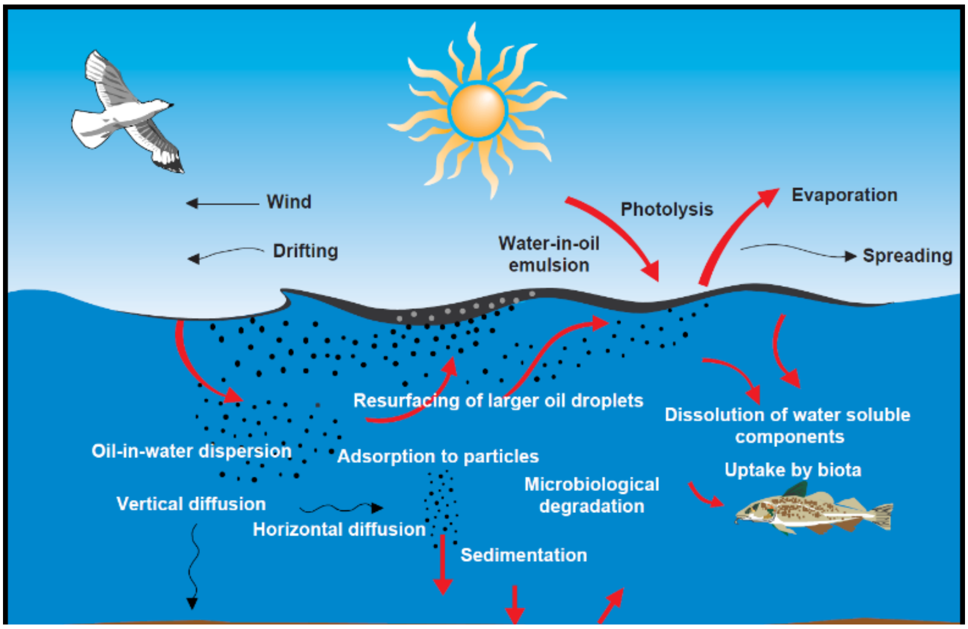
OC2022 A-050 - Open

Report

Weathering study of TOR II and evaluation of oil weathering properties on Eldfisk S and Ekofisk J

In relation to oil spill response and evaluation of the predicted behaviour relative to previous studies of Ekofisk oils

Authors
Kristin Rist Sørheim
Kaja Cecilie Hellstrøm



SINTEF Ocean AS

2022-05-19

SINTEF

SINTEF Ocean AS

Address:
Postboks 4762 Torgarden
NO-7465 Trondheim
NORWAY

Switchboard: +47 46415000

Enterprise /VAT No:
NO 937 357 370 MVA

Report

Weathering study of TOR II and evaluation of oil weathering properties on Eldfisk S and Ekofisk J

REPORT NO.	PROJECT NO.	VERSION	DATE
OC2022 A-050	302006459	1.0	2022-05-19

KEYWORDS:
Weathering
Oil weathering model
Oil spill response

AUTHORS
Kristin Rist Sørheim
Kaja Cecilie Hellstrøm

CLIENT(S)
ConocoPhillips Scandinavia AS

CLIENT'S REF.	NUMBER OF PAGES/APPENDICES:
Harald Lura	100 + 8 Appendices

CLASSIFICATION	CLASSIFICATION THIS PAGE	ISBN
Open	Open	978-82-7174-439-7

ABSTRACT

SINTEF Ocean has performed a standardized small-scale weathering study, including dispersibility testing, on TOR II. Limited laboratory studies were conducted for Ekofisk J and Eldfisk S to compare the weathering properties with previous tested Ekofisk oils with focus on the Ekofisk Blend 2000 (model oil) for environmental risk assessment and oil spill contingency for the Ekofisk area. A dispersibility study was also performed on Eldfisk S, but this was not included for Ekofisk J containing production chemicals that likely reduce the emulsification ability of the oil.

The obtained laboratory data have been used to predict the weathering properties of TOR II and the Ekofisk oils by use of the SINTEF Oil Weathering Model (OWM). In addition, historical data (density) of oils from the Ekofisk area have been evaluated to assess trends and variations in the time series.

PREPARED BY	CHECKED BY	APPROVED BY
Kristin Rist Sørheim	Per S. Daling	Tore Aunaas
Kristin R.Sørheim Kristin R.Sørheim (May 20, 2022 08:48 GMT+2)	Per S. Daling Per S. Daling (May 19, 2022 15:34 GMT+2)	Tore Aunaas (May 19, 2022 20:06 GMT+2)

Document History

VERSION	DATE	VERSION DESCRIPTION
0.1	2022-04-06	Draft for review
1.0	2022-05-19	Final version

Table of Contents

1 Executive summary 6

1.1 TOR II 6

1.2 Eldfisk S and Ekofisk J 8

1.3 Historical data of Ekofisk blends 8

2 Introduction 9

3 Small-scale laboratory testing of TOR II 10

3.1 Gas chromatographic (GC/FID) characterization 10

3.2 Asphaltene and wax content 13

3.3 Physical properties of fresh and weathered residues 13

3.4 Emulsifying properties 15

3.4.1 Emulsification 15

3.4.2 Water uptake and maximum water content 15

3.4.3 Efficiency of emulsion breaker and stability of emulsions 16

3.4.4 Emulsion viscosities and yield stress 16

3.5 Chemical dispersibility 17

3.5.1 Dosage testing of dispersant 17

3.3.3 Systematic dispersant testing and dispersibility limits 19

4 OWM weathering predictions of TOR II 21

5 Weathering properties and response of TOR II 31

5.1 Oil properties 31

5.2 Flash point – Fire/explosion hazard 31

5.3 Solidification 32

5.4 Emulsion formation 33

5.5 Submerged oil and evaporation 33

5.6 Film thickness 35

5.7 Mechanical recovery 35

5.8 Mechanical dispersion by high-capacity water flushing 36

5.9 Use of chemical dispersants 37

6 Summary of response options for TOR II 39

7 Experimental results for Ekofisk J and Eldfisk S 40

7.1 Physio-chemical properties 40

7.2 Water uptake and maximum water content 41

7.3 Efficiency of emulsion breaker and stability of emulsions 43

7.4 Emulsion viscosities 43

7.5 Dispersibility of Eldfisk S 44

8 Summary Eldfisk S and Ekofisk J 46
- 8.1 Comparison with model oil (Ekofisk Blend 2000) 46
- 8.2 Response options Eldfisk S 46
- 8.3 Response options Ekofisk J 46

9 Evaluation of historical data for Ekofisk blends 47

10 References 50

A Description of SINTEF Oil Weathering Model (OWM) 51

B Predicted weathering behaviour of Eldfisk S and Ekofisk J 53
- B.1 Eldfisk S 2021 53
- B.2 Ekofisk J 2021 62

C Comparison of OWM predictions of TOR II and Ekofisk oils 71
- C.1 Evaporative loss 71
- C.2 Pour point 72
- C.3 Water content 73
- C.4 Emulsion viscosity 74
- C.5 Surface oil 75

D The behaviour of crude oil on the sea surface 76
- D.1 The chemical composition of crude oils and condensates 76
- D.2 Main oil categories related to weathering 77
- D.3 Physical properties of crude oils 77
  - D.3.1 Rheological properties 78
  - D.3.2 Pour point 79
  - D.3.3 Flash point 79
- D.4 The behaviour of crude oil spilled at sea 80
  - D.4.1 Evaporation 81
  - D.4.2 Spreading 81
  - D.4.3 Drift of an oil slick 82
  - D.4.4 Water-in-oil (w/o) emulsion 82
  - D.4.5 Oil-in-water (o/w) dispersion 84
  - D.4.6 Water solubility 85
  - D.4.7 Photo-oxidation 85
  - D.4.8 Biodegradation 85
  - D.4.9 Sedimentation 86
  - D.4.10 Deep water releases 86
  - D.4.11 Shallow releases 88

E Experimental setup 89
- E.1 Oil samples and test temperature 89
- E.2 Small-scale laboratory testing 89

E.2.1 Evaporation ... 89
E.2.2 Physical and chemical analysis ... 90
E.2.3 Emulsification properties ... 90
E.2.4 Chemical dispersibility testing ... 91

F Input data to SINTEF Oil Weathering Model (OWM) ... 93
F.1 TOR II ... 93
F.2 Eldfisk S ... 94
F.3 Ekofisk J ... 95

G Chemical characterisation of the fresh oil on GC/MS on TOR II ... 98

H Categorization of TOR II, Ekofisk J and Eldfisk S from 2021 ... 99

1 Executive summary

In general, 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 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 remove an oil spill from the sea surface. Input from the experimental weathering data is input to SINTEF Oil Weathering Model (OWM) to predict the properties of oils as weathered over time.

This summary includes the main findings from this study:

- A weathering study of TOR II, a crude oil from the Tor field, has been conducted. The dispersibility testing on TOR II was included to estimate viscosity limits and time-window for dispersant use. The laboratory data are used as input to the SINTEF Oil Weathering Model (OWM) for weathering predictions at 5 and 15 °C. The weathering properties of TOR II have also discussed in relation to oil spill response. The summary below gives the main changes predicted for TOR II when weathered on the sea surface assuming sufficient initial film thicknesses, typically >0.1 mm.
- A limited weathering study were conducted on Eldfisk S and Ekofisk J, including dispersibility testing of Eldfisk S to estimate viscosity limits and time-window for dispersant use. Dispersibility study of Ekofisk J was omitted due to the content for production chemicals. Response options of Eldfisk S and Ekofisk J have been evaluated.
- Comparison of weathering properties of Eldfisk S and Ekofisk J with previous tested Ekofisk blends from 2015 to evaluated if the existing Ekofisk Blend 2000 can still be valid as a model oil for environmental risk assessments and contingency planning for Ekofisk blends. Laboratory data of Eldfisk S and Ekofisk J and were also compared with previous tested Ekofisk oils from 2015.
- Historical data of oils from the Ekofisk area have been evaluated to find trends and variations in densities by time.

1.1 TOR II

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

- TOR II is a paraffinic crude oil with medium density (0.834 g/mL) with a content of volatile (43 vol %, 250°C+) that cause a moderate degree of evaporative loss: E.g., after 12 hours the evaporative loss is in the range of 32-35 wt. % at 10 m/s wind speed.
- The combination of a relatively high content of wax (7.07 wt.%), asphaltenes (0.06 wt.%), and density, TOR II forms stable water-in-oil emulsions with high water uptake of 75-80 vol .%
- The emulsion formed are expected to be persistent on the sea surface. E.g., the OWM predictions indicate a lifetime at 15 m/s wind speed of 2 days. In calmer weather conditions the lifetime is predicted to be >5 days.
- As much as 65 % 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 can increase 2-2.5 times relative to the volume due to emulsification
- The residue at sea may form semi-solid lumps/material particularly in calm sea conditions (< 2-5 m/s wind speeds) due to the high pour points of +18 and +27 °C for the 150 and 250°C+ residues, expecting to be less pronounced in summer conditions than in colder seawater temperatures.

Risk of fire /explosion hazard in oil spill response:

If free gas is not associated with an oil release (e.g stabilized oil at 1 atm.), the flash point of the oil is the most important parameter when evaluating the potential for fire /explosion hazard. In such cases when the oil is spilled on the sea surface it assumes to reach the ambient water temperature within a short time. The fire hazard, based on the volatile components from the oil, may be high if the flash point of the oil is below the sea temperature.

For TOR II, the flash point is predicted to exceed the sea temperature within the first 15 minutes at wind speeds (2-15 m/s). 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. TOR II reaches this limit (60 °C) in 3 hours after a spill at calm wind speed (2 m/s) at summer and 6 hours in winter conditions respective, and more rapidly at higher wind speeds. However, this limit is not considered at relevant for oil recovery vessels with A class certification for transport of liquids (Class I/II, flash point <60 °C).

A "safety" zone should be established early and downwind from the spill site before any response actions in case of an acute oil spill involving free gas. In a response operation, explosimeters should be utilized to measure concentrations of free gas to minimize the risk for fire and explosion hazard at the spill site.

Effect of adding emulsion breaker:

The emulsions of TOR II were stable but easily released about 82-99 % of incorporated water when adding concentrations (500 and 2000 ppm by weight) of the emulsion breaker (Aerosol OT-SE surfactant). The highest concentration (2000 ppm) was shown to be slightly more effective than 500 ppm. Use of emulsion breaker may effectively be used 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.

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. This study shows that the emulsion viscosities of TOR II surpassed 1000 mPa·s about 4-6 hours at 5 m/s wind speed (5 and 15 °C), and about 1.5-2 hours at 10 m/s wind speed at 5 and 15 °C. Moreover, viscosities larger than 20 000 mPa·s are known to reduce the flowability of the oil/emulsion when using traditional weir skimmers. However, TOR II has predicted emulsion viscosities lower than this limit within 5 days weathering at summer and winter conditions.

Chemical dispersion:

TOR II is expected to have potential for chemical dispersion but requires energy in terms of breaking waves (>5 m/s wind speeds) and /or artificial energy to enhance the dispersion. The oil was found to be reduced dispersible with the dispersant Dasic Slickgone NS (DOR; dispersant-to-oil ratio 1:25) for viscosities <9000 mPa·s with use of the low energy test (IFP), and poor/low dispersible >9000 mPa·s (high energy test, MNS). In the field, if the oil is reduced dispersible, additional energy e.g., thrusters, Fire Fighting (Fi-Fi) systems, higher DOR by repeated dispersant application may increase the efficacy of the dispersant treatment.

Solidification of residue at sea:

Increased weathering potentially increases the high pour points to the point of solidification (elastic properties) at the sea surface. 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. In such cases, if solidified (low emulsified /water free) lumps are observed on the sea surface, a lower dispersant effectiveness is likely.

High-capacity water flushing (mechanical dispersion):

The emulsification is the limiting factor for this strategy. The predicted film thicknesses > 0.2-0.3 mm are the estimated upper limits for effective use of water flushing. Water flushing should therefore not be considered as a main response option for TOR II and could be a supplementary method in areas 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 TOR II.

1.2 Eldfisk S and Ekofisk J

Physico-chemical properties of Eldfisk S and Ekofisk J show consistent data with the previous tested Ekofisk blends (Ekofisk J, Eldfisk B and Eldfisk Kompleks) from 2015. In addition, Eldfisk S and Ekofisk J from this study showed physio-chemical properties closer to Ekofisk Blend 2000 compared to their counterparts analysed in 2015. The use of the existing model oil, Ekofisk Blend 2000, can still be considered as valid, and is the same conclusion given for the Ekofisk blend study from 2015.

Chemical dispersion and mechanical recovery of Eldfisk S

Emulsions of Eldfisk S were found to be good dispersible for viscosities <1000 mPa·s (DOR 1:25), i.e., in non-breaking waves (<5 m/s wind speeds), and poorly/low dispersible for viscosities >10000 mPa·s in breaking waves conditions (> 5m/s wind speeds). Eldfisk S showed reduced dispersibility in the range between 1000-10000 mPa·s. In the field, additional energy in calm sea conditions or higher DOR by repeated dispersant application may increase the dispersant effectiveness when viscosities are between 1000 mPa.s and 10000 mPa·s. For boom leakage of confined oil, the emulsion viscosity exceeds 1000 mPa·s after 1.5- 2 hours at 10 m/s wind speed but are stretched up to 9-12 hours for very low wind speed (2 m/s). Overall, Eldfisk S has a wide window of opportunity for traditional weir-skimmer head due to viscosities <20 000 mPa·s, e.g., 4-5 days of weathering at summer and winter conditions at 10 m/s wind speed.

Chemical dispersion and mechanical recovery of Ekofisk J:

The batch of Ekofisk J for testing in 2021 contained production chemicals and showed unexpected emulsifying properties (low water uptake and low emulsion viscosity) compared with the other Ekofisk oils. The dispersant testing was therefore omitted for Ekofisk J in agreement with COPSAS. However, based on the physico-chemical properties and weathering predictions based on the SINTEF OWM Crude Assay (CA) module, it can be assumed that Ekofisk J not spiked with production chemicals have similarities in viscosity limits and the time-window for use of dispersant as Eldfisk S and Ekofisk Blend 2000.

Similar, the time-window for use of weir skimmers for viscosities <20 000 mPa·s is also likely to be close to Eldfisk S. The response options for Ekofisk J are however based on the predictions based on the CA-model and synthetical weathering data, and the assumption are therefore more uncertain than having the experimental data for Ekofisk J to be used as input to the SINTEF OWM for predictions.

Moreover, a spill from a release of Ekofisk J containing production chemicals will have lower water uptake and emulsion fraction and is expected to have a higher degree of natural dispersion due the content of surface-active compounds (low interfacial tension (IFT)). The oil is further expecting to have a long time-window for dispersants use (>5 days). High emulsion viscosity will either not be a challenge for use of weir skimmers, but leakages of confined oil for viscosity <1000 mPa·s should be considered.

1.3 Historical data of Ekofisk blends

SINTEF has received historical crude assay data for Ekofisk J, Eldfisk B (similar as Ekofisk Kompleks) and Eldfisk S from 2000 to 2022. In addition to recent data of TOR II (2020-2022). The trends in densities over these years has been plotted and evaluated. A similar evaluation of was performed for Ekofisk blends in 2015. Note, from May 2020 a drop in the data set was observed resulting somewhat lower densities for alle the oils and is likely caused by the methodology.

- Ekofisk J shows minor variation of densities between 2000-2020. From December 2020 a decrease in density occurs due to inclusion of TOR II, that has a lower density than Ekofisk J.
- Eldfisk S shows a significant increase of densities from 2000-2007 and show only marginal variation in density up to the recent data from 2022.
- Eldfisk B has varied densities over the years, being low in 2000, high in 2005 and then relatively stable between 2010-2019. After the methodically drop in density in 2020, the density appears to be stable only with some minor differences.

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 D describes the general physical and chemical properties and weathering processes of oil spilled on the sea surface.

According to the Norwegian Environment Agency and the Petroleum Safety Authority Norway (Ptil) regulations for petroleum activities (Aktivitetsforskriften §59), the characterization of oils with respect to their weathering properties and fate in the marine environment should be performed for all oils coming into production and regularly re-check (limited) studies of previously tested oils. SINTEF Ocean has performed a standardized small-scale weathering study, including dispersibility testing, on TOR II. Limited laboratory studies were conducted for Ekofisk J and Eldfisk S to compare the weathering properties with previous tested Ekofisk oils with focus on the Ekofisk Blend 2000 (model oil) for environmental risk assessment and oil spill contingency for the Ekofisk area. A dispersibility study were also performed on Eldfisk S but were omitted for Ekofisk J due to production chemicals that reduce the emulsification of the oil. The obtained laboratory data have been used to predict the weathering properties of TOR II and the Ekofisk blends by use of the SINTEF Oil Weathering Model (OWM). A comparison of weathering properties of Eldfisk S and Ekofisk J with previous tested Ekofisk blends from 2015 has been performed to evaluated if the existing Ekofisk Blend 2000 can still be valid as a model oil for environmental risk assessments and contingency planning for Ekofisk blends. In addition, an evaluating of historical data (density) of the Ekofisk blends over several years has been assessed for trends and variations. An overview of the Ekofisk area is given in Figure 2-1.

