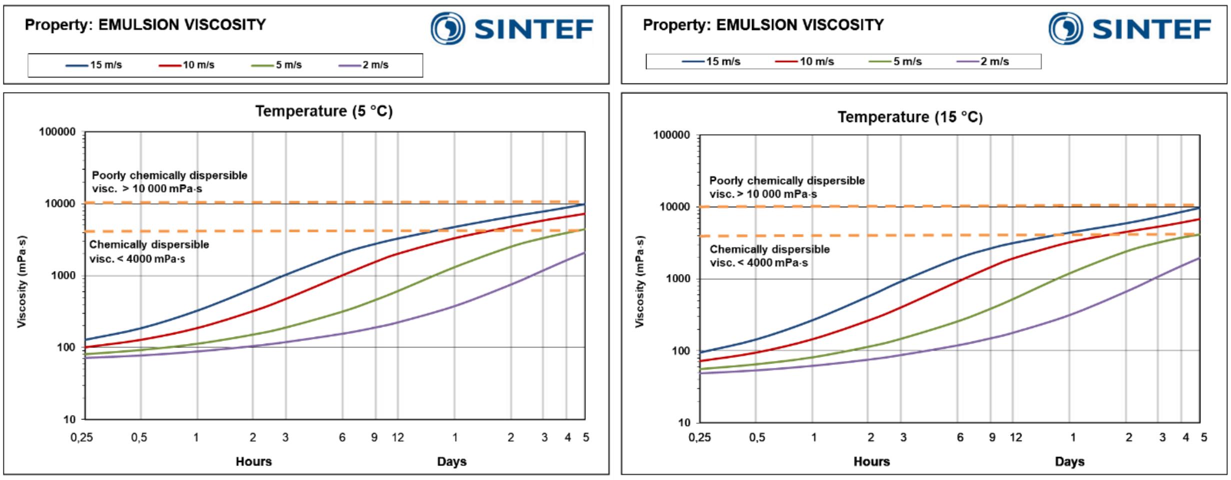


Figure 6-7 *Predicted emulsion viscosity for Heidrun Åre 2023 at 5 °C (left) and 15 °C (right) included the dispersibility limits stated in chapter 3.*

Summary use of chemical dispersants:

- Emulsions of Heidrun Åre 2023 was found to be good dispersible with use of Dasic Slickgone NS for viscosities <4000 mPa.s (DOR 1:25) in non-breaking waves (<2-5m/s wind speeds), and not/poorly dispersible for viscosities >10 000 mPa.s assuming breaking waves (>5-10 m/s wind speeds).
- In the field, additional energy or higher DOR by repeated dispersant application may increase the dispersant effectiveness when the oil is reduced dispersible for viscosities in the range of 4000 -10 000 mPa.s

7 Categorization oil map

A semi-quantitative categorization has been developed by SINTEF to map crude oils into four main groups: Paraffinic, waxy, naphthenic, and asphaltenic oils, based on their typically physiochemical properties, as described below.

Naphthenic oils typically exhibit disrupted n-alkane (paraffins) patterns due to high degree of biodegradation of the oil in the reservoir. The content of paraffins is therefore normally low in for these oils and have low pour points (typically <-10 °C) with corresponding low wax content. Such biodegraded crude oils may have high densities and a high degree of UCM (Unresolved Complex Mixture) consisting of a wide range of complex components, such as resins and naphthenes, but this is not true for all naphthenic oils.

Paraffinic oils are often characterized by low to medium density, which reflects high content of light and saturated components, such as paraffins (n-alkanes). Paraffinic crudes differ mainly from the waxy crudes with a lower wax content (typically < 6 wt. %), hence the pour point of the fresh crude is often lower compared with waxy crude oils. Paraffinic crudes exhibit medium to high evaporation loss, with rapid and high-water uptake, and normally form stable emulsions.

Asphaltenic oils have high content of heavier components reflected by high densities (typically > 0.9 g/mL) and low evaporation loss. The asphaltenic crudes often exhibit low pour points (typically >-4 °C) due to the high asphaltene content (> 1 wt. %) preventing wax precipitation and formation of a wax lattice structure. Compared with paraffinic and waxy crudes the asphaltenic crude oils usually have both a slower and a lower maximum water uptake. The asphaltenic crude oils form very stable, highly viscous, and persistent blackish emulsions with long expected lifetime on the sea surface. The high stability is caused by the stabilization of the polar components in the oil.

Waxy oils often exhibit high pour points due to large content of wax components (typically > 6 wt. %). These oils tend to solidify producing elastic properties on the sea surface, particularly observed at low seawater temperatures. Solidification is typically pronounced if the seawater temperature is 5-15 ºC below the pour point. Waxy crude oils typically exhibit a light to medium evaporative loss. The water uptake can vary extensively, whereas the emulsions can be very stable or even highly unstable depending on the content of stabilizing and polar surface-active components like the asphaltenes and resins.

The categorization of a selection of Norwegian crude oils including Heidrun Åre 2023 is given in Figure 8-1.

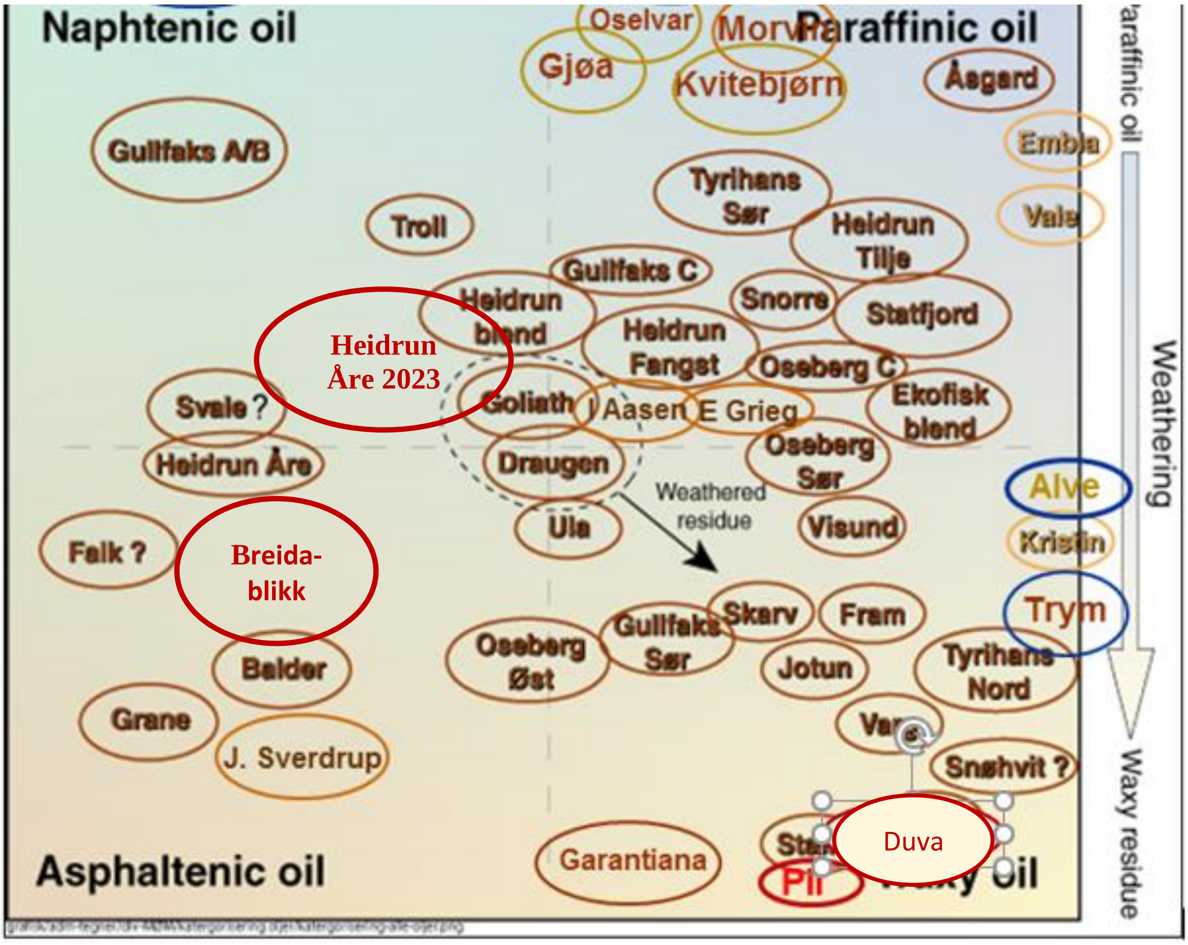


Figure 7-1 *Categorization of a selection of Norwegian crude oils from previous studies including Heidrun Åre 2023.*

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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

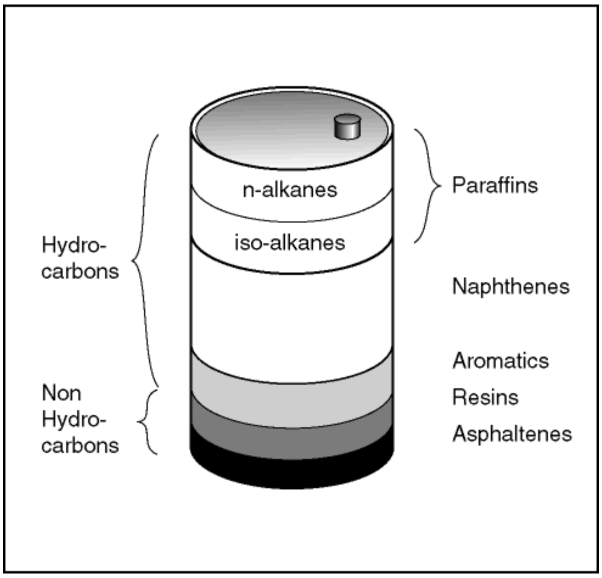


Figure A-1 The chemical composition of crude oils.

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.

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.2Main 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.3Physical 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:

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

In the present study, the density of the oil is presented as specific gravity.

The density of fresh crude oils normally lies in the range 0.78 to 0.95 g/mL (50 to 10 °API).

A.3.1 Rheological properties

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

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

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

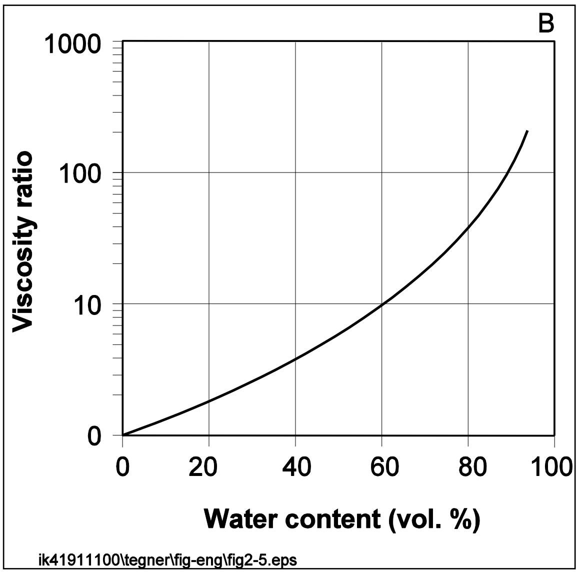


Figure A-2 *Example of viscosity ratio as a function of water content.*

A.3.2 Pour point

The temperature at which oil ceases to flow when cooled without disturbance under standardized conditions in the laboratory is defined as the oil's pour point (ASTM-D97). The method accurately determines the temperature at which the oil become semi-solid under the specified laboratory conditions. Due to the movement at the sea surface, the oil may remain a liquid at sea at temperatures as low as *5 to 15^{o}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.4The behaviour of crude oil spilled at sea