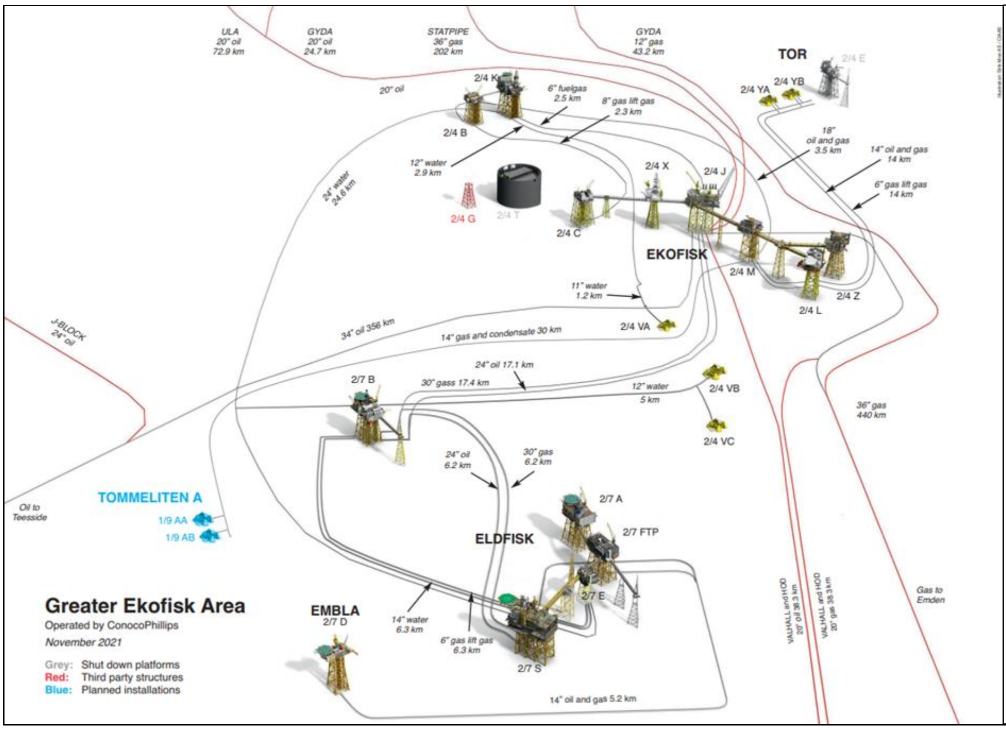


Figure 2-1 Overview of Ekofisk area.

Ekofiskområdet som består av feltene Ekofisk, Eldfisk, Embla og Tor ligger i den sørlige delen av norsk sektor i Nordsjøen. Vanndybden er 80 meter ved Ekofisk og 70 m ved Tor og Eldfisk

Ekofisk ble påvist i 1969, og opprinnelig plan for utbygging og drift (PUD) ble godkjent i 1972. Tor feltet ble bygget ut med en plattform med produksjonsstart i 1978 og stengt 2015. Feltet er bygget ut på nytt med oppstart i desember 2020. To bunnrammer produserer til Ekofisk. Olje og gass sendes til eksportrørledninger via prosessanlegget på Ekofisk J.

Gass fra Ekofisk-området transporteres via Norpipe gassrørledning til Emden i Tyskland, mens oljen sendes i Norpipe oljerørledning til Teesside i Storbritannia.

3 Small-scale laboratory testing of TOR II

Description of the experimental setup for the small-scale weathering study, including dispersibility methods are described in Appendix E. Physico-chemical parameters and weathering properties of TOR II are compared with other Ekofisk oils including Ekofisk J and Eldfisk S (2021) from this present study, and previous studies from 2000 (Ekofisk Blend) and 2015 (Ekofisk J, Eldfisk B and Eldfisk Kompleks), as listed in Table 3-1. The experimental results of Ekofisk J and Eldfisk S from 2021 are given in chapter 6.

Table 3-1 Overview of TOR II and other Ekofisk oils in comparison in this report.

Oil	SINTEF-ID	SINTEF report number	Reference
TOR II	2021-6958	This report	Sørheim and Hellstrøm, 2021
Eldfisk S	2021-6959	This report	Sørheim and Hellstrøm, 2021
Ekofisk J	2021-6960	This report	Sørheim and Hellstrøm, 2021
Ekofisk Blend (2000)	2000-0624	STF6 A01090	Moldestad et al, 2001
Ekofisk J (2015)	2015-0474	A27361	Hellstrøm and Brandvik, 2015
Eldfisk B (2015)	2015-0475	A27361	Hellstrøm and Brandvik, 2015
Eldfisk Kompleks (2015)	2015-0476	A27361	Hellstrøm and Brandvik, 2015

3.1 Gas chromatographic (GC/FID) characterization

The hydrocarbon profile of TOR II 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 TOR II and the corresponding evaporated residues at three different degrees of evaporative loss of volatiles with boiling points 150, 200 and 250°C+ (see Appendix E.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.

The gas chromatogram of TOR II in comparison with Eldfisk S and Ekofisk J (2021) are shown in Figure 3-2 as GC/FID chromatograms. Appendix G shows the result of the chemical characterization of the fresh oils on GC/MS.

The gas chromatograms show the n-alkenes as systematic narrow peaks and the peaks to the left in the chromatograms represent the components with the lowest boiling point. As can be seen in Figure 3-1, these components are gradually removed with higher distillation temperature. More complex components, such as resins and naphthenes, are not as easily separated as *n*-alkanes and form a broad and poorly defined bump below more pronounced peaks. The bump is often described as "Unresolved Complex Mixture", or UCM. Heavier compounds such as asphaltenes (> nC40) are not possible to analyse with this technique.

TOR II, Eldfisk S and Ekofisk J from this current study are typically paraffinic crude oils and have very similar hydrocarbon profiles. The gas chromatograms from this study are also very similar to previous tested Ekofisk oils of Ekofisk Blend 2000 (Moldestad et al, 2001), and Ekofisk J, Eldfisk B, Eldfisk Kompleks from 2015 (Hellstrøm and Brandvik, 2015).

Gas chromatography (GC/FID) is an important tool for oil characterisation and for oil spill identification as an initial step. Common screening parameters used for identification, as well as for the degree of biodegradation, are the *n*C17/Pristane and *n*C18/Phytane ratios. Table 3-2 shows the ratios of TOR II in comparison with other Ekofisk crude oils. Overall, the ratios >1 are typically for paraffinic crude oils. The ratios are in the same range for the Ekofisk oils, but the Ekofisk Blend 2000 expresses the highest ratios for nC17/Pristane and nC18/Phytane compared with the other Ekofisk oils for comparison.

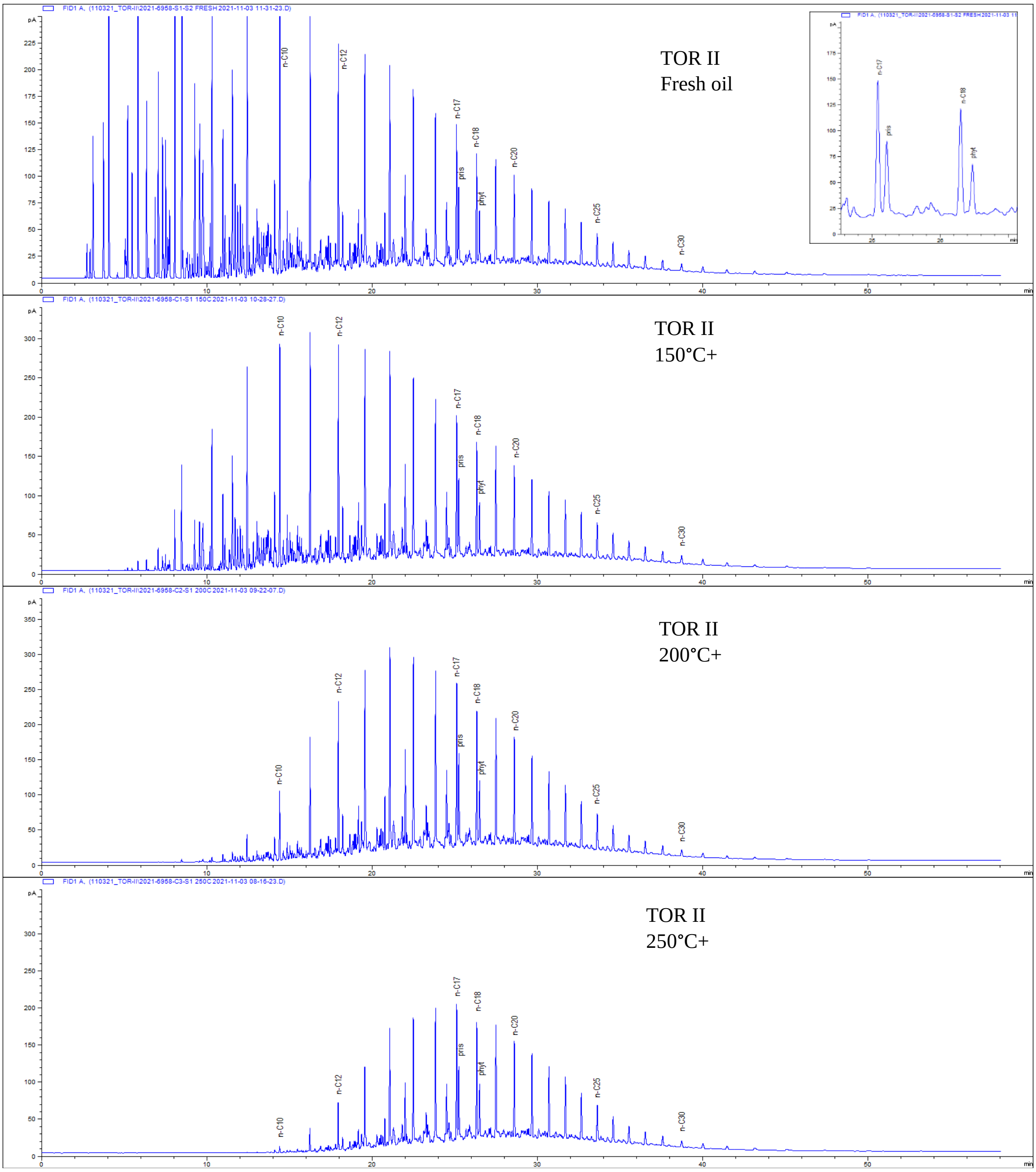


Figure 3-1 GC/FID chromatograms of fresh sample and evaporated residues of TOR II crude oil.

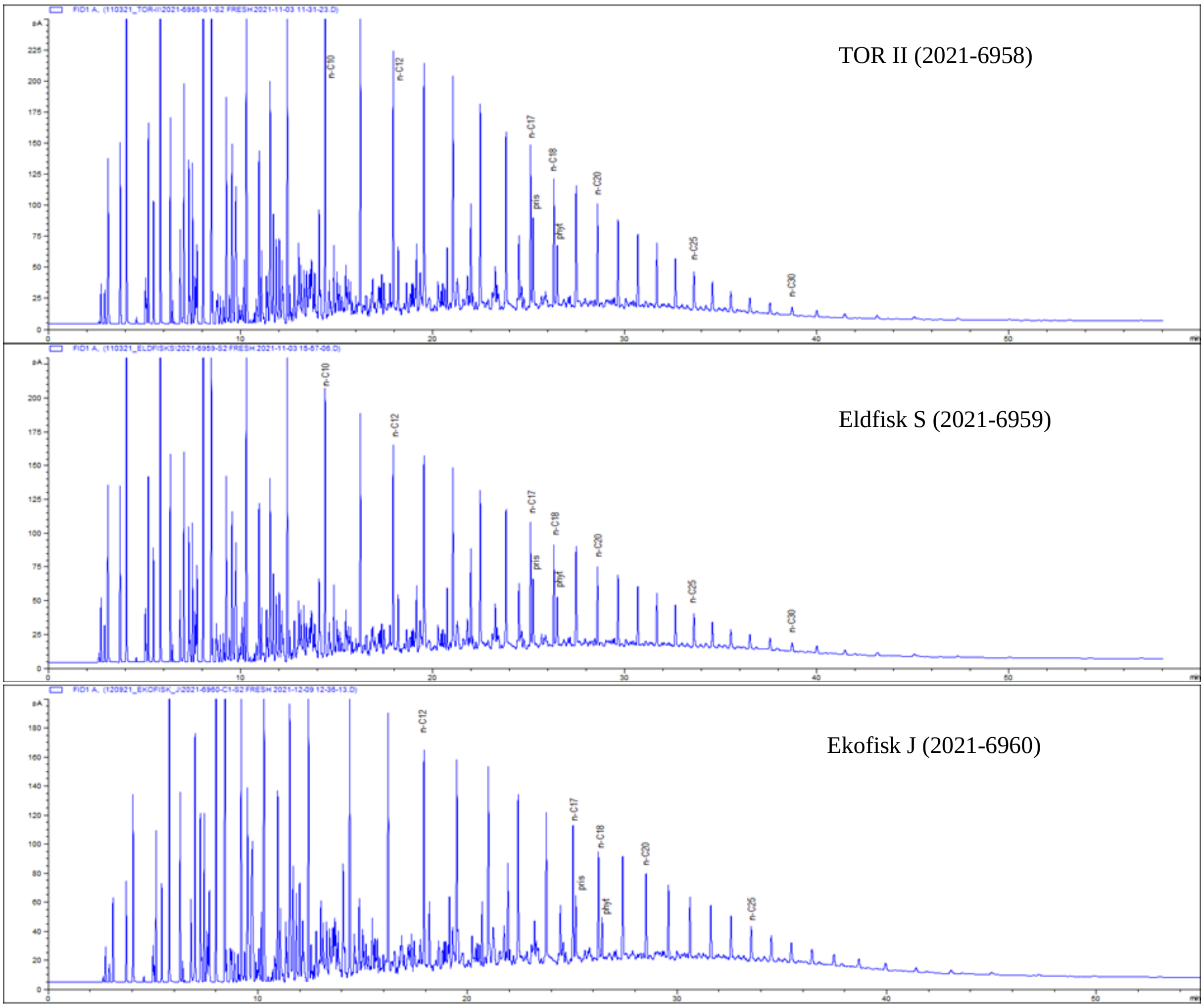


Figure 3-2 *GD/FID chromatograms of fresh TOR II, Eldfisk S and Ekofisk J from 2021. The retention times may differ between the chromatograms due to different temperature programs (relative comparison).*

Table 3-2 *n*C$_{17}$/*Pristane and n*C$_{18}$/*Phytane ratios* for fresh Ekofisk oils.*

Oil	***n*C$_{17}$/Pristane**	***n*C$_{18}$/Phytane**
TOR II	1.8	2.1
Eldfisk S (2021)	1.8	2.0
Ekofisk J (2021)	2.0	2.4
Ekofisk Blend (2000)	2.9	3.1
Ekofisk J (2015)	2.2	2.6
Eldfisk B (2015)	2.2	2.5
Eldfisk Kompleks (2015)	2.0	2.1

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

3.2 Asphaltene and wax content

The chemical properties of asphaltene and wax contents are given in Table 3-3 for TOR II, Eldfisk S and Ekofisk J from this current study in comparison with previous tested Ekofisk oils.

Eldfisk S (2021) exhibits the highest content of asphaltenes of the fresh oil (0.10 wt%), whilst TOR II, Ekofisk J (2021), Eldfisk Kompleks (2015), and Ekofisk Blend (2000) have very similar asphaltene content in the range of 0.06-0.08 wt%. Ekofisk J (2015) has the lowest content of asphaltenes of 0.02 wt.% (fresh oil).

TOR II has the highest wax content of 7.07 wt.% compared with the other Ekofisk oils. The wax content of Ekofisk J has increased from 3.69 wt.% (2015) to 4.27 wt.% (2021) and are now closer to Ekofisk Blend (2000) that had a wax content of 4.93 wt.%. Overall, the wax contents of Ekofisk crude oils are in the medium range, whilst TOR II that tendence towards more waxy crude oil (i.e., wax > 6 wt.%).

Table 3-3 Asphaltene ("hard") and wax content for TOR II and Ekofisk crude oils for comparison.

Oil	**Residue**	**Asphaltenes "hard"* (wt. %)**	**Wax (wt. %)**
TOR II	Fresh	0.06	7.07
	150°C+	0.07	8.52
	200°C+	0.09	10.2
	250°C+	0.10	11.8
Eldfisk S (2021)	Fresh	0.10	3.99
	150°C+	0.12	4.76
	200°C+	0.14	5.60
	250°C+	0.17	6.65
Ekofisk J (2021)	Fresh	0.07	4.27
	150°C+	0.08	5.14
	200°C+	0.09	5.57
	250°C+	0.10	6.34
Ekofisk Blend (2000)	Fresh	0.07	4.93
	150°C+	0.08	5.87
	200°C+	0.09	6.57
	250°C+	0.10	7.36
Ekofisk J (2015)	Fresh	0.02	3.69
	250°C+	0.03	5.62
Eldfisk B (2015)	Fresh	0.02	4.30
	250°C+	0.02	6.42
Eldfisk Kompleks (2015)	Fresh	0.08	3.55
	250°C+	0.12	5.66

**n-heptane (nC7) precipitation*

3.3 Physical properties of fresh and weathered residues

Physical properties of TOR II and the other Ekofisk crude oils are listed in Table 3-4. Overall, there are many similarities between the oil tested from the Ekofisk area with minor differences.

TOR II has a lower density of 0.834 g/mL than the highest value for Ekofisk J (2021) (0.854 g/mL). TOR II has also a higher evaporative loss (43 vol. %) of the 250°C+ residue, whilst Ekofisk J (2021) has the lowest evaporative loss of 36 vol. %, a slight decrease from Ekofisk J (2015) of 39 vol. %. TOR II and Eldfisk S (2021) have very similar evaporative loss for all the residues. The true boiling point curve (TBP) of TOR II compared with the other Ekofisk blends is given in Chapter 7 (Figure 7-1). Among these oils, Ekofisk Blend 2000 exhibit the lowest TBP.

TOR II has the highest pour point of +6 °C among the oils for comparison, whilst Ekofisk J (2015) has the lowest pour point of -12 °C. The pour point of Ekofisk J (2015) has increased from -12 °C to -3 °C in 2021, and is now closer to the pour point of Ekofisk Blend 2000 of 0 °C.

The viscosities of the Ekofisk fresh oils measured at 13 °C with a shear rate of 10s^{-1} are in the range of 14-93 mPa·s and are in the range of 1051-3800 mPa·s for the 250°C+ residues. TOR II has a viscosity 20 mPa·s of the fresh oil and 2458 mPa·s of the 250°C+ residue and are in the middle range compared with the Ekofisk oils. Ekofisk Blend 2000 has still the highest viscosity of 93 mPa·s but is not significantly higher than the other oils from the Ekofisk area.

The interfacial tension (IFT) was measured for TOR II, Eldfisk S and Ekofisk J from this current study. The IFT for Ekofisk J was 11 mN/m and significantly lower than for TOR II and Eldfisk S with values of 23 and 17 mN/m, respectively. The low IFT of Ekofisk J in 2021 is likely due to production chemicals in the oil (ref. ConocoPhillips), and hence lowered the emulsification of the oil, as further described in chapter 7.

Table 3-4 Physical properties of TOR II, Ekofisk J (2021) and Eldfisk S (2021) in comparison with previous tested Ekofisk crude oils.

Oil type	**Residue**	**Evap. (vol. %)**	**Residue (wt. %)**	**Density (g/ml)**	**Flash point (°C)**	**Pour point (°C)**	**Visc. (mPa·s) 13°C (10 s^{-1})**	**IFT (mN/m)**
TOR II	Fresh	0	100	0.834	-	6	20	23
	150°C+	19	83	0.858	43.5	18	144	27
	200°C+	34	69	0.875	92	24	576	27
	250°C+	43	60	0.885	123	27	2458	29
Eldfisk S (2021)	Fresh	0	100	0.842	-	0	18	17
	150°C+	19	84	0.872	40.5	-	116	16
	200°C+	33	71	0.889	82.5	-	566	16
	250°C+	44	60	0.906	127	24	2493	19
Ekofisk J (2021)	Fresh	0	100	0.854	-	-3	17	11*
	150°C+	19	83	0.880	49.5	-	90	-
	200°C+	26	77	0.889	74.5	-	205	-
	250°C+	36	67	0,901	113	21	1051	20
Ekofisk Blend 2000	Fresh	0	100	0.851	-	0	93	-
	150°C+	18	84	0.876	-	12	374	-
	200°C+	28	75	0.888	-	15	1380	-
	250°C+	37	67	0.899	-	21	3800	-
Ekofisk J (2015)	Fresh	0	100	0.846	-	-12	14	-
	250°C+	39	66	0.902	-	-	1310	-
Eldfisk B (2015)	Fresh	0	100	0.854	-	0	50	-
	250°C+	37	67	0.905	-	-	2258	-
Eldfisk Kompleks (2015)	Fresh	0	100	0.842	-	0	36	-
	250°C+	41	63	0.899	-	-	1599	-

*-: No data available *Low IFT (pendant drop method)is likely due to production chemicals in the Ekofisk J (2021)*

3.4 Emulsifying properties

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

3.4.1 Emulsification

Emulsification testing of TOR II 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 maximum water content after 24 hours rotation are shown in Figure 3-3 at 13 °C. The figure shows from left to right four emulsions prepared from the residues of 150°C+, 200°C+ and 250°C+, respectively.