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

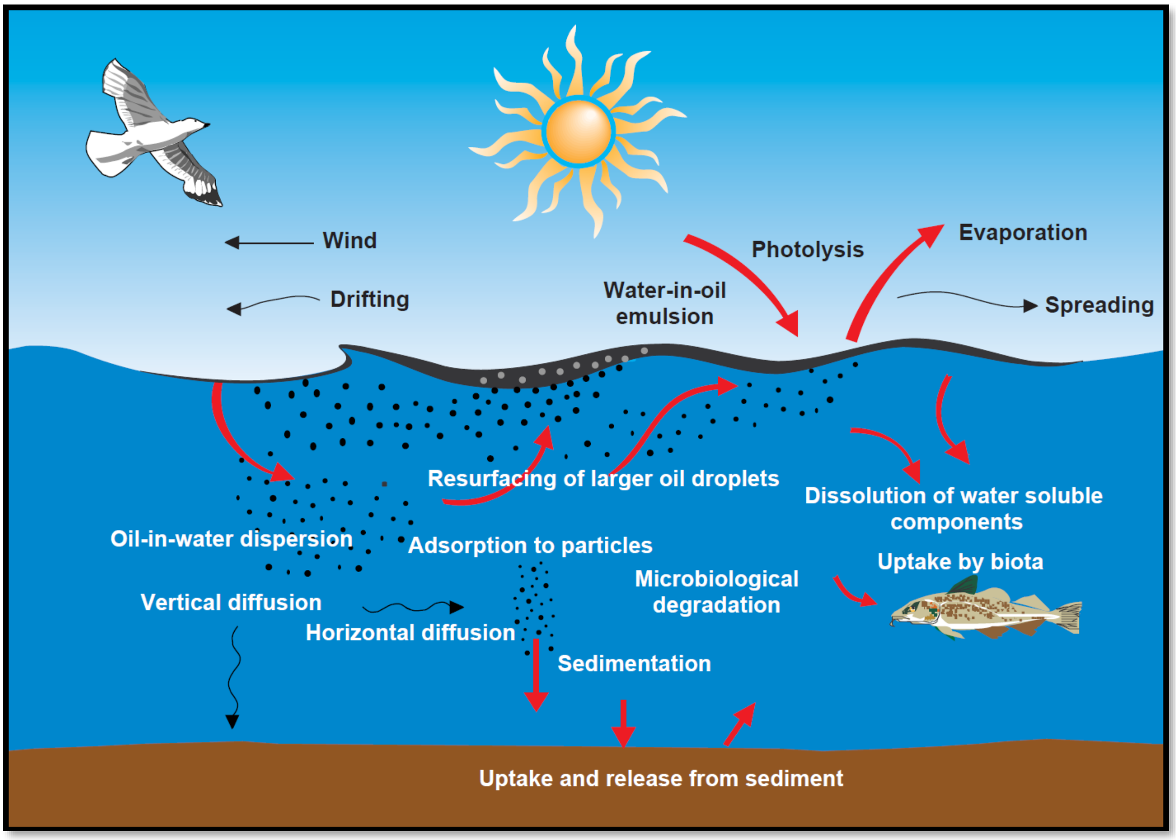


Figure A-3 *Illustrating the weathering processes that take place when oil is spilled on the sea surface.*

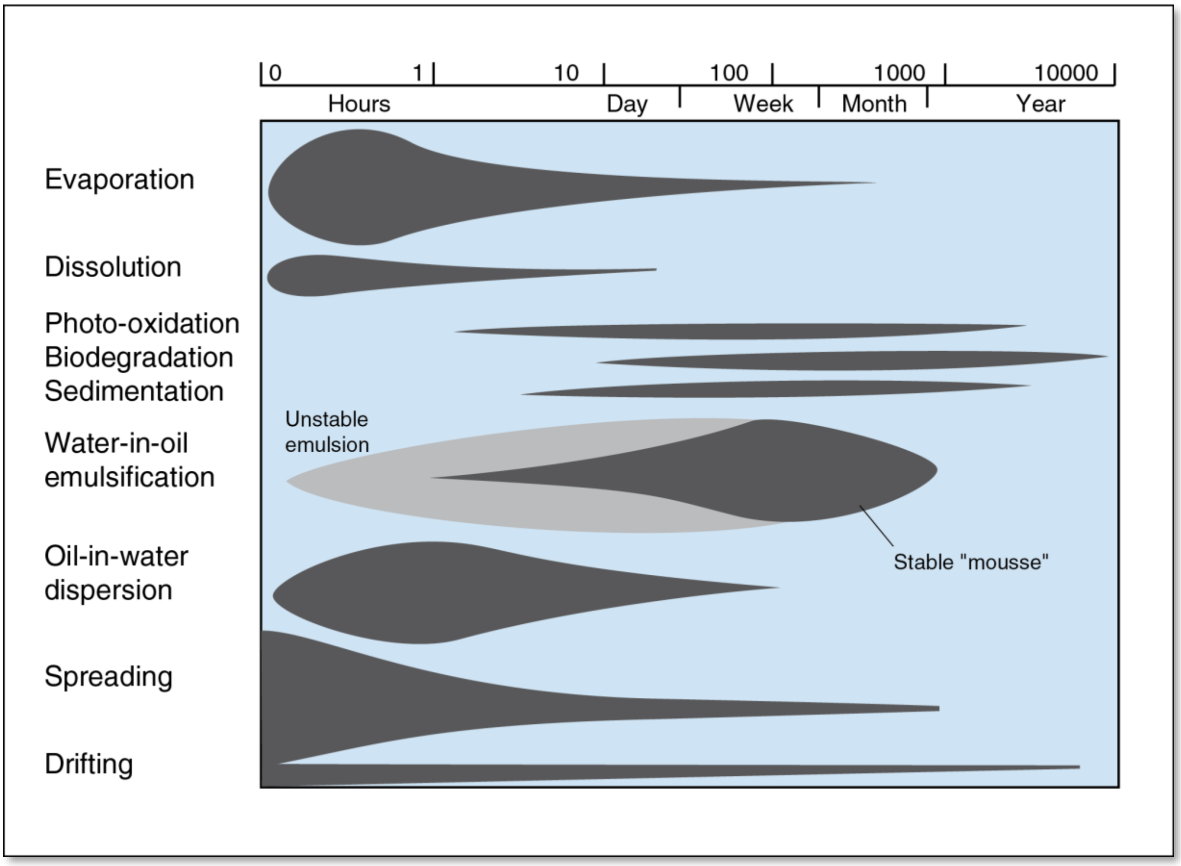


Figure A-4 Weathering processes' relative importance over time. Note: logarithmic scale.

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.

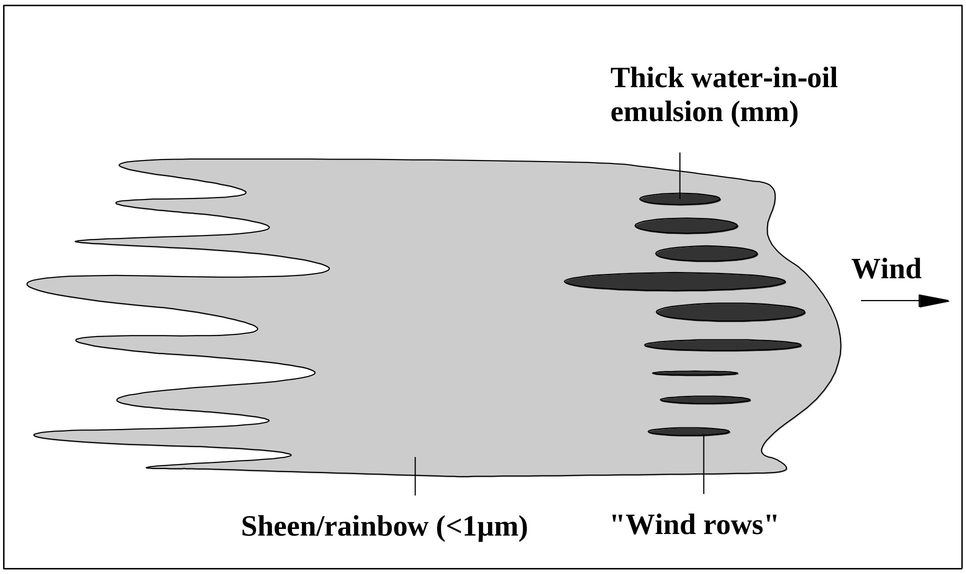


Figure A-5 The spreading of oil spilled on the sea surface and the distribution within the oil slick.