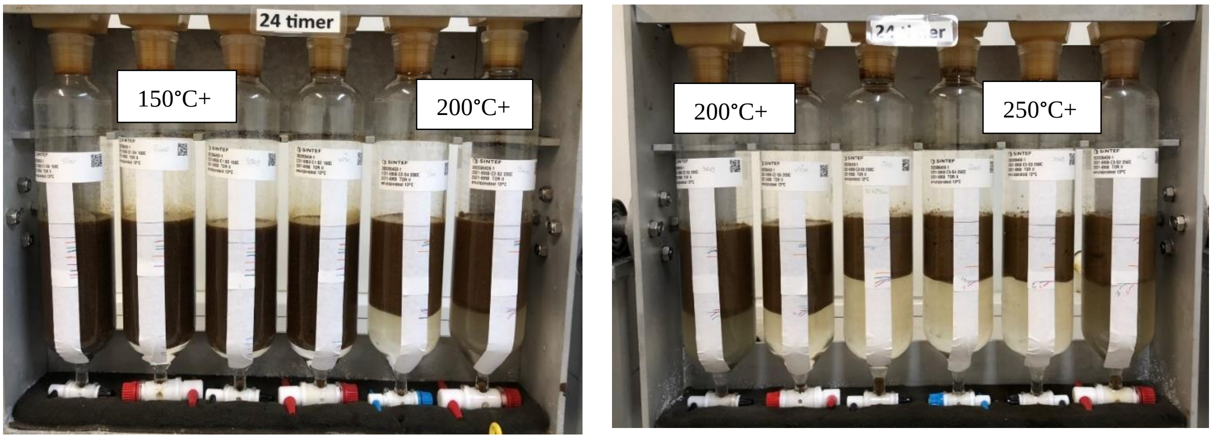


Figure 3-3 The rotating cylinders at the start and after 24 hours of rotation at 13 °C.

3.4.2 Water uptake and maximum water content

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. $T_{1/2}$ is a constant defined as the time (hours) it takes to incorporate half of the maximum water uptake (vol. %) in 24 hours (rotating time) and is derived from the tabulated data for each residue.

Table 3-5 Water uptake for the evaporated residues of TOR II crude oil at 13 °C.

Mixing time	**150˚C + (Vol. % water)**	**200˚C + (Vol. % water)**	**250˚C + (Vol. % water)**
Start	0	0	0
5 min	28	11	0
10 min	44	23	14
15 min	51	29	37
30 min	62	49	72
1 hour	69	84	78
2 hours	77	85	78
4 hours	86	85	78
6 hours	86	84	78
24 hours	90	85	78
$T_{1/2}$	0.23	0.35	0.27

** 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 water from oil-emulsion 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 was evaluated on different emulsified residues of TOR II at 13 °C. The choice of emulsion breaker was selected in agreement with ConocoPhillips and NOFO.

The results show that the emulsified oil volume decreased after treatment with the emulsion breaker, as water was released from the emulsion as shown in Table 3-6 at 13 °C. Overall, adding 2000 ppm (0.2 ppm w.%) of the emulsion breaker relative to the oil were slightly more efficient (93-99 %) to break the emulsion compared with a lower concentration of 500 ppm (82-96 %).

The emulsion stability was studied by quantifying the amount of volume fraction of water released from the emulsion after 24 hours settling time (after 24 hours rotation). Overall, TOR II forms stable w/o-emulsions of the 150, 200 and 250°C+ residues, as shown in the first main row of Table 3-6 (no emulsion breaker added).

Table 3-6 Stability of emulsion and the effect of emulsion breaker at 13 °C on TOR II.

Residue	**Emulsion breaker**	**Water-in-oil emulsion (vol. %) at 13 °C**			
		Reference	**24 hours ***	**Stability ratio****	**% Effect. (released water)**
150ºC+	none	90	89	0.95	5
200ºC+	none	85	85	0.94	6
250ºC+	none	78	77	0.96	4
150ºC+	OT-SE 500 ppm	90	25	0.04	96
200ºC+	OT-SE 500 ppm	85	41	0.12	88
250ºC+	OT-SE 500 ppm	78	39	0.18	82
150ºC+	OT-SE 2000 ppm	90	3	0.01	99
200ºC+	OT-SE 2000 ppm	85	17	0.03	97
250ºC+	OT-SE 2000 ppm	78	19	0.07	93

ppm: parts per million, relative to oil fraction of emulsion
**: 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*

3.4.4 Emulsion viscosities and yield stress

Table 3-7 gives the viscosities of oil residue fractions of TOR II with different water content (water free, 50 vol. %, and 75 vol. % and maximum water) at 13 °C. 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 ($10s^{-1}$) compared to the viscosities measured at higher shear rate ($100s^{-1}$). 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 / 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 (flow limit) 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 on the fluid to make it flow and hence spread and is mainly pronounced for *non-Newtonian* oils where the viscosities vary with the shear rate. The measurements were performed by applying a gradually increasing oscillating force to the sample where the deformation of the oil sample is measured. Results are given in Table 3-7. TOR II has for the emulsion of the 250°C+ residue relatively high yield stress and expect the oil to have reduced flowability after some days at sea.

Table 3-7 Viscosity and yield stress of water-free and emulsions on TOR II.

Residue	**Water content (vol. %)**	**Viscosity (mPa·s) 13 °C**		**Yield stress**
		10 s^{-1}	**100 s^{-1}**	**Pa**
Fresh	0	20	14	0
150°C+	0	144	66	0
200°C+	0	576	209	0.33
250°C+	0	2458	583	2.76
150°C+	50	694	247	1.61
200°C+	50	1673	545	1.41
250°C+	50	3353	706	2.61
150°C+	75	778	203	1.79
200°C+	75	2936	869	1.79
250°C+	75	5774	1452	20.2
150°C+	80	543	144	3.56
200°C+	78	2922	795	7.50
250°C+	80	7132	1411	12.2

3.5 Chemical dispersibility

The dispersibility testing on TOR II included:

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

3.5.1 Dosage testing of dispersant

Dosage testing at 13 °C was performed using Dasic Slickgone NS on the TOR II emulsion (200°C+ / 50 vol. %). The dosage test helps to identify optimal design conditions for dispersant use and was performed with dispersant-to-emulsion ratio (DER) of 1:25, 1:50, 1:100 and 1:200, and with no dispersant added. The dosage testing was performed using the low-energy IFP test (Institute Français du Pétrole), reflecting non-breaking waves (<5 m/s wind speed), in combination with the high-energy MNS test (Mackay-Nadeau-Szeto). The results are presented in Table 3-10. Pictures from the dosage testing (MNS-test) on TOR II are given in Figure 3-4 and Figure 3-5.

The dosage testing on TOR II showed high effects with use of the high-energy test (MNS) in the range of 84-97 % (DER 1:25, 1:50 and 1:100), whilst DER of 1:200 had reduced effect of 60 %. The higher effect of 1:50 (97 %) vs. 1:25 (87 %) is probably due to formation of larger oil droplets in the water column from the 1:50 that influenced on the results (Figure 3-4). For the low-energy test (IFP), the results indicated very low effect (< 5 %) of adding dispersant to the emulsion, producing larger oil droplets in mm size. This means that breaking waves (> 5 m/s wind speeds) or artificial energy in non-breaking waves (< 5 m/s wind speeds) are necessary to disperse or break up surface emulsion of TOR II. No effect was observed with no dispersant added to the emulsion of TOR II, as shown in Figure 3-5.

Table 3-8 *Dosage rate testing on TOR II crude oil using the IFP-and MNS-test on the 200°C+ emulsion at 13 °C*

Dispersant (Dosage rate)	**Efficiency of dispersant on 200°C+/50 vol. % emulsion**		**Viscosity (mPa·s) 10 s^{-1}, 13°C**
	IFP	**MNS**	
Dasic NS (1:25)	4.9	87	1673
Dasic NS (1:50)	2.8	97	1673
Dasic NS (1:100)	1.4	84	1673
Dasic NS (1:200)	-	60	1673
No dispersant	-	4	1673

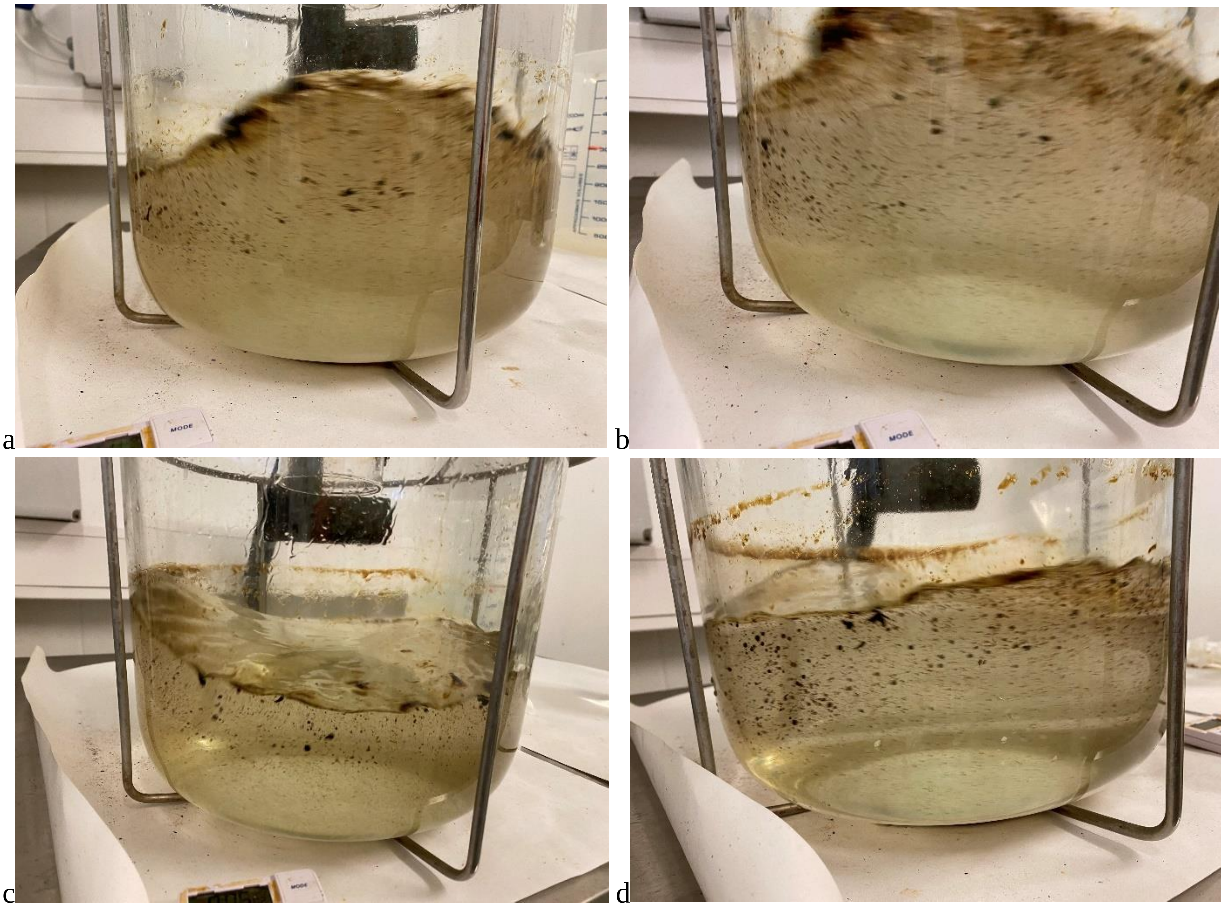


Figure 3-4 *a: DOR 1:25, b: DOR 1:50, c: DOR 1:100, and d: DOR 1:200 for MNS (50 % emulsion)*

Figure 3-5 *MNS without dispersant added to the emulsion(no disp).*

3.3.3 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 is tabulated Table 3-9.

Table 3-9 Efficiency of dispersant on weathered TOR II oil/emulsions at 13 °C.

Residue	Water content (vol. %)	Viscosity (mPa·s) 10 s^{-1}	Viscosity (mPa·s) 100 s^{-1}	Efficiency (%)	Efficiency (%)
				IFP	MNS
150°C+	0	144	66	63	100
200°C+	0	576	209	4	77
250°C+	0	2458	583	-	9
150°C+	50	694	247	27	100
200°C+	50	1673	545	5	87
250°C+	50	3353	706	5	84
150°C+	75	778	203	41	100
200°C+	75	2936	869	8	55
250°C+	75	5774	1452	-	47
150°C+	80	543	144	26	93
200°C+	78	2922	795	-	71
250°C+	80	7132	1411	-	25

-Not analyzed

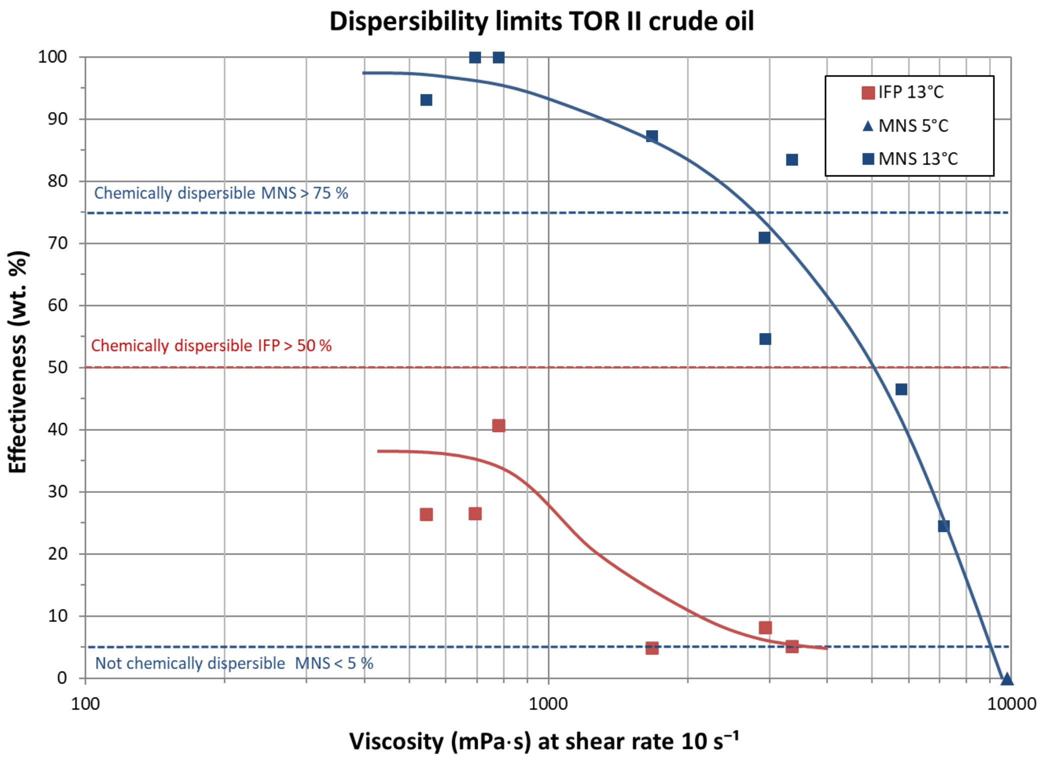


Figure 3-6 Dispersant effectiveness limits on TOR II.

TOR II was found to be reduced chemically dispersible for viscosities lower than 9000 mPa·s (IFP-test, non-breaking waves <5 m/s wind speeds) and found not or poor chemically dispersible >9000 mPa·s based on the high energy MNS-test, reflecting breaking waves conditions (>5 m/s wind speeds) (Figure 3-6). This means that TOR II may require additional energy and/or higher dispersant dosage or multiple applications to enhance effective dispersion. The dispersibility limits are also summarised in Table 3-10.

Table 3-10 Estimated viscosity limits for use of dispersant for TOR II emulsion and the criteria for definition of time window.

Dispersibility	**Criteria (wt. %)**	**Dispersibility limits based on oil viscosities (mPa·s)**
Chemically dispersible*	IFP efficiency > 50%	Not obtained*
Not chemically dispersible	MNS efficiency < 5 %	9000

** TOR II is reduced chemically dispersible by use of the low-energy IFP test.*

4 OWM weathering predictions of TOR II

Predictions of TOR II have been conducted with use of SINTEF Oil Weathering Model (OWM). A description of OWM is given in Appendix A. A standard 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 the OWM

Oil type:	Crude oil
Geographical area:	North Sea
Terminal oil film thickness:	1 mm
Release rates:	1.33 metric tonnes/minute for 15 minutes; a total of 20 metric tonnes
Sea temperature:	5 °C and 15 °C
Wind speed:	2 m/s, 5 m/s, 10 m/s and 15 m/s

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 TOR II has drifted on the sea surface, the following prediction charts can be used to determine the remaining oil/emulsion's chemical, physical and emulsifying properties. Table 4-1 gives an example for the following scenario:

- Drift time: 12 hours
- Sea temperature: 5 °C/15 °C
- Wind speed: 10 m/s

Table 4-1 Weathering properties for TOR II obtained from the prediction charts after 12 hours of weathering.

Property	**Winter temperature (5 °C, 10 m/s)**	**Summer temperature (15 °C, 10 m/s)**
Evaporation, vol. %	32	35
Water content, vol. %	75	79
Flash point, °C	95	106
Pour Point, °C	24	26
Viscosity, mPa·s*	5600	4000

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

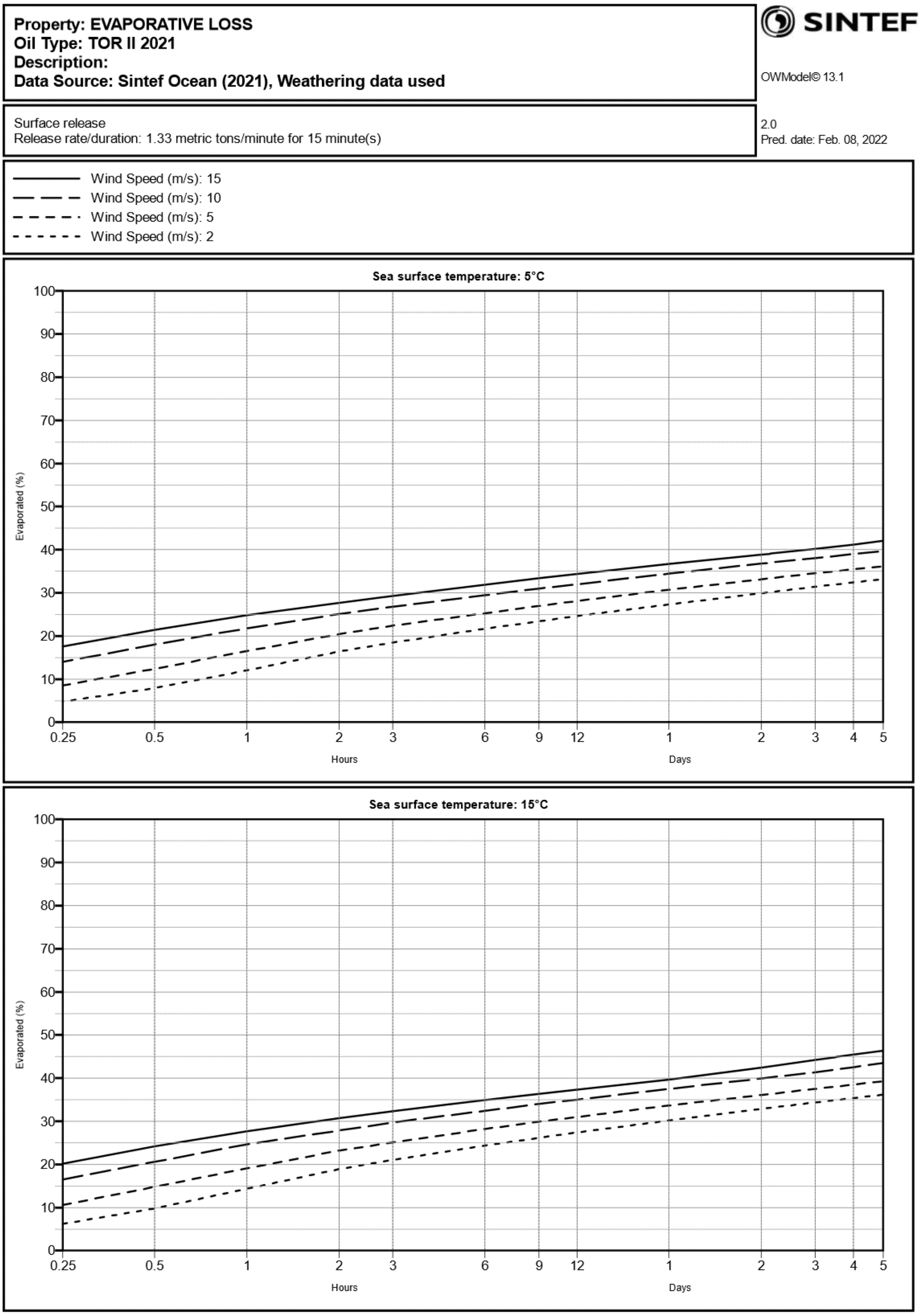


Figure 4-1 Evaporative loss of TOR II crude oil predicted at sea temperatures of 5 °C and 15 °C.