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.

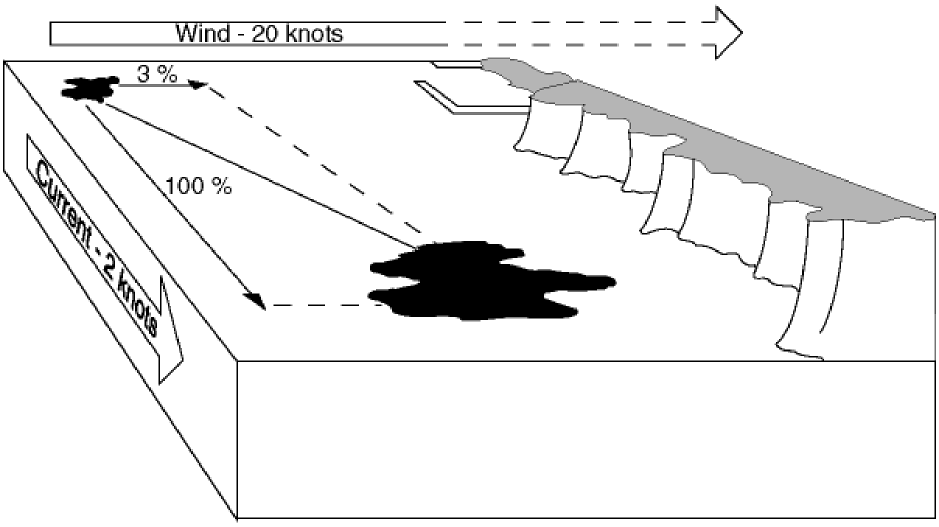


Figure A-6 An illustration showing how wind and current can influence the drifting of an oil slick.

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.

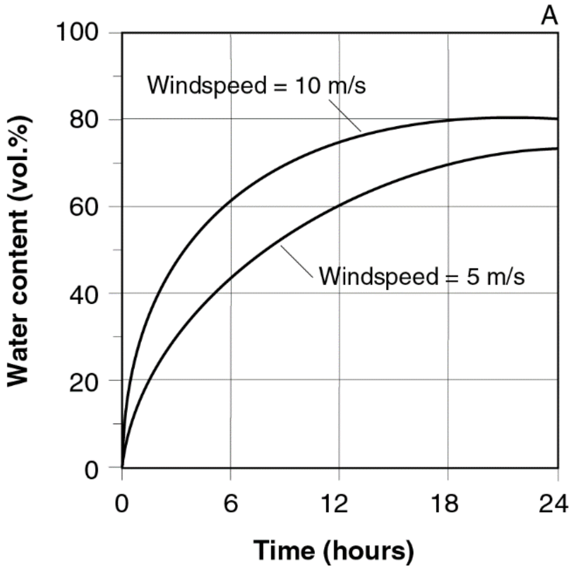


Figure A-7 Example of how weather conditions influence the w/o emulsion formation for typical oils.

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.

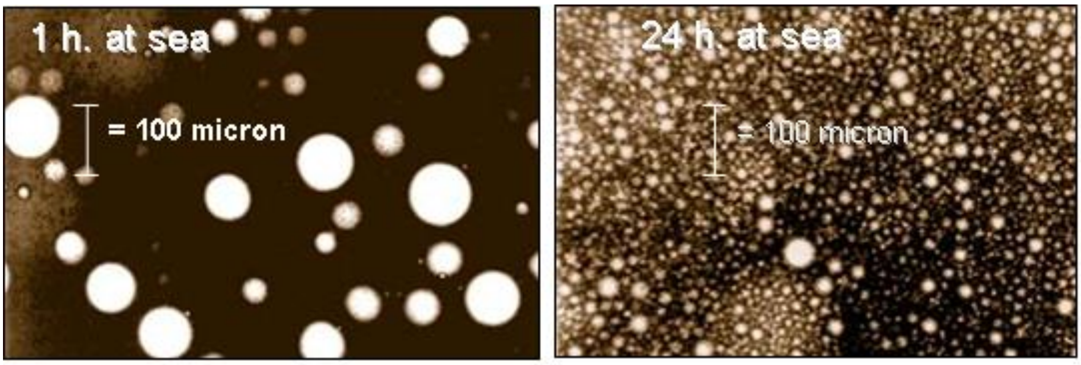


Figure A-8 Microscope pictures of w/o emulsion after (A) 1 h. and (B) 24 h. in a rotating cylinder.

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.

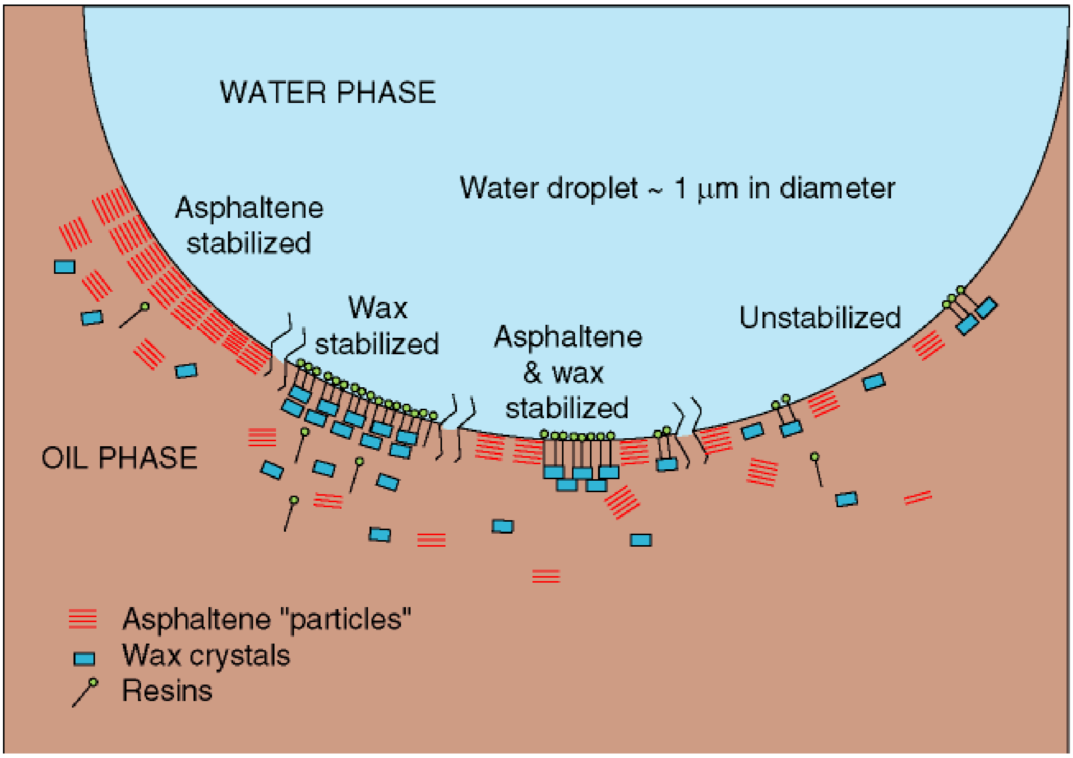


Figure A-9 Interfacial layer stabilized by wax and asphaltenes in w/o emulsion.