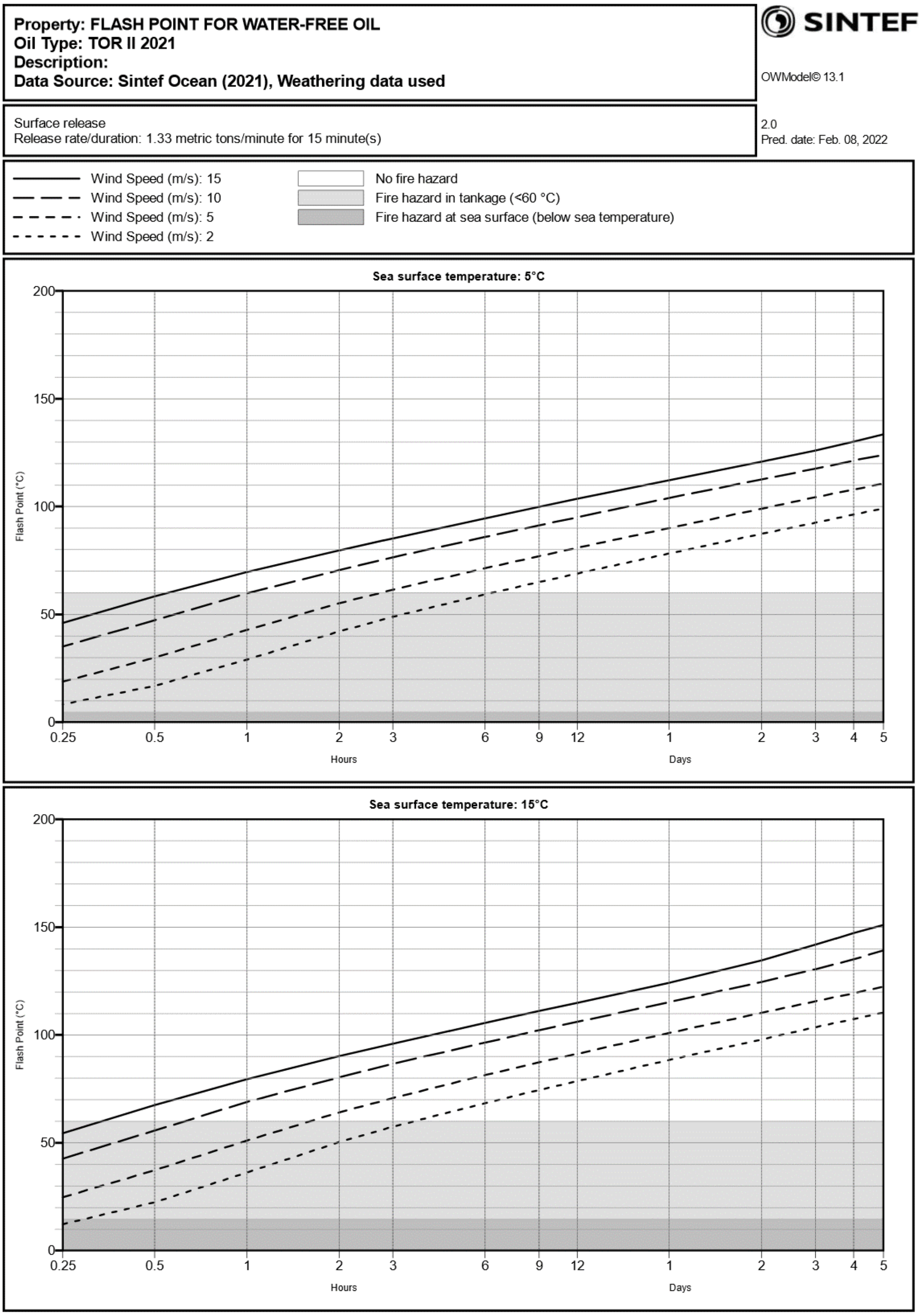


Figure 4-2 Flash point of TOR II predicted at sea temperatures of 5 °C and 15 °C.

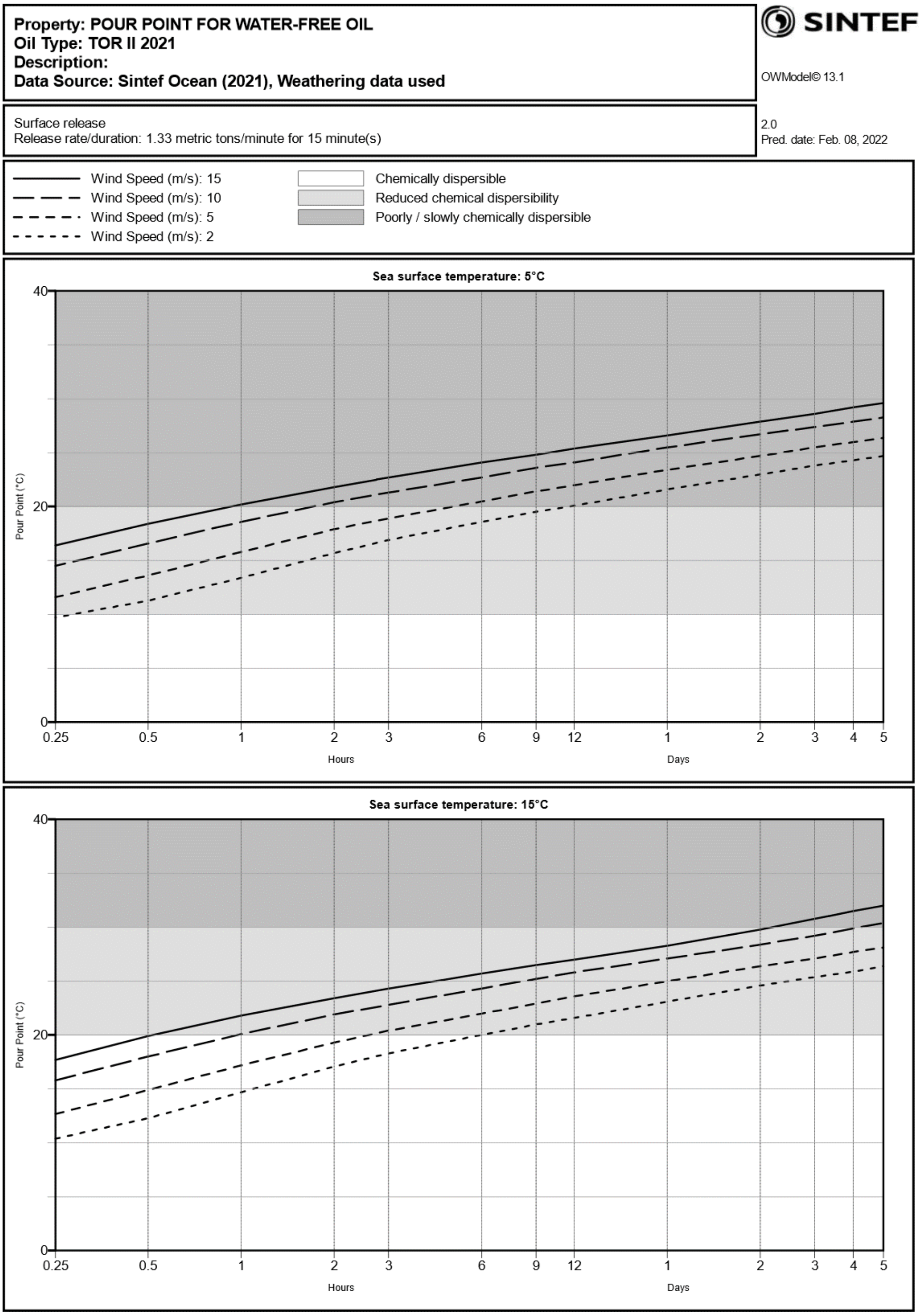


Figure 4-3 *Pour point (water-free residue) of TOR II predicted at sea temperatures of 5 °C and 15 °C.*

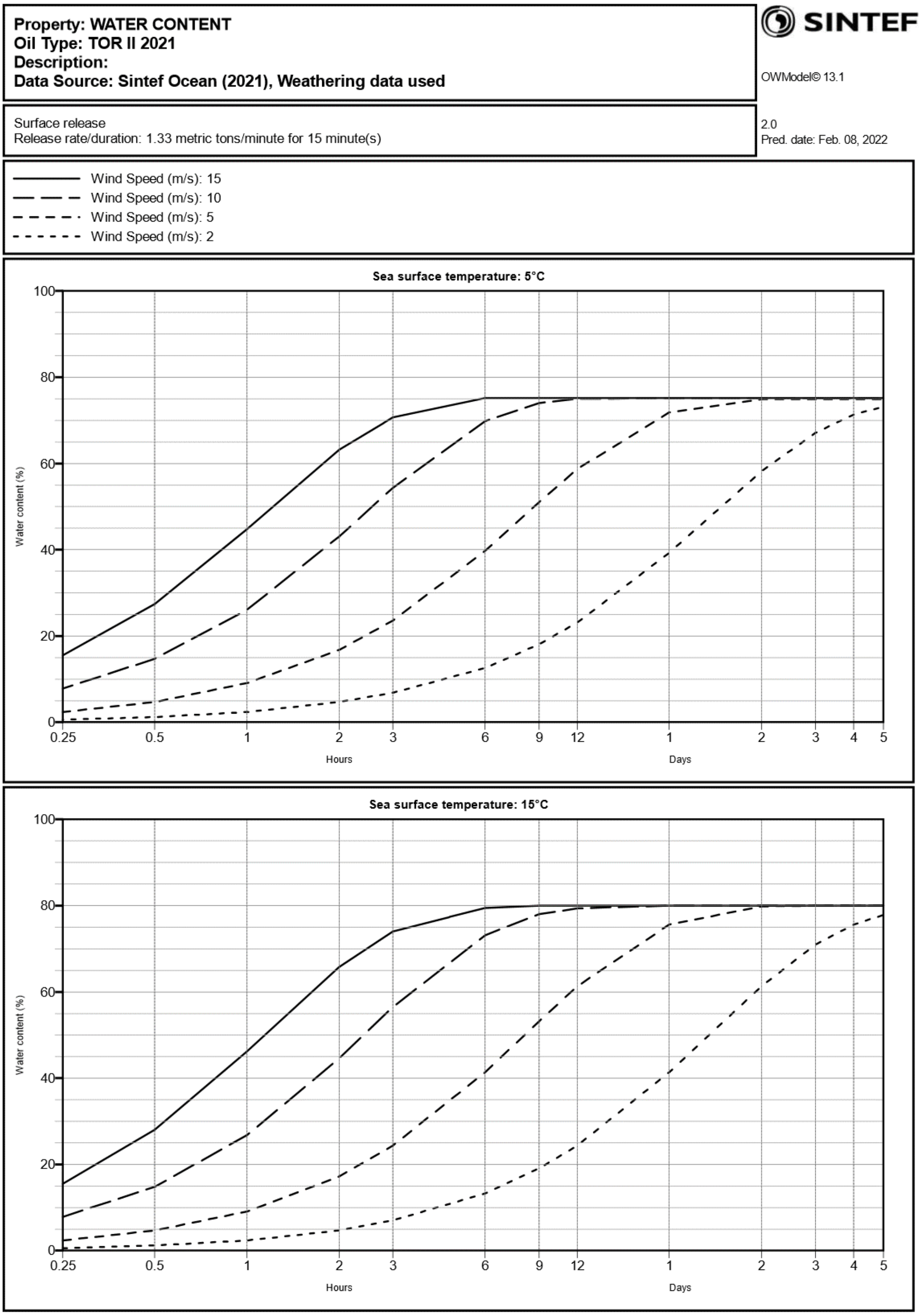


Figure 4-4 Water content of TOR II predicted at sea temperatures of 5 °C and 15 °C.

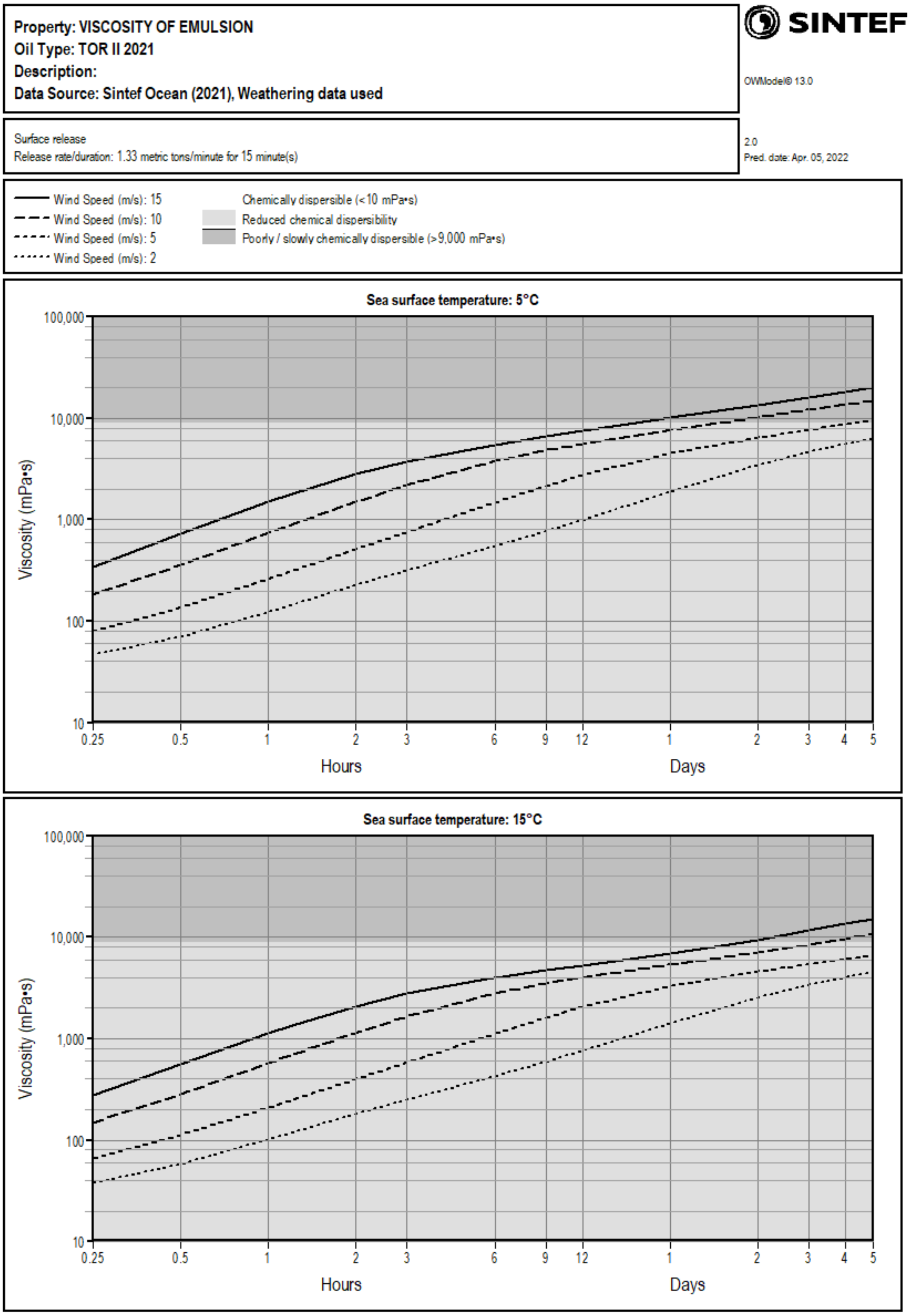


Figure 4-5 *Viscosities of TOR II emulsions predicted at sea temperatures of 5 °C and 15 °C. Predictions are based on measurements performed at a shear rate of 10 s^{-1}.*

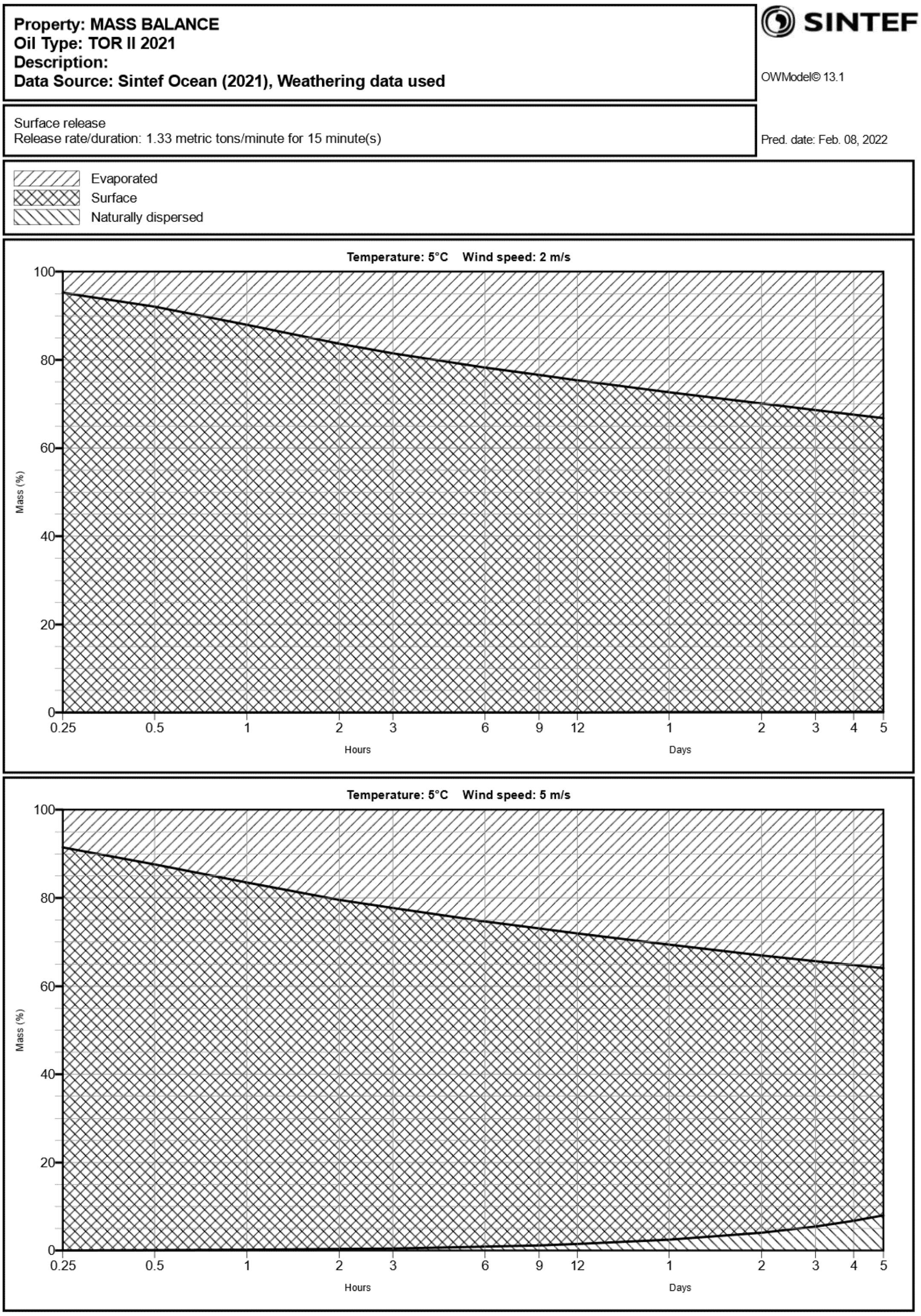


Figure 4-6 Predicted mass balance for TOR II at 5 °C and wind speeds of 2 and 5 m/s.

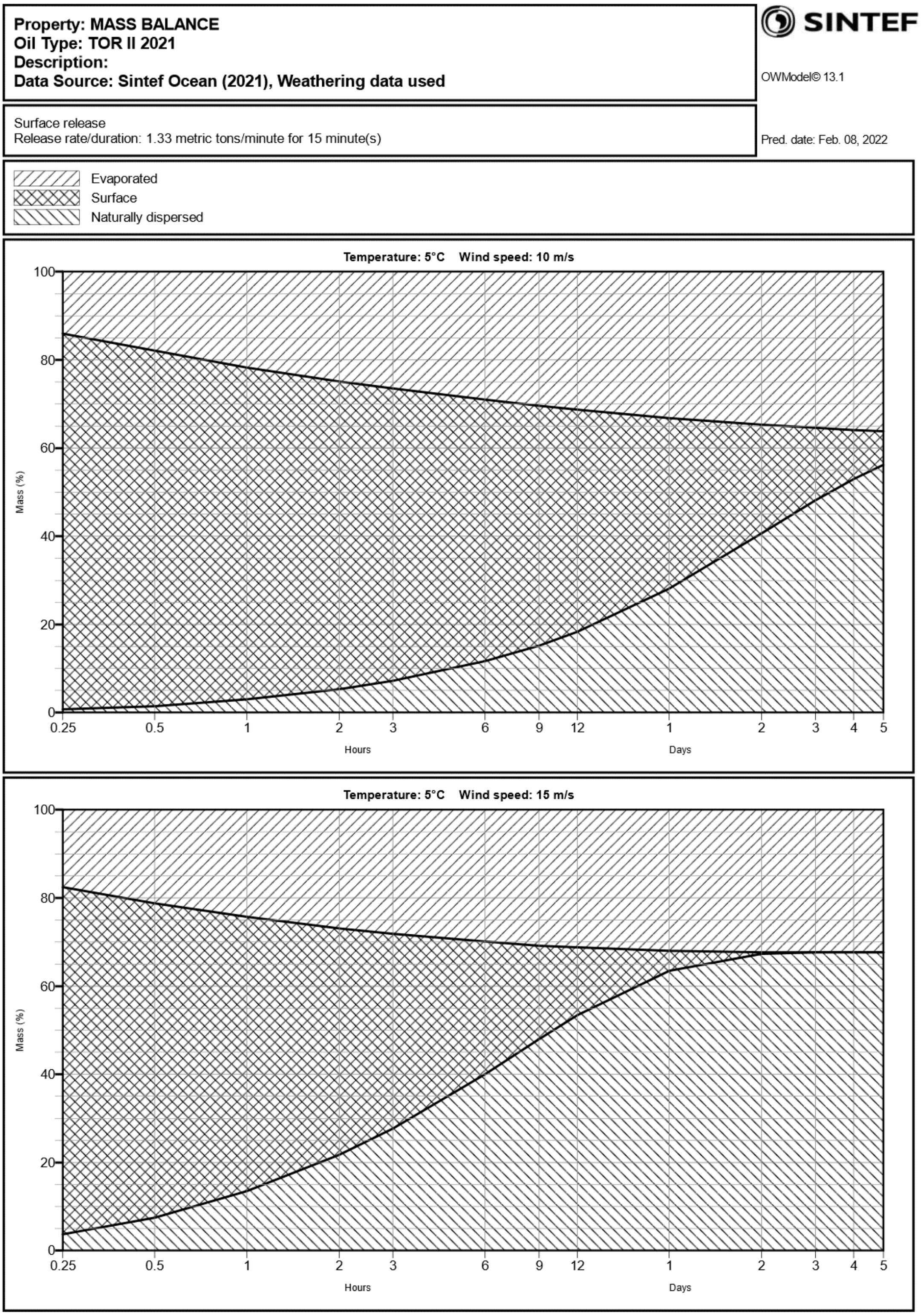
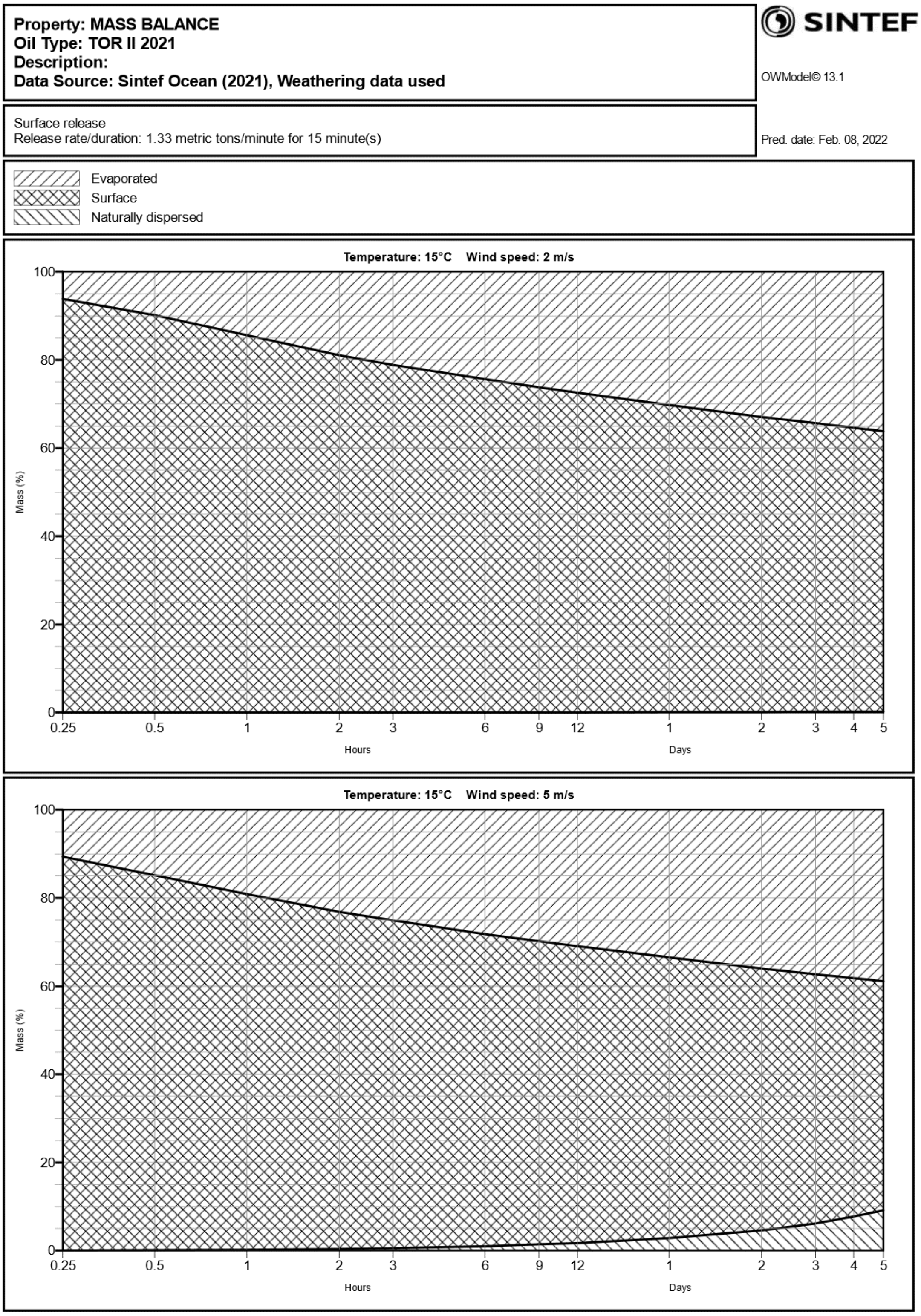


Figure 4-7 Predicted mass balance for TOR II at 5°C and wind speeds of 10 and 15 m/s.



Property: MASS BALANCE
Oil Type: TOR II 2021
Description:
Data Source: Sintef Ocean (2021), Weathering data used

OWModel© 13.1

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

Pred. date: Feb. 08, 2022

Figure 4-8 Predicted mass balance for TOR II at 15 °C and wind speeds of 2 and 5 m/s.

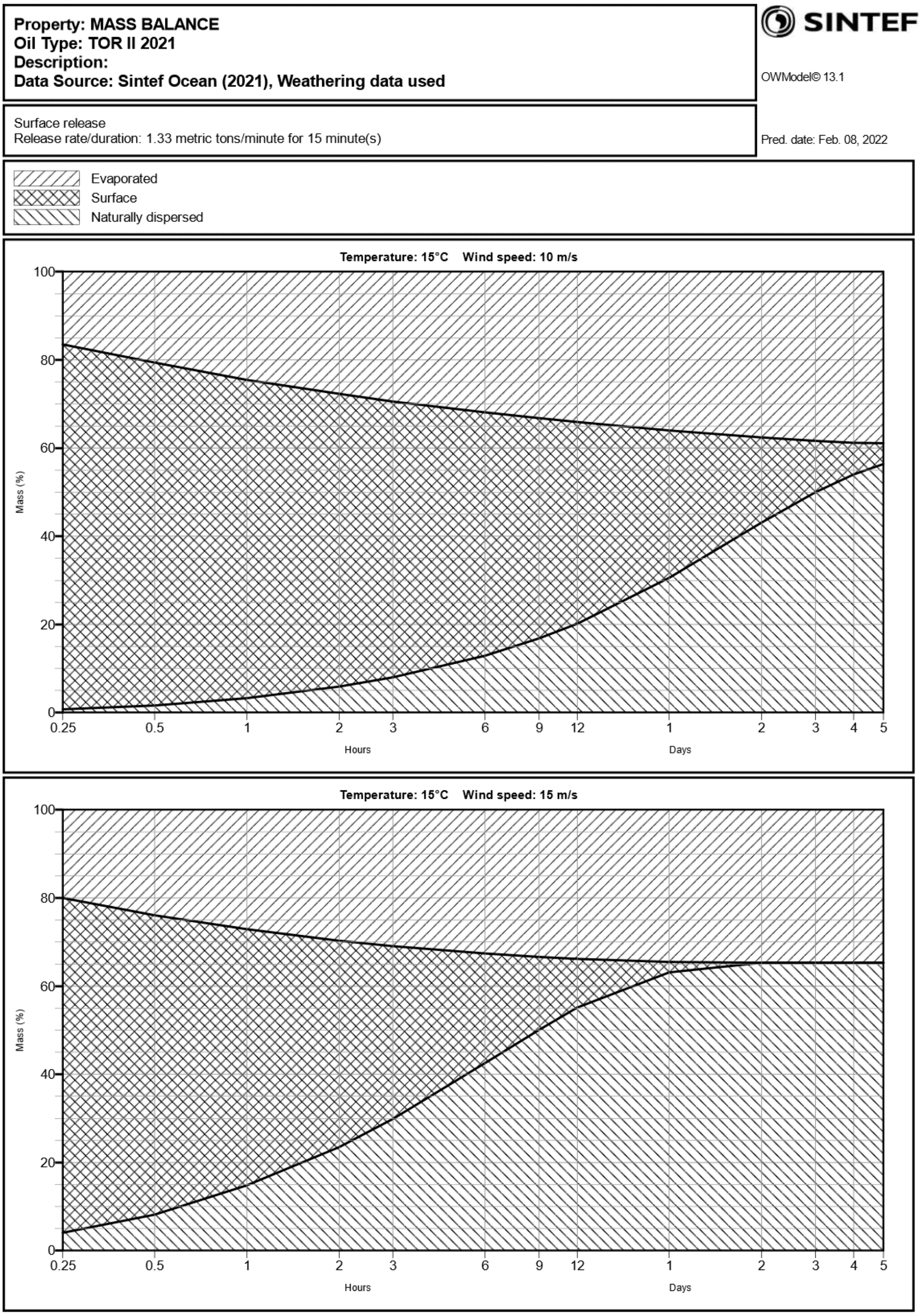


Figure 4-9 *Predicted mass balance for TOR II at 15 °C and wind speeds of 10 and 15 m/s.*

5 Weathering properties and response of TOR II

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

5.1 Oil properties

The specific physico-chemical parameters of TOR II are input to SINTEF OWM. The physico-chemical analysis of the fresh and topped residues show that TOR II is a paraffinic crude oil with a medium density of 0.834 g/mL with a low content of asphaltenes (0.06 wt. %) and a medium to high wax content of 7.07 wt. %. TOR II has a moderate evaporate loss of 43 vol. % of the 250°C+ residue. The fresh oil has a viscosity of 20 mPa.s at shear rate $10s^{-1}$ (13 °C) and increases by evaporation to 2458 mPa.s ($10s^{-1}$) for the waterfree 250°C+ residue. The fresh oil has a relatively high pour point of +6 °C, that increases significantly to +27 °C upon evaporation (250°C+). Moreover, TOR II forms stable water-in-oil emulsions with moderate to high viscosities that partly or totally breaks with application of emulsion breaker (Aerosol OT-SE surfactant).

5.2 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 spill on the sea surface, the (heated) oil rapidly will be cooled to the ambient seawater temperature within a short period of time. The potential for fire/explosion hazard will be at its greatest if the flash point of the oil is below the seawater temperature.

The flash points for TOR II are expected to surpass the sea temperature within 15 minutes at 5 and 15 °C, at wind speeds of 2 -15 m/s predicted from a standardized release rate of $80m^3/h$, as shown in Figure 4-3 and Figure 5-1. A rate of $25m^3/h$ will have no significant difference in oil weathering predictions compared to the standardized release rate. However, care should be taken during the first 0.5 hour, and use of explosimeter is recommended. Less than 1-hour delay time can be predicted related to fire/explosion hazard related to the flash point of the drifting oil itself.

Moreover, some vessels/storage tanks engaged in oil recovery operations may not be classified to carry liquids with flash points lower than 60 °C, e.g., towing vessels, smaller cargo, or other vessels available in the emergency. This means that fuels or oils with the flash point less than 60 °C, are for those type of vessels not permitted as cargo. However, this limit is not considered as relevant for oil recovery vessels with A-class certification for transport of liquids (Class I/II, flashpoints < 60 °C), according to NFPA classification of Flammable and Combustible Liquids (http://www.thetankshop.ca).Refers to the flash point predictions in Figure 4-3 and Figure 5-1.

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 be utilized continuously, and one should be aware of the possibility for varying release rates if "free" gas is involved.

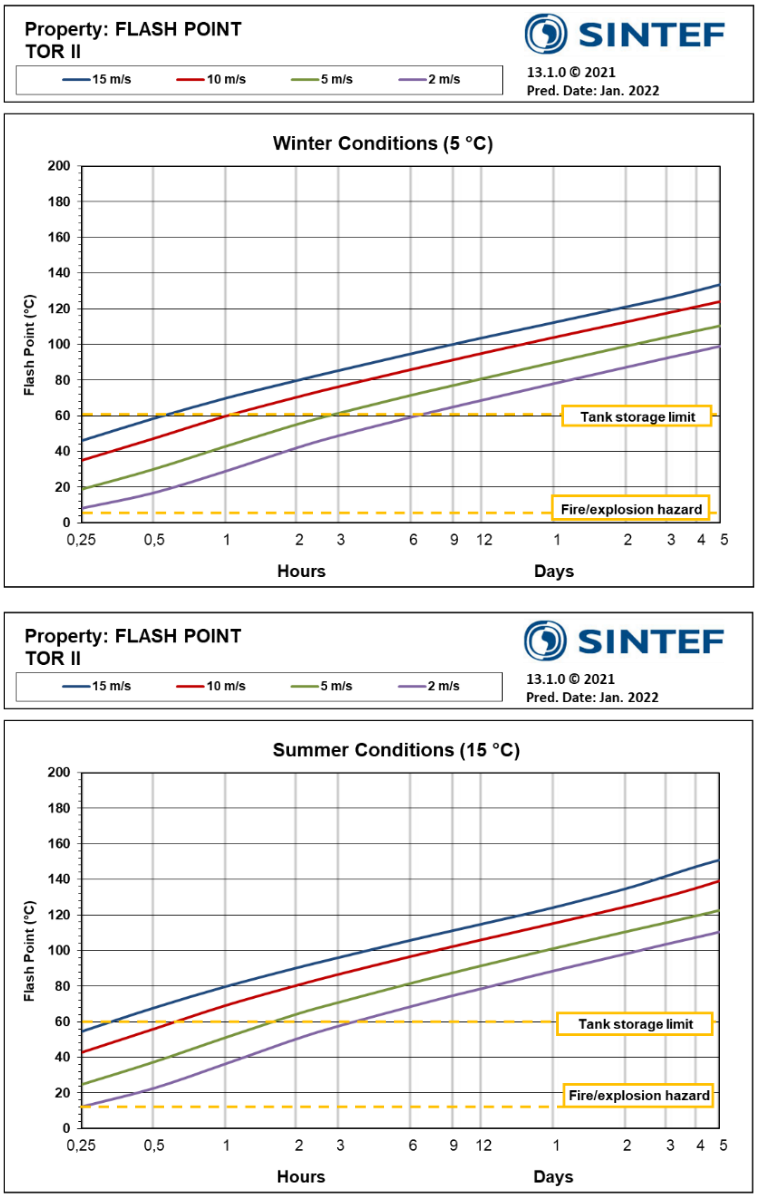


Figure 5-1 Flash point at different sea states for TOR II crude oil in winter and summer conditions.

5.3 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 most pronounced when the pour point of the fresh crude oil is typically 5-15 °C above the sea temperature, and in cold seawater temperatures.

TOR II has high pour points of its residues, and a remaining water-free residue at sea may therefore have a potential to solidify, particularly in winter condition as shown for the pour point prediction in Figure 4-3.

5.4 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 5-2 shows the predicted mass balance of remaining surface emulsion and surface oil as a function of weathering of TOR II. The figure shows an increase in the volume of emulsion relative to the volume og released oil with a factor of 2-2.5.

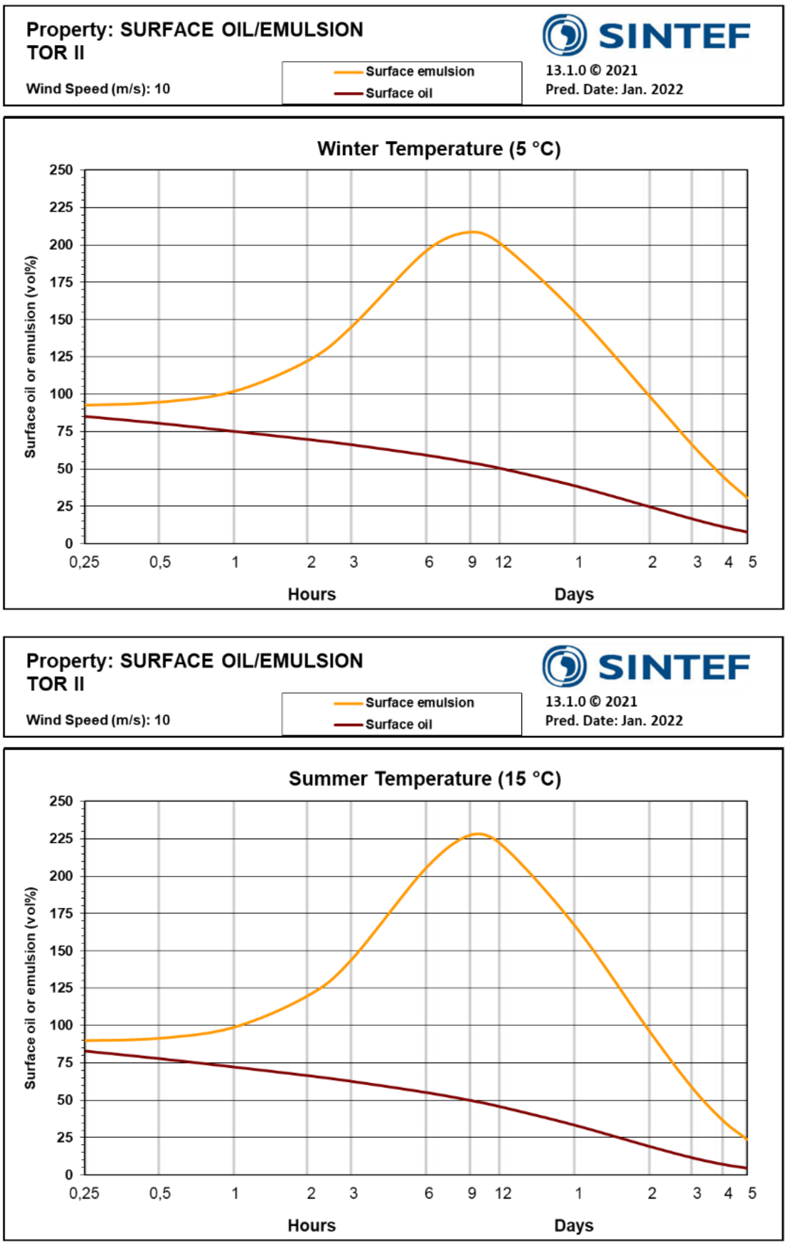


Figure 5-2 Difference in the total slick volume due to emulsification compared to non-emulsified oil. Decrease in total volume due to evaporation and natural dispersion at 10 m/s wind speed at temperatures of 5 °C and 15 °C.