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

A.4.6 Water solubility

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

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

A.4.7 Photo-oxidation

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

A.4.8 Biodegradation

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

At sea, the formation of oil droplets by natural or chemical enhanced dispersion will increase the biodegradation rate in the water mass by 10 to >100 times compared to surface oil due to increased water/oil interfacial area. When immobilised on hydrophobic synthetic fabrics, n-alkanes biodegraded within 2-4 weeks at North Sea conditions (13°C; Brakstad and 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.

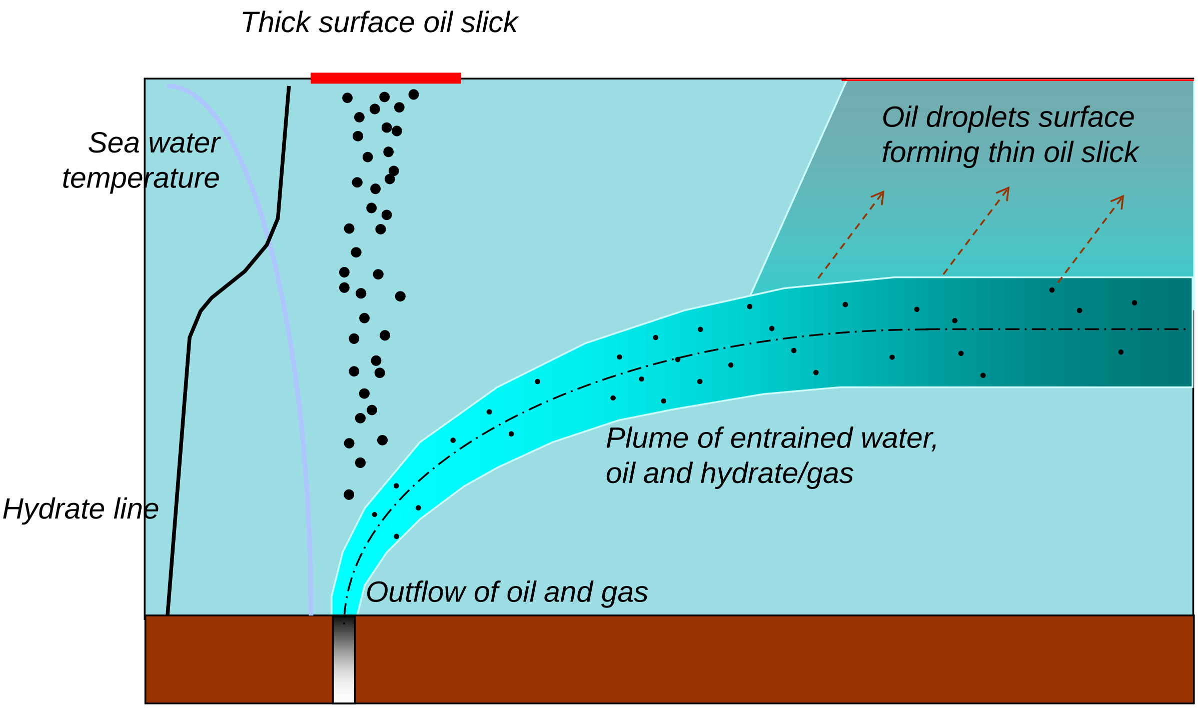


Figure A-10 Illustration of possible creation of thick surface oil slick (> 200 µm) from deep-water release of oil.

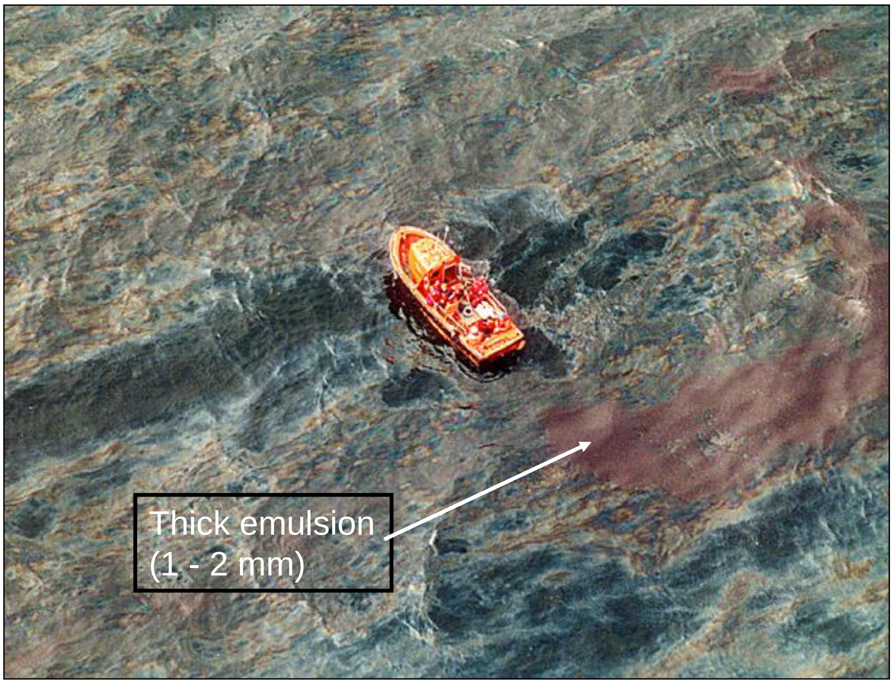


Figure A-11 Surface oil slick (initial thickness > 200 µm) from the experimental deep-water release "DeepSpill" in 2000. Surface oil is emulsifying like an oil slick from a surface batch release (from Leirvik et al., 2011).

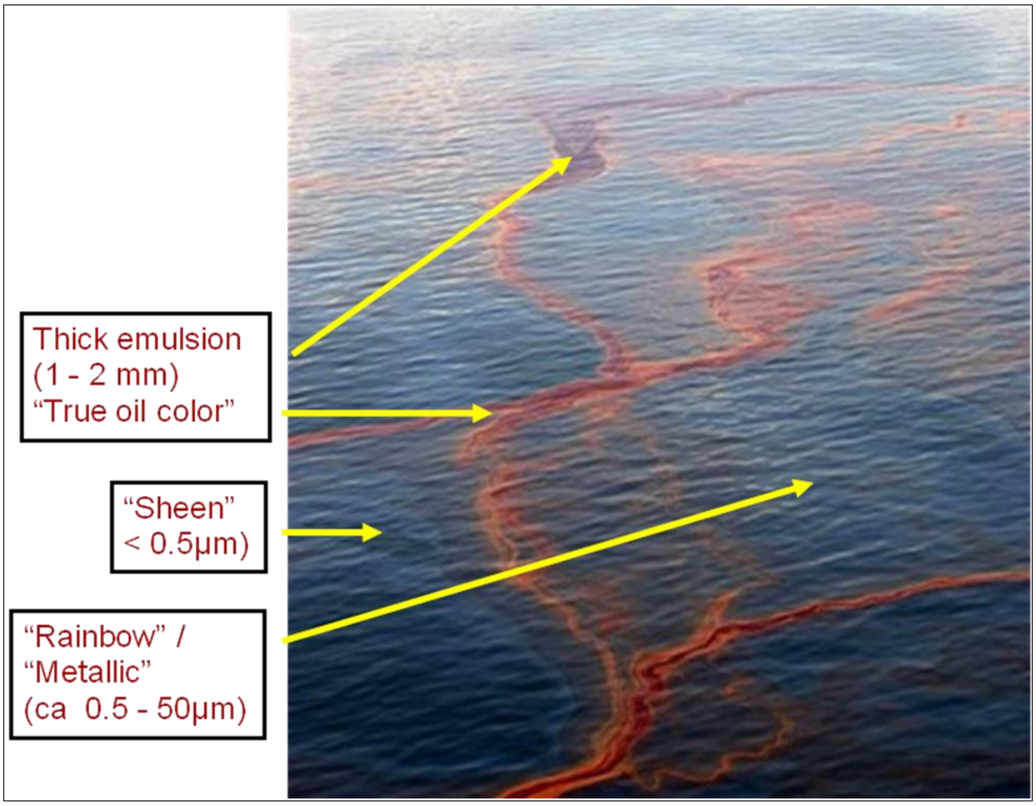


Figure A-12 Surface oil slick (initial thickness > 200 µm) from the DWH deep-water release. Surface oil is emulsifying like an oil slick from a surface batch release.

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.

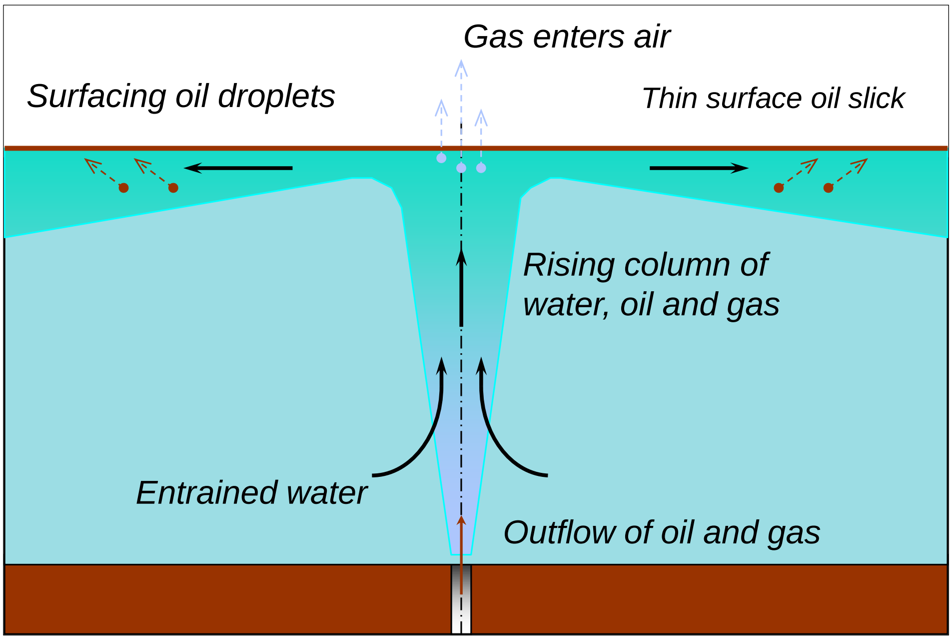


Figure A-13 *Illustration of possible creation of thin surface oil slick (< 200 µm) from a shallow subsurface release (<500 m).*

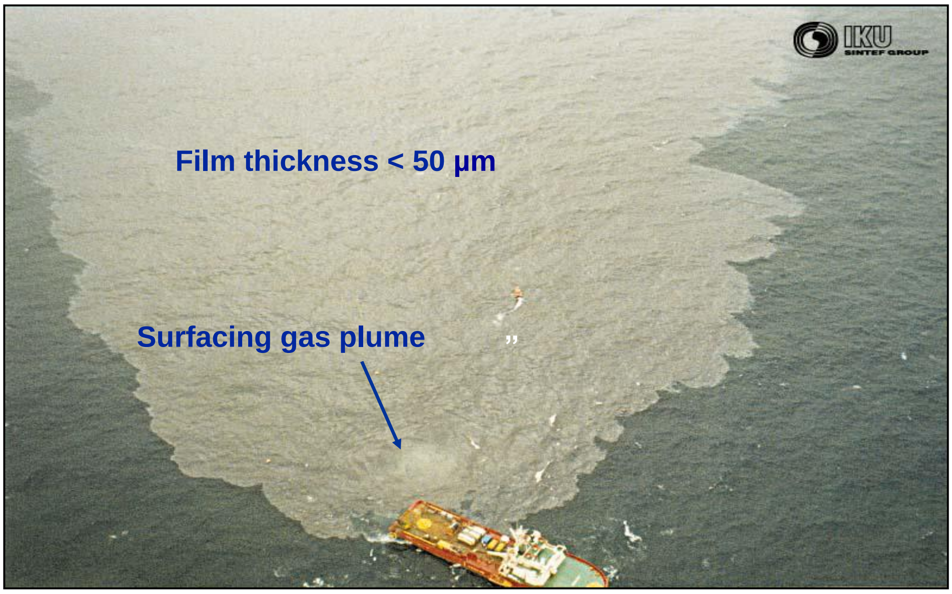


Figure A-14 *Surface oil slick (< 50 µm) from experimental subsurface release at 106 m in 1996. The surface oil did not emulsify and had a very limited lifetime (hours) due to the low film thickness and high rate of natural dispersion (even at < 10 m/s wind).*

B Experimental setup and HSE

B.1 Oil sample and test temperature

SINTEF Ocean received 4x10 litres Jerray cans of Heidrun Åre 2023 crude oil on 13.06.2023. The oil sample were registered in LIMS and given SINTEF ID: 2023-4732.