5.5 Submerged oil and evaporation

The lifetime of an oil spill at sea depends on the oil's composition, the release conditions (e.g., on the surface, underwater) and environmental conditions (temperature, wind, waves). Submerged oil (natural dispersion) and evaporation are the main weathering processes that remove an oil spill from the sea surface. The remaining surface oil after a release depends on the wind speeds and typically oils are more persistent on the sea surface with lower wind. Submerged oil /naturally dispersed oil may temporarily resurface when the wind calms down again.

Figure 5-3 shows the predicted remaining surface oil over time for different wind speeds and temperatures for TOR II. Only minor difference in lifetime between 5 and 15 °C for this oil. At high wind speeds of 15 m/s, no oil is predicted to remain on the sea surface after 2 days of weathering. Considerably larger spills are expected to produce longer lifetimes, and individual modelling may be necessary.

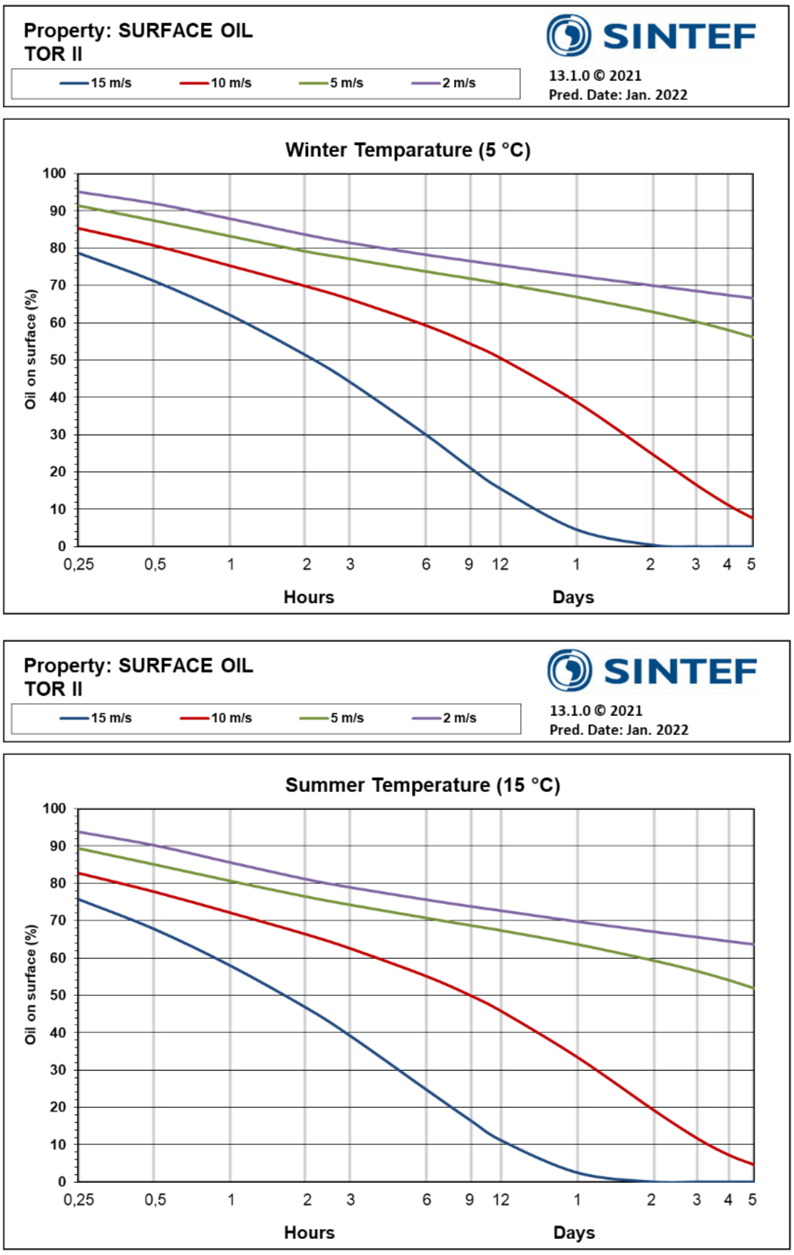


Figure 5-3 Remaining surface oil under different sea states for TOR II at 5 °C and 15 °C.

5.6 Film thickness

In general, mechanical recovery requires normal minimum film thicknesses > 0.1-0.2 mm. Film thicknesses higher than 0.05-0.1 mm are considered for application of oil spill dispersants. Lower film thicknesses (e.g., metallic /rainbow) are likely to disperse naturally under breaking waves conditions and can be enhanced in non-breaking waves by mechanical dispersion (chapter 5.8). Figure 5-4 shows the predicted film thickness of TOR II assuming that the initial oil film thickness is sufficient high to emulsify, typically >0.1 mm. The increase in film thickness after 1-2 hours is due to emulsification. Other factors like emulsion viscosities should also be considered when evaluate response options, as described in the next chapters.

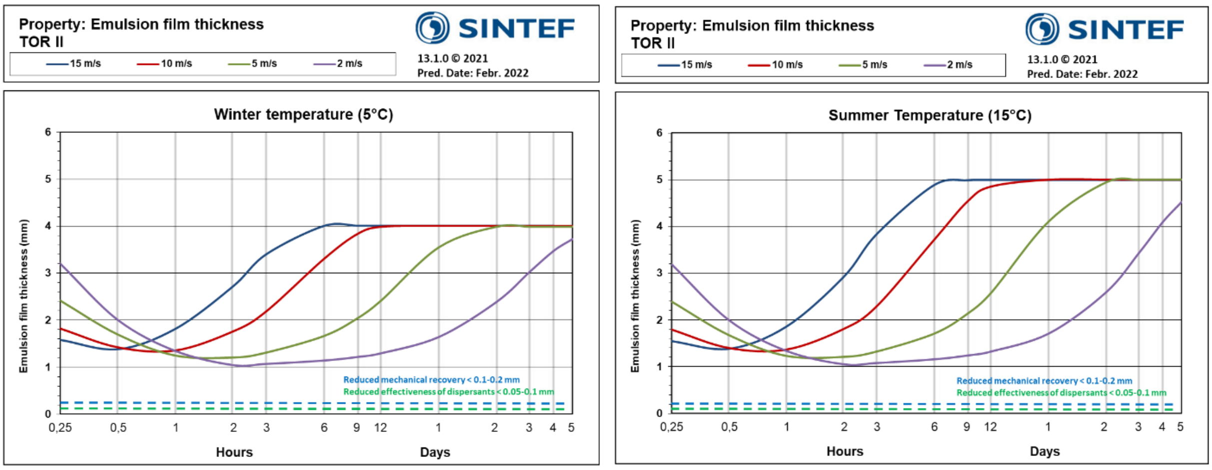


Figure 5-4 *Predicted film thickness of TOR II at 5 and 15 °C, assuming that the initial oil film thickness is sufficient high to emulsify.*

5.7 Mechanical recovery

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 recovery boom. Boom leakage is particularly pronounced if the viscosity of the oil or the w/o-emulsion is lower than 1000 mPa·s (Nordvik et al., 1992). The lower viscosity limit for an optimal mechanical clean-up operation has therefore been estimated to 1000 mPa·s. However, other factors like the operational speed of recovery vessel and current weather conditions will also influence on the risk of boom leakage.

Weir skimmers may reduce recovery rates (m3/h) when skimming oils with viscosities in the range 15-20 000 mPa.s (Leirvik et al., 2001). NOFO is operating with viscosity limits for skimmer efficiency as followed: primary use of weir skimmers (< 20 000 mPa.s), combination of weir and high-visc. skimmers (20-50 000 mPa.s), and primary high-visc. skimmer (> 50 000 mPa·s).

The emulsion viscosities of TOR II are shown in Figure 5-5 at 5 and 15 °C. For boom leakage of confined oil, the emulsion viscosity exceeds 1000 mPa·s after 1.5- 2 hours at 10 m/s wind speed, but the time are stretched up to 12 hours for very low wind speed (2 m/s). Overall, TOR II has a wide window of opportunity for traditional weir-skimmer head due to viscosities < 20 000 mPa·s within 5 days of weathering at summer and winter conditions.

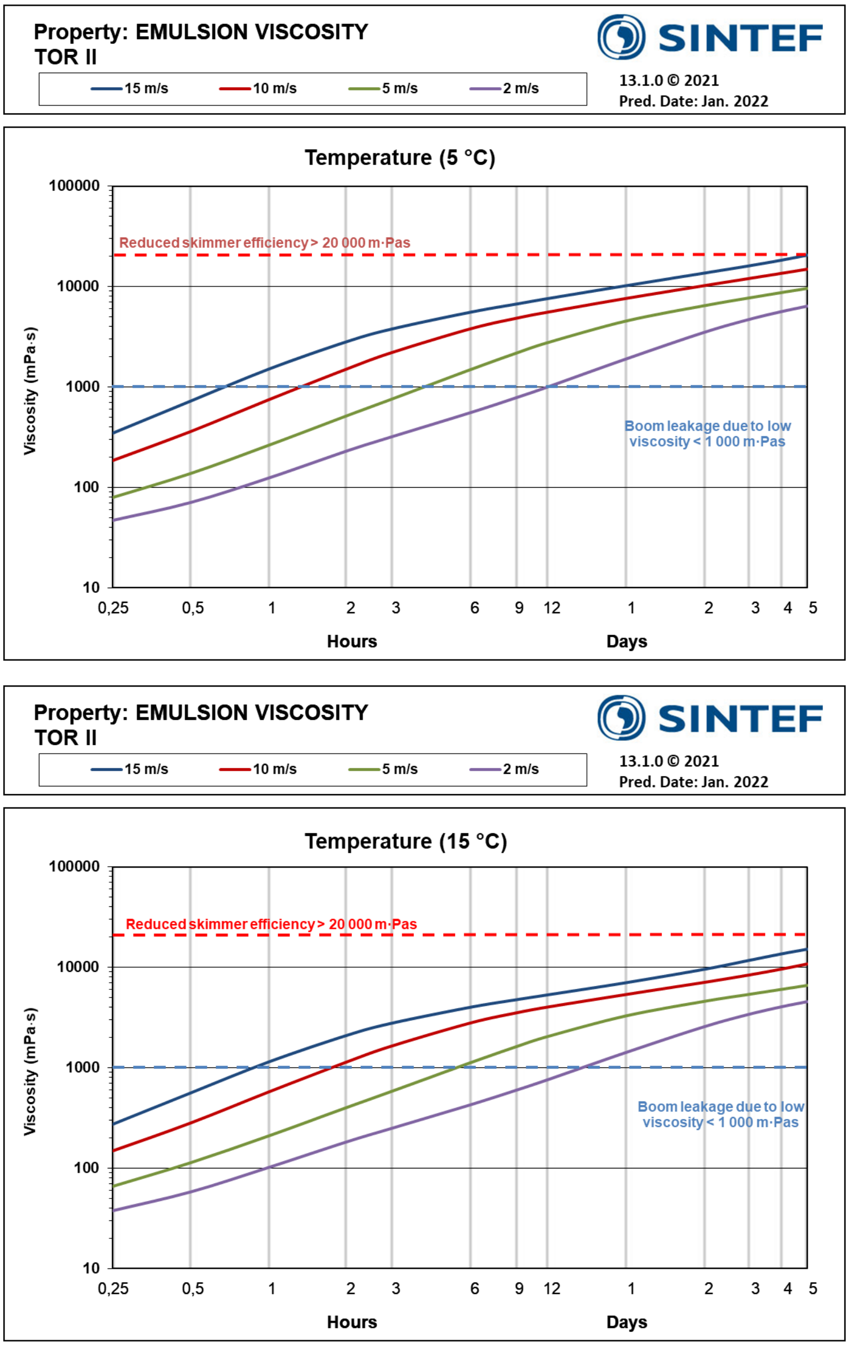


Figure 5-5 *Predicted emulsion viscosity for TOR II at 5 °C and 15 °C compared with expected viscosity limits for boom leakage and poor flow to weir skimmers.*

5.8 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 fire-fighting (Fi-Fi) systems could possibly break up the oil/residue into smaller droplets and enhance the dispersion. 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.

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

5.9 Use of chemical dispersants

The viscosity limit for effective dispersant use was estimated to 2800 mPa·s, and the viscosity limit for when the emulsified oil is not or poorly dispersible was estimated to 9000 mPa·s. The viscosity limits were based the high energy MNS-test on TOR II reflecting breaking waves >5 m/s wind speeds. This means that TOR II requires breaking waves to break up a chemically treated slick. In cases were the oil (emulsion) is expected to be reduced dispersible, additional energy or use of a higher dispersant dosage by repeated dispersant application is recommended to possible enhance the dispersant efficiency. Providing additional energy through use of Fi-Fi systems or thrusters after dispersant application may increase the dispersion effectiveness in calm weather condition.

The window of opportunity for use of dispersant Dasic Slickgone NS is presented in Figure 5-6. The oil-emulsion is e.g., predicted to be (reduced) dispersible up to 2-4 days at summer conditions, and 1-2 days in winter conditions with wind speeds 10-15 m/s, and longer time-window in calmer wind speeds (2-5 m/s wind speeds).

High pour points could reduce the dispersant effectiveness, where the dispersant droplets have a reduced ability to diffuse into the oil and may appear as droplets on the surface of solidified oil slick and be washed off the slick by wave activity. In certain weather conditions, low emulsification rate may enhance formation of solidified lumps, particularly at 5 °C. In a spill situation, the use of a simplified dispersibility testing kit is therefore recommended to assess the potential for chemical dispersion.

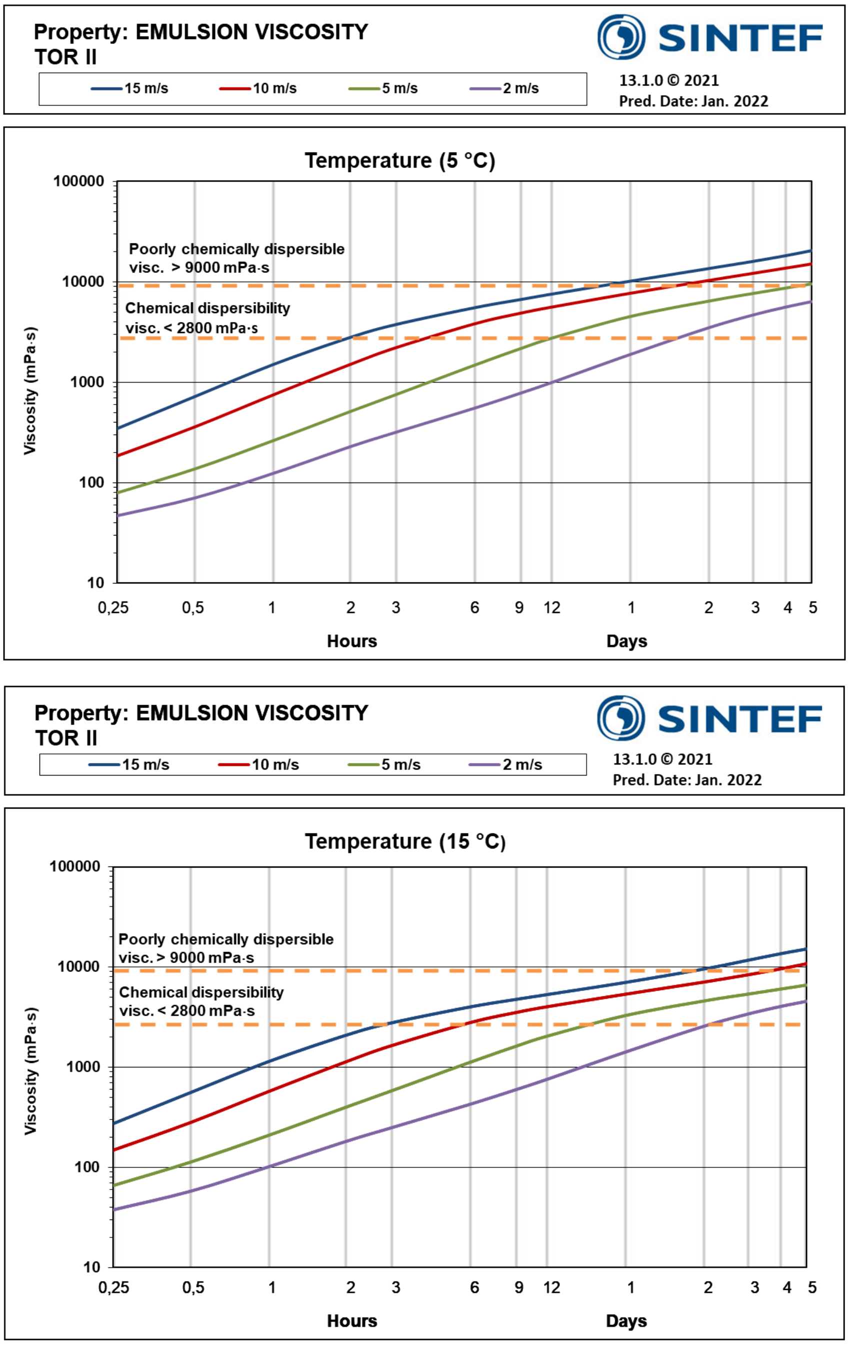


Figure 5-6 *Predicted emulsion viscosity for TOR II at 5 °C and 15 °C compared with dispersibility limits stated in chapter 0.*

6 Summary of response options for TOR II

TOR II is a medium density paraffinic crude oil that forms stable water-in-oil (w/o) emulsion in scenarios where the (initial) film thickness >0.1 mm. An evaluation of a potential subsurface release has however not been evaluated for TOR II.

High pour point of surface residue may cause solidification at sea, particularly in low temperature and calm sea conditions. High pour points typically prevent or reduce the dispersant efficiency.

Mechanical recovery:

- TOR II 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

Use of chemical dispersants*:*

- Emulsions of TOR II is found to be reduced dispersible with use of Dasic Slickgone NS for viscosities < 9000 mPa·s (DOR 1:25), and not/poorly dispersible for viscosities > 9000 mPa·s assuming breaking waves conditions (> 5m/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.

High-capacity water flushing (mechanical dispersion):

- The emulsification is the limiting factor for this strategy.
- 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 TOR II.
- Mechanical dispersion be used a supplementary /secondary method on e.g., peripherical areas of thin oil films of metallic/rainbow appearances in calm weather conditions.

Monitoring and remote sensing:

- Monitoring and remote sensing should be used a support in a response operations for TOR II.