The weathering dispersibility study (small-scale) were performed at 13 °C agreed upon with the Client. The oil sample was pre-handled, heated to about 50 °C and homogenised before distillation and further analysis.

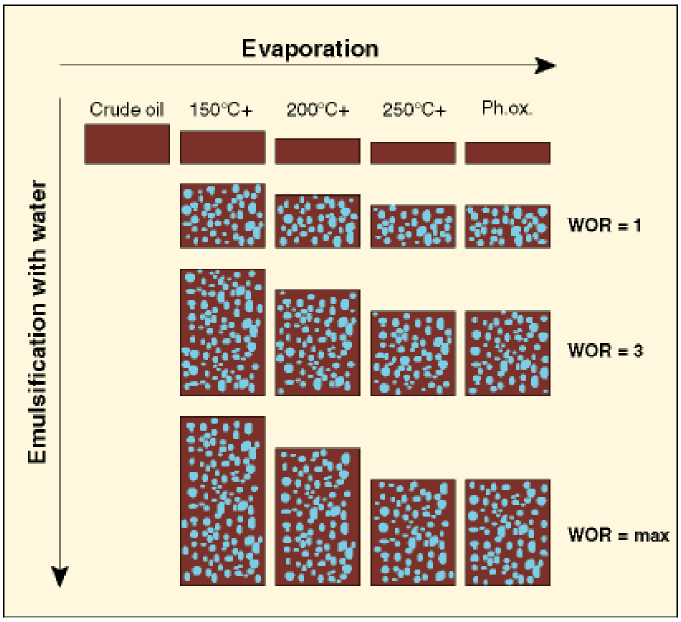
Figure B-1 Heidrun Åre crude oil 2023, 4x10 L. Sampe from A-16. Info: "død" olje fra A-16 (Åre-olje). Tatt 09.09.23 NB! ca 1,2 % vann. 0 partikler. 6 ppm Phasetreat 14862 (Naftanat/emulsjonshemmer).

B.2 Water content

Water content in the oil phase was quantified by use Karl Fisher titration for HSE and risk assessment prior to the topping/distillation step to simulate evaporative loss at sea by topping/distillation. The water content was well below the HSE limit <2 vol. %, and no extra precautions were needed for Heidrun Åre 2023 prior to topping.

B.3 Small-scale laboratory testing

To isolate and map the various weathering processes at sea, the crude oil was exposed to a systematic, stepwise procedure developed at SINTEF (Daling et al., 1990). The general procedure is illustrated in Figure B-2.



WOR: Water to Oil Ratio

WOR=1: 50 vol.% water

WOR=3: 75 vol.% water

WOR=max: the maximum water content

Figure B-2 Small-scale laboratory weathering flow chart of oil.

B.4 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.5 Physical and chemical analysis

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

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

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

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

Chemical property	Analytical method
Wax content	Bridiè et al, 1980
“Hard” asphaltene	IP 143/90

Chemical characterization by GC-FID and GC-MS

- The distribution of hydrocarbons (nC_5-nC_{40}) was analysed using a Gas Chromatograph coupled with a Flame Ionisation Detector (GC-FID). The Gas Chromatograph used was an Agilent 6890N with a 30m DB1 column.

- The analysis and quantification of PAHs, phenols, and alkylated phenols (C_0-C_4) were completed using an Agilent 6890 Gas Chromatograph coupled with 5973 MSD detector (GC-MS) operating in SIM mode (Selected Ion Monitoring)

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

B.6 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.

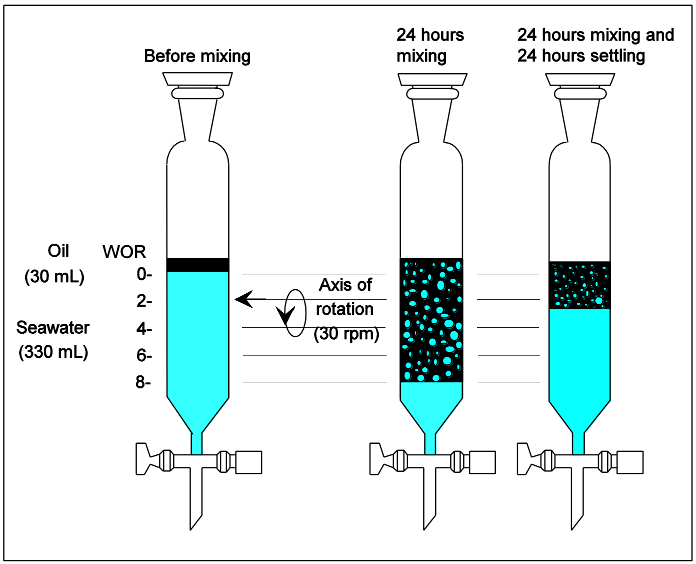


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Figure B-3 Principle of the rotating cylinder method.

B.7 Chemical dispersibility testing

There are several different tests for evaluating the effect of chemical dispersants. The energy input will differ in the different tests, and the obtained efficiency will be representative of different wave energies. At SINTEF, the IFP and MNS test is used in dispersibility testing. IFP and MNS test apparatus are shown in Figure B-4.

IFP (Institute Français du Pétrole test, Bocard *et al.*, 1984) is a low energy test estimated to represent low wave energies (2-5 m/s wind speed). A surge beating up and down in the test vessel at a given frequency, gives energy input to the seawater column. The water column is continuously diluted, which gives a more realistic approach to field conditions, compared to other tests.

MNS (Mackay-Nadeau-Szeto test, Mackay and Szeto, 1980) is estimated to correspond to a medium to high sea state condition. The energy input in this system, applied by streaming air across the oil/water surface, produce a circular wave motion. The sample of the oily water is taken under dynamic conditions after a mixing period of 5 min.

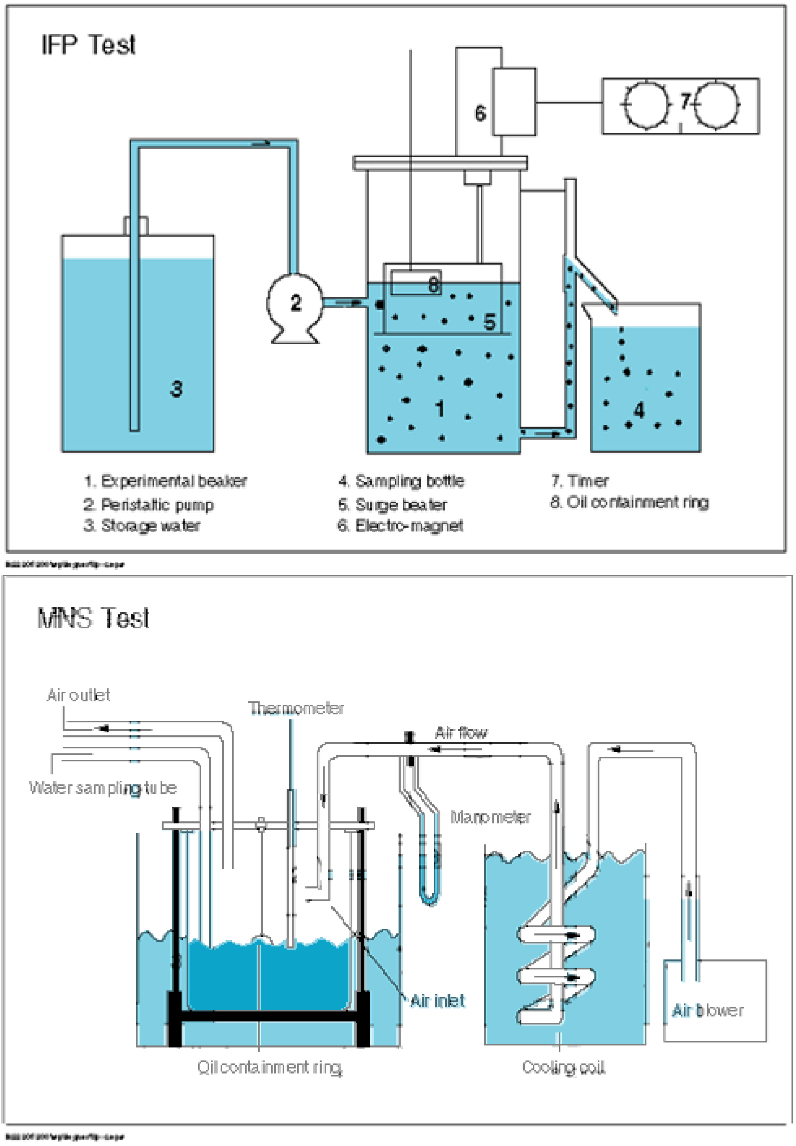

Figure B-4 *Laboratory apparatus for effectiveness testing of dispersants.*

C Input data to SINTEF Oil Weathering Model (OWM)

The laboratory data used as input to the SINTEF OWM for Heidrun Åre 2023 are given from Table C-1 to Table C-3. The oil weathering predictions at 5 and 15 °C were based on the laboratory data at 13 °C.

Table C-1 Physical and chemical properties Heidrun Åre, 2023

Properties of fresh oil	**Heidrun Åre 2023**
Density (g/mL)	0.8998
Pour point (°C)	-26
Reference temperature (°C)	13
Viscosity at ref. temp. (mPa·s = cP) *	43
Flash point (°C)	-
Asphaltenes (wt. %)	0.15
Wax Content (wt. %)	0.78
Dispersible for visc. <	4000
Not dispersible for visc. >	10 000

** Measured at shear rate 10 s^{-1}-: Not analyzed /no data*

Table C-2 True boiling point (TBP) curve of Heidrun Åre, 2023
TBP based on report from Equinor. Report no: FORV-22-05-30-002.

Temp. °C	**Heidrun Åre 2023, vol. %**	**Heidrun Åre 2023, wt%**
36.5	0.54	0.35
69.2	0.87	0.6
126.1	3.44	2.81
151.3	4.80	4.03
196.4	9.71	8.48
253.9	22.02	20.09
303	35.28	32.89
331	43.03	40.44
357	49.39	46.73
381	55.13	52.47
402	59.89	57.27
423	65.03	62.51
441	69.25	66.83
449	70.80	68.43
466	74.16	71.92
481	76.92	74.80
502	80.49	78.56
522	83.54	81.80
596	92.14	81.80
647	96.16	95.59
675	97.75	97.40
688	98.51	98.15

Table C-3 Lab weathering data for Heidrun Åre, 13 °C.

Properties	**Fresh**	**150°C+**	**200°C+**	**250°C+**
Boiling Point Temp. (°C)	-	212.5	255.7	304.0
Vol. Topped (%)	0	5.5	11.5	21.6
Weight Residue (wt. %)	100	95.5	90.3	80.8
Density (g/mL)	0.8998	0.9093	0.9171	0.9272
Pour point (°C)	-36	-36	-36	-30
Flash Point (°C)	-	43.5	73.5	111
Viscosity of water-free residue (mPa.s =cP)*	43	66	169	295
Viscosity of 50% emulsion (mPa.s = cP)*	-	471	804	1853
Viscosity of 75% emulsion (mPa.s = cP)*	-	1295	1514	3896
Viscosity of max water (mPa.s = cP)*	-	691	1254	4288
Max. water cont. (vol. %)	-	55.9	62.0	71.7
(T1/2) Halftime for water uptake (hrs)	-	0.61	0.43	0.63
Stability ratio	-	0.17	0.13	0.65

** Measured at shear rate 10s^{-1}*
- No data

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 Heidrun Åre 2023 (fresh oil) from GC-MS analysis and TBP oil fraction.

0.500	1	C1-C4 gasses (dissolved in oil)
0.100	2	C5-saturates (n-/iso-/cyclo)
0.376	3	C6-saturates (n-/iso-/cyclo)
0.024	4	Benzene
0.800	5	C7-saturates (n-/iso-/cyclo)
0.083	6	C1-Benzene (Toluene) et. B
1.317	7	C8-saturates (n-/iso-/cyclo)
0.175	8	C2-Benzene (xylenes; using O-xylene)
1.834	9	C9-saturates (n-/iso-/cyclo)
0.291	10	C3-Benzene
2.500	11	C10-saturates (n-/iso-/cyclo)
0.085	12	C4 and C4 Benzenes
3.851	13	C11-C12 (total sat + aro)
0.064	14	Phenols (C0-C4 alkylated)
0.150	15	Naphthalenes 1 (C0-C1-alkylated)
9.850	16	C13-C14 (total sat + aro)
-	17	Unresolved Chromatographic Materials (UCM: C10 to C36) 0 0 0
0.283	18	Naphthalenes 2 (C2-C3-alkylated)
6.717	19	C15-C16 (total sat + aro)
0.223	20	PAH 1 (Medium soluble polyaromatic hydrocarbons (3 rings-non-alkylated;<4 rings)
7.777	21	C17-C18 (total sat + aro)
8.000	22	C19-C20 (total sat + aro)
11.701	23	C21-C25 (total sat + aro)
0.299	24	PAH 2 (Low soluble polyaromatic hydrocarbons (3 rings-alkylated; 4-5+ rings)
43.000	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.