7 Experimental results for Ekofisk J and Eldfisk S

In 2015, SINTEF studied weathering properties of three crude oil blends of Ekofisk J, Eldfisk B and Eldfisk Kompleks. The Crude Assay (CA) module in SINTEF OWM, with some supplements of laboratory testing, was used to generate data profiles for use in OWM, to assess the validity of continued use of Ekofisk Blend 2000 as a model oil for risk assessment and contingency analysis for the Ekofisk area. Based on the obtained results and predicted behaviour, Ekofisk Blend 2000 was then (in 2015) deemed valid for continued use. It was also recommended to evaluate the properties of the blends on a regular basis to track any possible changes in key weathering properties.

In this current study, SINTEF received new samples in 2021 for re-evaluation of Ekofisk J and Eldfisk S (previously named Eldfisk Kompleks) alongside TOR II crude oil. The Ekofisk oils (Ekofisk J and Eldfisk S) from 2021 have undergone similar testing as in 2015, with regards to physio-chemical properties (viscosity, density, wax and asphaltene content, evaporation and pour point) needed for using the CA-module. A limited emulsion test was also performed to generate data regarding water uptake, emulsion stability and effect of emulsion breaker, and in addition, dispersibility testing was performed on emulsions of Eldfisk S at varying degree of weathering. Ekofisk J from 2021 was found to contain production chemicals, which influenced on the emulsifying properties (lowering the water uptake) making the oil unsuitable for further dispersibility testing.

The laboratory results for Ekofisk J 2021 and Eldfisk S 2021have partly been presented in Chapter 3, alongside TOR II. Additional data are presented and discussed here, while the SINTEF OWM predictions are given in Appendix B. In addition, Appendix C presents OWM comparisons of various predicted properties for Ekofisk J 2021, Eldfisk S 2021, TOR II, Ekofisk J 2015, Eldfisk Kompleks 2015 and Eldfisk B 2015. Chapter 8 gives an evaluation of historical data (densities) based on crude assay of oils from the Ekofisk area.

7.1 Physio-chemical properties

In general, the physio-chemical properties of the Ekofisk blends are in the same category of paraffinic crude oils and show only smaller degree of differences. Table 3-3 and Table 3-4 in Chapter 3 show both previous and recent results for various properties of a selection of oils from the Ekofisk area.

Wax and asphaltene

Compared to their 2015 counterparts, Ekofisk J 2021 and Eldfisk S 2021 have wax and asphaltene contents that are closer to those of Ekofisk Blend 2000.

Evaporative loss and density

Eldfisk S 2021 has similar evaporative loss and densities as those found for Eldfisk Kompleks in 2015. The density of Ekofisk J 2021 is slightly higher than that of Ekofisk J 2015, but the densities of the 250°C+ residues are similar to each other. The evaporative loss of Ekofisk J 2021 is slightly lower than that of Ekofisk J 2015, whereas the weight of residue is similar, indicating that Ekofisk J 2015 contained somewhat more lighter components. Compared to Ekofisk Blend 2000, Ekofisk J 2021 is similar, while Eldfisk S 2021 is a lighter oil with both lower densities and higher evaporative loss.

Pour point and viscosity

Eldfisk S 2021 and Ekofisk J 2021 have very similar pour points for fresh oil and weathered residue as Ekofisk Blend 2000, see Table 3-4. Fresh Ekofisk J 2015 had a lower pour point than Ekofisk J 2021, which could be due to the higher content of lighter components and some lower wax content. The pour point of fresh Eldfisk Kompleks 2015 and fresh Eldfisk S 2021 are identical. Of the reported viscosities, Ekofisk Blend 2000 has the highest viscosity of both fresh oil and residues. For Ekofisk J the viscosities are similar in 2015 and in 2021. Eldfisk S 2021 has a lower viscosity for fresh oil but higher viscosity for 250°C+ residue compared to Eldfisk Kompleks 2015.

True boiling point curve

The true boiling point curve of Eldfisk S was delivered by Intertek WestLab. For Ekofisk J and TOR II, Intertek Sunbury provided simulated distillation curves based on samples sent by SINTEF. All boiling point curves were compared to their respective laboratory data with regards to evaporative loss. Some adjustments were made for Eldfisk S, to compensate for a higher presence of lighter components in the sample analysed by Intertek WestLab. The boiling point curves of TOR II, Eldfisk S and Ekofisk J are given in Figure 7-1, along with previous boiling point curves for Ekofisk Blend, Ekofisk J, Eldfisk Kompleks and Eldfisk B.

Ekofisk Blend 2000 is seen to have the lowest boiling point curve, providing conservative data with regards to evaporation. Comparisons of Eldfisk S 2021 (blue solid line) and Eldfisk Kompleks 2015 (blue dotted line), show some variations initially, but better correlations in the higher temperatures (>200 °C). Ekofisk J 2021 (solid green line) and Ekofisk J 2015 also show good correlation above 200 °C.

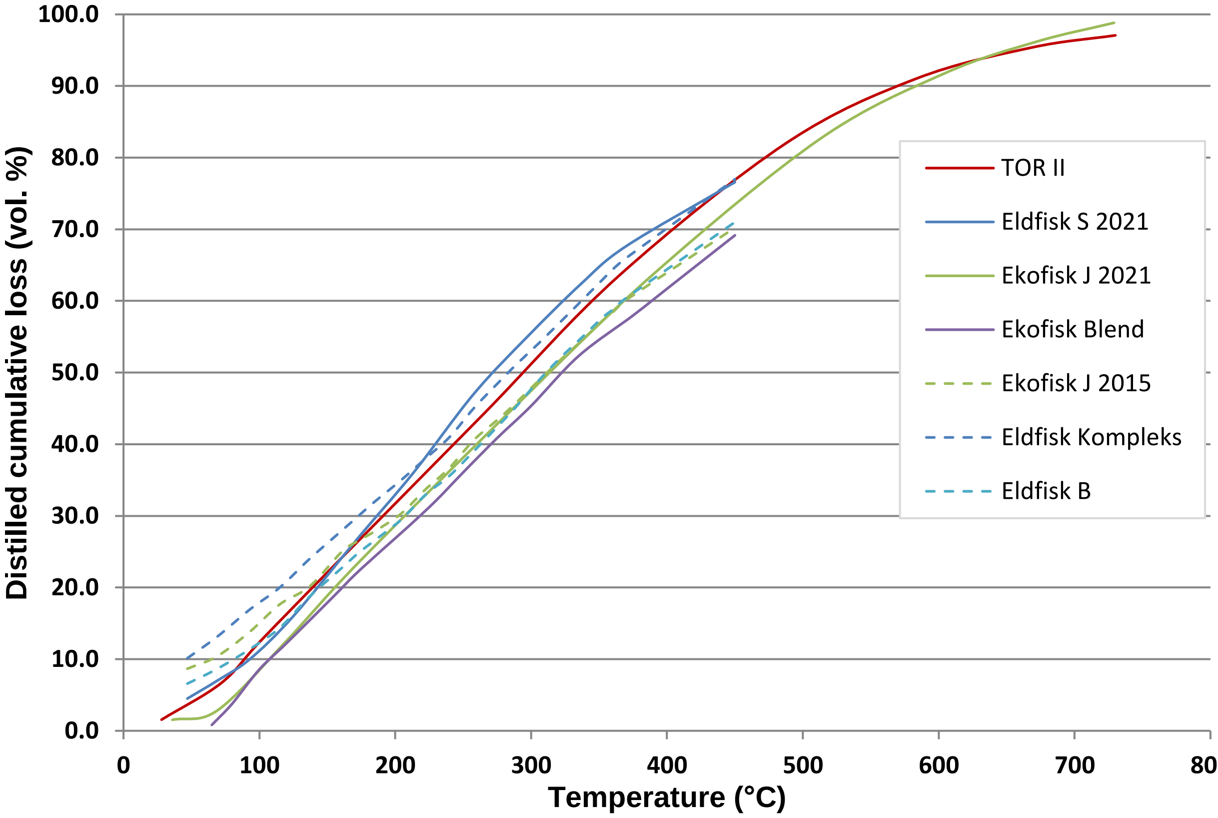


Figure 7-1 True boiling point curves of TOR II and other Ekofisk oils (blends).

7.2 Water uptake and maximum water content

Parameters for kinetics (rate of water uptake) and maximum water uptake was studied with the rotating cylinders. Figure 7-2 shows the rotating cylinders containing Eldfisk S 2021 (left) and Ekofisk J 2021 after 24 hours of rotation. Cylinders of 150 and 200°C+ were added to the test setup to obtain water uptake and stability data for these residues as well as for the 250°C+ residues. The water uptake of Eldfisk S 2021 is similar to that of Eldfisk Kompleks 2015, with 75 vol. % in 2021 compared to 77 vol.% in 2015 for the 250°C+ residue. Due to production chemicals, the water uptake of Ekofisk J 2021 250°C is significantly lower (41 vol %) compared to results from 2015 (75 vol. %).

Figure 7-2 Rotating cylinders containing Eldfisk S (left) and Ekofisk J (right) after 24 hours of rotation at 13 °C. The Ekofisk J 2021 contains production chemicals and show lower degree of emulsification than expected for similar oil without prod. chemicals.

The water contents in the water-to-oil emulsions of Eldfisk S 2021 and Ekofisk J 2021 are shown in Table 7-1 as a function of time, with Ekofisk Blend 2000 in comparison. $T_{1/2}$ is a constant defined as the time (hours) required to incorporate half the maximum water quantity and is derived from the tabulated data for each residue.

While the $T_{1/2}$-value of Ekofisk J 2021 is not directly comparable due to the presence of production chemicals, a longer halftime was also observed in 2015 (then $T_{1/2} = 1.90$) for Ekofisk J compared to Ekofisk Blend 2000 and Eldfisk Kompleks 2015. With a $T_{1/2}$-value of 0.37 for the 250°C+ residue, Eldfisk S 2021 show similar $T_{1/2}$-values as observed for Eldfisk Kompleks in 2015 (then 0.35).

Table 7-1 Water uptake for the evaporated residues of Eldfisk S and Ekofisk J at 13°C. Historical data for Ekofisk Blend 2000 for comparison.

Mixing time	**Eldfisk S (2021) (Vol. % water)**			**Ekofisk J (2021) (Vol. % water)**			**Ekofisk Blend 2000 (Vol. % water)**
	150˚C+	**200˚C+**	**250˚C+**	**150˚C+**	**200˚C+**	**250˚C+**	**250°C+**
Start	0	0	0	0	0	0	0
5 min	17	3	2	12	12	2	13
10 min	30	14	17	14	19	9	22
15 min	38	21	27	14	19	10	32
30 min	44	33	48	12	14	11	39
1 hour	48	47	68	14	17	20	49
2 hours	50	57	73	12	19	26	64
4 hours	52	62	74	3	23	31	72
6 hours	52	63	74	6	19	31	77
24 hours	52	64	75	6	19	41	78
$T_{1/2}$	0.14	0.51	0.37	N.C*	N.C*	N.C*	0.53

**Not calculated for Ekofisk J 2021 with production chemicals.*

7.3 Efficiency of emulsion breaker and stability of emulsions

The stability of the emulsions from the weathered residues of Eldfisk S 2021 and Ekofisk J 2021 was tested by quantifying the amount of water released from the emulsion during 24 hours of settling after 24 hours of rotation. In addition, the efficiency of the emulsion breaker (OT-SE, new since 2015) was evaluated. The results are given in Table 7-2 along with historical results for Ekofisk Blend 2000. The emulsions of both Eldfisk S 2021 and Ekofisk J 2021 showed high stability ratio, similar to Ekofisk Blend 2000. Both Eldfisk S 2021 and Ekofisk J 2021 responded also well to the application of emulsion breaker.

Table 7-2 Stability of emulsion and effect of emulsion breaker on Ekofisk J and Eldfisk S, tested at 13°C.

Oil	**Emulsion breaker**	**Water-in-oil emulsion (vol. %) at 13 °C**		
		Reference	**24 hours ***	**Stability ratio****
Ekofisk J (2021) 250°C+	None	41	39	1.00
	OT-SE 500 ppm	41	0	0.00
	OT-SE 2000 ppm	41	0	0.00
Eldfisk S (2021) 250°C+	None	75	76	1.00
	OT-SE 500 ppm	75	39	0.21
	OT-SE 2000 ppm	75	0	0.00
Ekofisk Blend 2000 250°C+	none	78	78	0.97
	Alc. O 60 % 500 ppm	78	40	0.19
	Alc. O 60 % 2000 ppm	78	0	0.00

7.4 Emulsion viscosities

The viscosities measured for Eldfisk S 2021 and Ekofisk J 2021, on fresh oil, water-free residues and emulsions, are presented in Table 7-3. Viscosities relevant for comparison are marked in bold. The viscosities of Ekofisk J 2021 were significantly lower than Ekofisk Blend 2000 and are also lower than the viscosities measured in 2015. This is most likely attributed to the presence of production chemicals that lowers the water uptake and the emulsion viscosity. The viscosities of Eldfisk S 2021 are slightly lower than Eldfisk Kompleks 2015 but are still in the same range.

Table 7-3 Viscosities of Ekofisk oils (blends).

Oil	Residue	Water content (vol. %)	Viscosity (mPa·s) 13 °C	
			10 s^{-1}	100 s^{-1}
Eldfisk S 2021	**Fresh**	**0**	**18**	**14**
	150°C+	0	116	68
	200°C+	0	566	241
	250°C+	**0**	**2493**	**791**
	150°C+	50	415	159
	200°C+	50	1528	528
	250°C+	50	3787	714
	150°C+	75	759	190
	200°C+	75	2765	669
	250°C+	75	7227	759
	150°C+	41	549	122
	200°C+	60	1900	568
	250°C+	**76**	**6723**	**513**
Ekofisk J 2021	**Fresh**	**0**	**17**	**16**
	150°C+	0	90	70
	200°C+	0	205	147
	250°C+	**0**	**1051**	**486**
	250°C+	**42**	**1442**	**328**
Ekofisk Blend 2000	**Fresh**	**0**	**92**	**38**
	250°C+	**0**	**3800**	**885**
	250°C+*	**78**	**11132**	**1929**
Eldfisk Kompleks 2015	**Fresh**	**0**	**36**	**-**
	250°C+	**77**	**7564**	**-**
Ekofisk J 2015	**Fresh**	**0**	**14**	**-**
	250°C+	**75**	**11461**	-

7.5 Dispersibility of Eldfisk S

The dispersibility of Eldfisk S 2021 was tested using a DOR/DER ratio of 1:25 (4 wt.%) with Dasic Slickgone NS as the chosen dispersant, and a time window for dispersant application was established. The dispersibility was tested on emulsions at 13 °C. Figure 7-3 show the effectiveness relative to the emulsion viscosity, with lines indicating the dispersibility limits. Table 7-4 show the established viscosity limits for use of dispersant. Eldfisk S 2021 was found to be good chemically dispersible for emulsion viscosities below 1000 mPa·s, and poorly/low chemically dispersible for emulsion viscosities above 10 000 mPa·s. In the field, additional energy or higher DOR/DER by repeated dispersant application may increase the dispersion effectiveness, in calm weather condition, when the emulsion viscosity is between 1000-10 000 mPa·s.

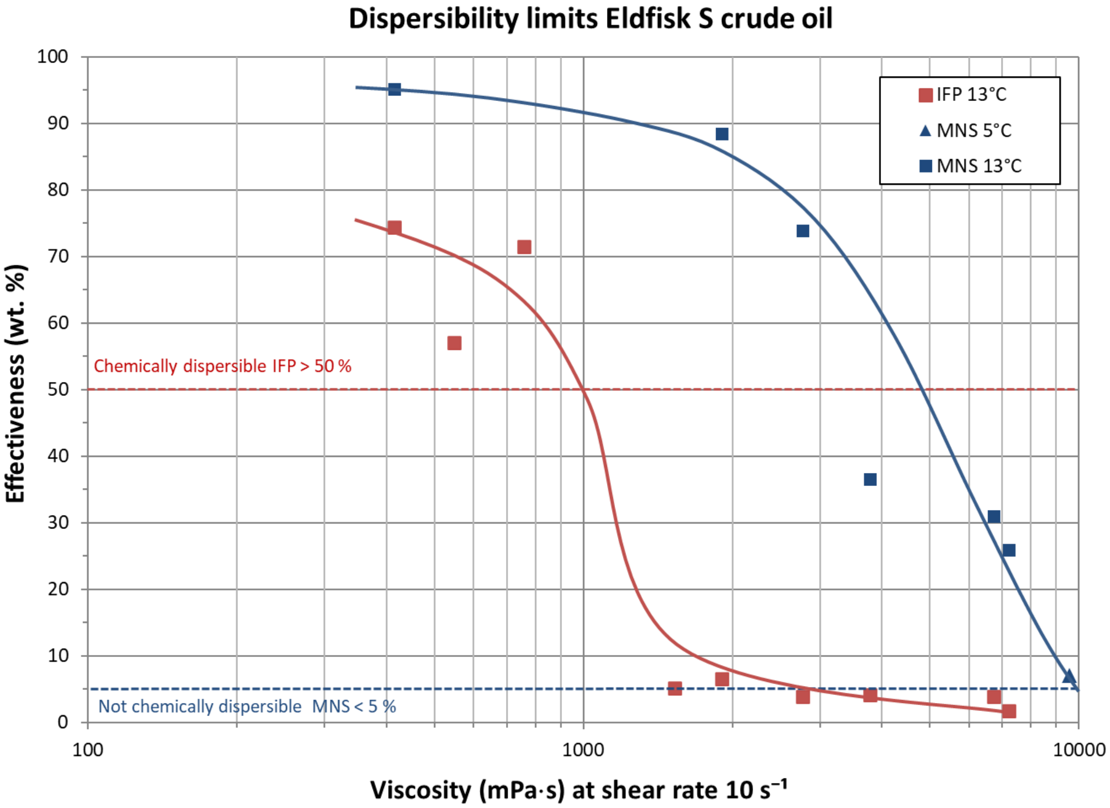


Figure 7-3 Dispersant effectiveness limits for Eldfisk S from 2021.

Table 7-4 Estimated viscosity limits for use of dispersant for Eldfisk S emulsion and the criteria for definition of time window.

Dispersibility	**Criteria (wt. %)**	**Dispersibility limits based on oil viscosities (mPa·s = cP)***
Chemically dispersible	IFP efficiency > 50 %	1000
Not chemically dispersible	MNS efficiency < 5 %	10 000

8 Summary Eldfisk S and Ekofisk J

8.1 Comparison with model oil (Ekofisk Blend 2000)

One of the objectives of this project was to compare the weathering properties of Ekofisk blends with the existing model oil, Ekofisk Blend 2000, and assess the use of this model oil for further environmental risk assessment and contingency analysis.

Ekofisk J and Eldfisk S from this current study do not differ significantly in their weathering properties compared with the Ekofisk blends tested in 2015 (Ekofisk J, Eldfisk B and Eldfisk Kompleks). Eldfisk S (2021) and Ekofisk J (2021) also have physio-chemical properties closer to those of Ekofisk Blend 2000 compared to their 2015 counterparts. The use of the existing model oil, Ekofisk Blend 2000, can therefore still be considered as valid, and this is the same conclusion given for Ekofisk blends from 2015 (Hellstrøm and Brandvik, 2015).

8.2 Response options Eldfisk S

Dispersibility: The effectiveness of chemical dispersants was also tested on Eldfisk J emulsions with use of Dasic Slickgone NS to determine the viscosity limits for use of dispersant. Emulsions of Eldfisk S were found to be dispersible for viscosities < 1000 mPa·s (DOR 1:25), i.e., in non-breaking waves (< 5 m/s wind speeds), and poorly/low dispersible for viscosities >10000 mPa·s in breaking waves conditions (> 5m/s wind speeds). In the field, additional energy or higher DOR by repeated dispersant application may increase the dispersant effectiveness when viscosities are between 1000 mPa.s and 10000 mPa·s. The time-window for use of dispersant is given in Appendix B, Figure B-5, where the oil can be dispersible up to one day for 10 m/s wind speed in summer and winter condition

Mechanical recovery: The emulsion viscosities of Eldfisk S are shown in Figure B-5 at 5 and 15 °C. For leakage of confined oil, the emulsion viscosity exceeds 1000 mPa·s after 1.5- 2 hours at 10 m/s wind speed but are stretched up to 9-12 hours for very low wind speed (2 m/s). Overall, Eldfisk S has a wide window of opportunity for traditional weir-skimmer head due to viscosities <20 000 mPa·s 4-5 days of weathering at summer and winter conditions, at 10 m/s wind speed.

8.3 Response options Ekofisk J

Dispersibility and mechanical recovery: The batch of Ekofisk J for testing in 2021 contained production chemicals and had therefore unexpected low water content and low emulsion viscosity compared with the other Ekofisk oils. The dispersant testing was therefore omitted for Ekofisk J in agreement with COPSAS. However, based on the physico-chemical properties and weathering predictions based on the CA-module, it can be assumed that Ekofisk J will have similarities in viscosity limits and the time-window for use of dispersant as Eldfisk S. Similar, the time-window for use of weir skimmer for viscosities < 20 000 mPa·s is also likely to be close to Eldfisk S. The response options for Ekofisk J are however based on the predictions based on the CA-model and synthetical data, and the assumption are therefore more uncertain than having the experimental data for Ekofisk J, as input to the SINTEF OWM for predictions.

A spill from a release of Ekofisk J containing production chemicals will have lower water uptake and emulsions and is expected to have a higher degree of natural dispersion due the content of surface-active compounds. Ekofisk J containing production chemicals is further expecting to have a long time-window for dispersants use (>5 days). High emulsion viscosity will either not be a challenge for use of weir skimmers, but leakages of confined oil for viscosity <1000 mPa·s should be considered.

9 Evaluation of historical data for Ekofisk blends

COPSAS provided SINTEF with historical crude assay (CA) data from 2000-2022 of Ekofisk J, Eldfisk B, Eldfisk S, and more recent data of TOR II (2020-2022). Note, that TOR II came in production from December 2020 and included in Ekofisk J blend. TOR II presents 16% of the Ekofisk export (from the last half year 2021).

By evaluating the trends in historical data, changes that can influence the weathering properties of an oil can be detected. Significant changes in properties may spark the need for a revised weathering study and a new or updated model oil. SINTEF has received historical data of measured densities of the oils and have evaluated these. A similar evaluation was performed in 2015 (Hellstrøm and Brandvik, 2015), and historical data from 2000, 2005, 2010, 2014 and 2015 was then used. These same years have been included in this report with the addition of data from 2018, 2020 and 2021, as well as available data from 2022.

Figure 9-1 shows all the received density data of the oils from May 2000 to February 2022. The historical data presented are based on density measured at 15 °C on a "true C7+ fraction" at a different laboratory, similar to the study in 2015. Note, a visible drop in density can be seen for all three oils between February and April of 2020 (Figure 8-1), and this is most likely due to methodology changes.

Overall, Eldfisk S is shown to have an increasing density from May 2000 to about 2007 and has slightly varying density between 2007-2020. From April 2020 to February 2022 the density of Eldfisk S seems to remain stable. Eldfisk B show a smaller increase in density between May 2000 to ca. 2003, and relatively stable densities until February 2020, and remains stable after the drop between February - April 2020. The densities of Ekofisk J are relatively stable from 2000 to 2020, as well as after the drop in early 2020. The decrease of Ekofisk J from December 2020 is due to the inclusion of TOR II. Densities measured for TOR II are also presented and are significantly lower than the other oils. The inclusion of TOR II to Ekofisk J has likely a significant influence on the density of Ekofisk J and may cause reason to consider a revised weathering study or a re-check study by time.

The average density for all the years, and the average ± 2 standard deviations are presented for the individual oils in Figure 9-2 to Figure 9-4. Table 9-1 summarizes the calculated average and standard deviation for the Ekofisk blends.

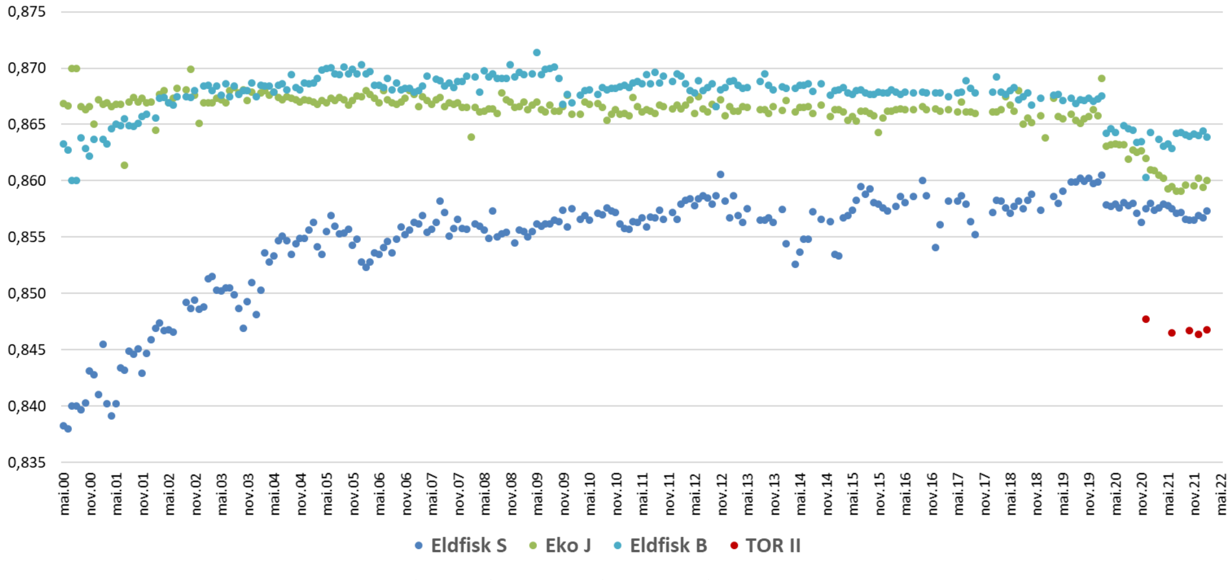


Figure 9-1 Historical density data for Eldfisk S, Ekofisk J, Eldfisk B and TOR II.

Ekofisk J

Historical data for the density of Ekofisk J is presented in Figure 9-2 for a selection of years, in chronologic order from left to right. Between 2000-2019 the density of Ekofisk J remained relatively stable with little variation. From 2020, significant changes occur. The previously mentioned drop in density early 2020 (likely due to the analytical method) is clearly seen within the purple dots in Figure 9-2, with lower densities lying close to 2 standard deviations from the average density. From late 2020 the density of Ekofisk J continues to drop lower than the -2 standard deviation line (lower green line). This is due to the inclusion of TOR II to the Ekofisk J blend.

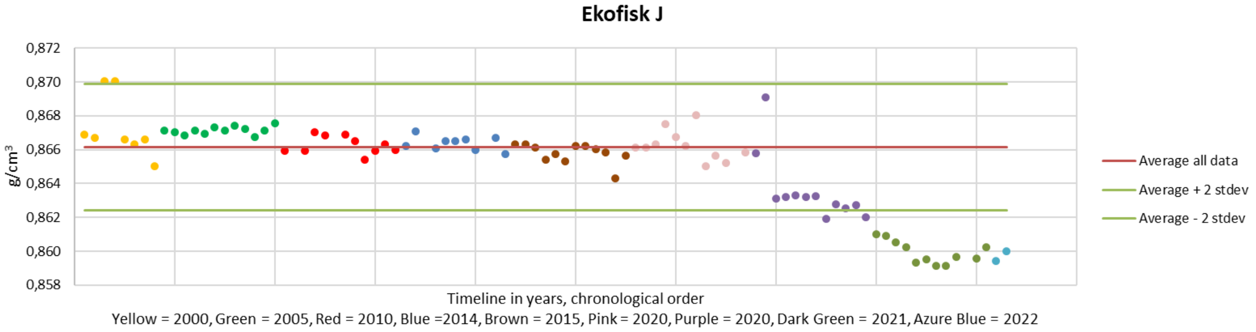


Figure 9-2 Historical data of the density of Ekofisk J.

Eldfisk B

The density of Eldfisk B has varied over the years, being low in 2000, high in 2005 and then relatively stable between 2010-2019. After the visible drop in density in early 2020, the density remains stable, though there is some minor variation. One purple dot (December 2020) is below the -2 stdev. The crude assay data (as received from COPSAS) for this time point show variance for many parameters not presented here, supporting the validity of the low density. The reason for this temporary drop in December 2020 is unknown to SINTEF.

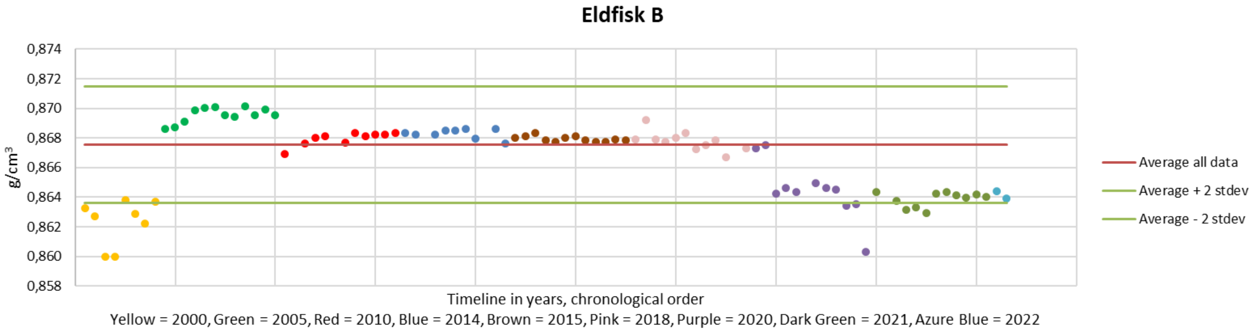


Figure 9-3 Historical data of density for Eldfisk B.

Eldfisk S

It is understood that Eldfisk S and Eldfisk Kompleks are synonyms of the same blend, since the historical data received for Eldfisk S match those received in 2015 for Eldfisk Kompleks. For simplicity, Eldfisk S will be used when discussing the oil in general.

Figure 9-1 shows that Eldfisk S had a gradual increase in density between 2000-2007. The methodical drop in density in 2020 (seen in Figure 9-1) is not as clear to see in Figure 9-4 since the densities measured in 2019 are not included. After the drop in density in 2020, Eldfisk S regained densities like those of 2015 and 2018. When compared to historical data (from 2005 and onwards), there are no indication of a significant change in density for Eldfisk S.

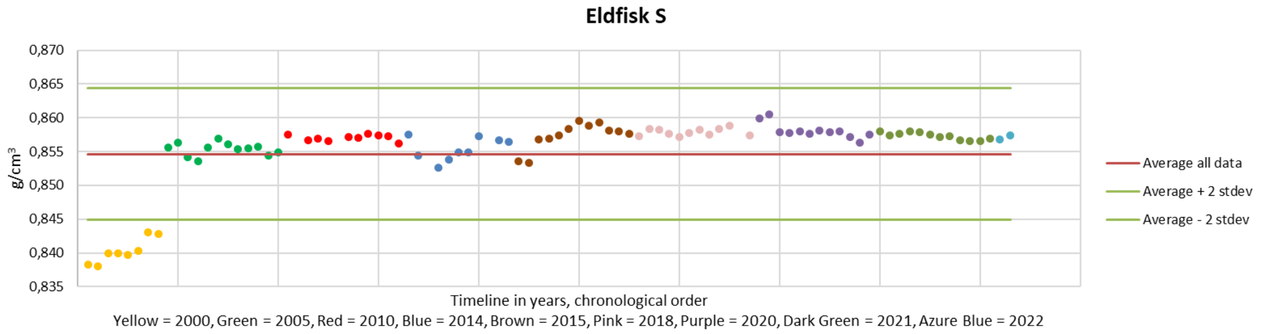


Figure 9-4 *Historical data of density for Eldfisk S.*

Table 9-1 *Calculated average and standard deviation for Ekofisk J, Eldfisk B and Eldfisk S.*

	Ekofisk J	**Eldfisk B**	**Eldfisk S**
Average density (all data)	0.8662	0.8676	0.8546
St.dev	0.0019	0.0020	0.0049
Average + 2 st.dev	0.8699	0.8715	0.8644
Average - 2 st.dev	0.8624	0.8636	0.8449

10 References

1. Bocard, C., Castaing, C. G. and Gatellier, C. 1984. "Chemical oil dispersion in trials at sea and in laboratory tests: The key role of the dilution process." Oil spill chemical dispersants: Research Experience and recommendations, ASTM STP 840. (T. E. Allen, ed.), Philadelphia, USA, pp. 125-142.
2. Brakstad, O.G., and Faksness, L.-G., (2000). Biodegradation of water-accommodated fractions and dispersed oil in the seawater column. Proceedings for the International Conference on Health, Safety and Environment in Oil and Gas Exploration and Production, Stavanger, 26-28 June 2000
3. Brakstad, O-G and A.G.G Lødeng 2005. "Microbial diversity during micro biodegradation of crude oil in seawater from the North Sea." Microbial Ecology 49:94-104
4. Bridié, A. L., Wanders, T. H., Zegweld, W. V. and den Heijde, H. B., 1980. Formation, Prevention and Breaking of Seawater in Crude Oil Emulsions, Chocolate Mousse. Marine Poll. Bull., vol. 11, pp. 343-348
5. Commission Internationale De L'Eclairage (CIE), ISBN No. 3 900 734 22 4, 1989.
6. Daling, P. S., Brandvik, P. J., Mackay, D. and Johansen, Ø. (1990): "Characterisation of crude oils for environmental purposes." Oil & Chemical Pollution 7, 1990, pp. 199-224.
7. Daling, P.S., Lewis, A., Sørheim, K.R., Gjesteland, I. 2017. Full-scale field testing of thin oil films from releases of light crude oil at sea. NOFO Oil-on-Water field trial in 2016. SINTEF report 2017:00030 Unrestricted. ISBN:978-82-21-40670-8.
8. Hellstrøm, K.C and Brandvik, P.J. 2015. Comparison of predicted properties of Ekofisk oils based on crude assay data. SINTEF report A27361. ISBN 9788214058505.
9. Hokstad, J. N., Daling, P. S., Lewis, A. and Strøm-Kristiansen, T. 1993: "Methodology for testing water-in-oil emulsions and demulsifiers. Description of laboratory procedures." Proceedings Workshop on Formation and Breaking of W/O Emulsions. MSRC, Alberta June 14-15, 24 p.
10. Johansen, Ø. 1991. "Numerical modelling of physical properties of weathered North Sea crude oils." DIWO-report no. 15. IKU-report 02.0786.00/15/91. Open.
11. Leirvik, F., Moldestad, M. and Johansen, Ø., 2001. Kartlegging av voksrike råoljers tilflytsevne til skimmere
12. McAuliffe, C.D. (1987). Organism exposure to volatile/soluble hydrocarbons from crude oil spills - a field and laboratory comparison. In: Proc. 1987 Oil Spill Conference. Washington, D.C., American Petroleum Institute. pp. 555-566.
13. Mackay, D. and Zagorski, W. 1982. "Studies of W/o Emulsions". Report EE-34: Environment Canada, Ottawa, Ontario.
14. Mackay, D. and Szeto, F. 1980. "Effectiveness of oil spill dispersants - development of a laboratory method and results for selected commercial products." Institute of Environmental Studies, University of Toronto, Publ. no. EE-16.
15. McDonagh, M., Hokstad, J. N. and Nordvik, A. B. 1995. “Standard procedure for viscosity measurement of water-in-oil emulsions”. Marine Spill Response Corporation, Washington, D.C. MRSC Technical Report Series 95-030, 36 p.
16. Moldestad, M. Ø., A. G. Melbye, et al. (2001).Ekofisk oljene, Gyda og Valhall- Egenskaper og forvitring på sjøen, karakterisering av vannløselige komponenter relatert til beredskap. SINTEF report no. STF66 A01090, ISBN: 821022886
17. Nordvik, A. B., Daling, P. and Engelhardt, F. R. 1992. "Problems in the interpretation of spill response technology studies." In: Proceedings of the 15th AMOP Technical Seminar, June 10-12, Edmonton, Alberta, Canada, pp. 211-217.
18. Perry JJ (1984). Microbial metabolism of cyclic alkanes In: Atlas RM (Ed) Petroleum Microbiology Macmillan Publ Co New York pp 61-98
19. Reed M., and C. Turner, 1991: Field Tests of Satellite tracked buoys to simulate oil drift. In Proceeding of the IOSC, SanDiego, CA. US., pp. 619 – 628
20. Reed, M., Turner, C. and Odulo, A. 1994. "The role of wind and emulsification in modelling oil spill and surface drifter trajectories." Spill Science and Technology, Pergamon Press (2): .143-157.
21. Singsaas, I., Daling, P. S. and Jensen, H., 1993. "Meso-scale laboratory weathering of oils". IKU report 22.2042.00/04/93, IKU, Trondheim, Norway, 81 p.
22. Stiver, W. and Mackay. D. 1984. "Evaporation rate of spills of hydrocarbons and petroleum mixtures." Environ, Sci. Technol., vol. 18 (11), pp. 834-840.
23. Sørheim, K.R., Daling, P.S., and F., Leirvik., 2017: "Mekanisk dispergering av tynne oljefilmer. Oljevern 2015". WP048. SINTEF rapport: OC2017 A-125, ISBN: 978-82-7174-300-0.

A Description of SINTEF Oil Weathering Model (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. 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. Moreover, 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. The SINTEF OWM is schematically shown in Figure A-1. SINTEF OWM was used to perform weathering predictions for TOR II crude oil from this study.

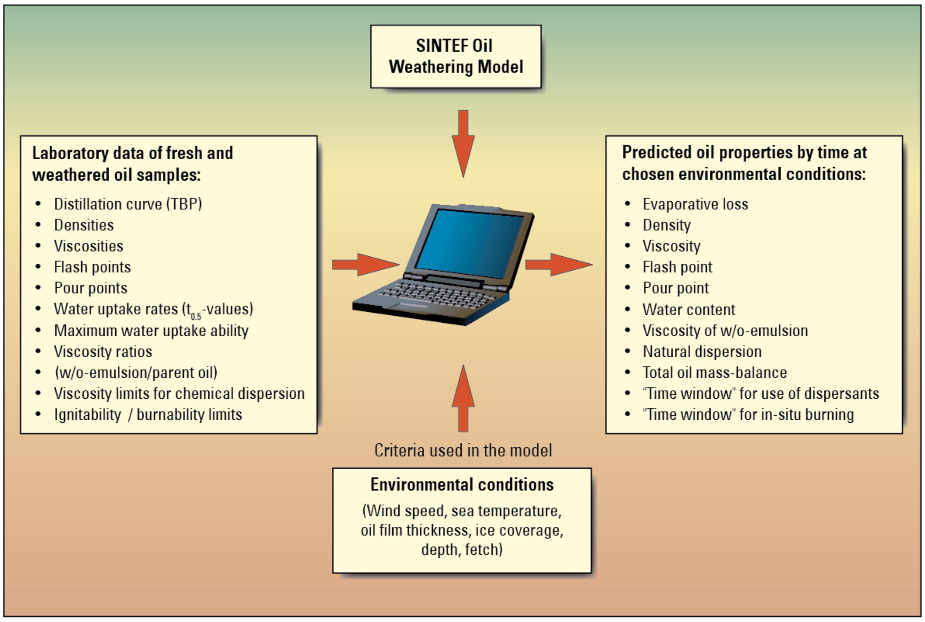


Figure A-1 Schematic input data to the SINTEF OWM and the predicted output oil properties.

In addition , SINTEF has developed a Crude Assay (CA)-module in the Oil Weathering Model (OWM) that enables the prediction of weathering properties of a crude oil based on multivariate analysis of a limited selection of physical-chemical properties, usually available in an oil's Crude Assay (Brandvik *et al.*, 2005; Strøm *et al.*, 2010). The CA-module uses values for pour point, viscosity, density, wax and asphaltene content as well as a true boiling point curve (TBP) for these predictions. Figure A-2 describes the method for obtaining a dataset for weathering properties by using the CA-module to the left, compared to the more traditional full scale weathering approach to the right. The CA- module was used to produce synthetical weathering data for predictions for the Ekofisk oils in 2015 (Hellstrøm and Brandvik, 2015), and was also used to produce synthetical weathering data for Ekofisk J from this current study.

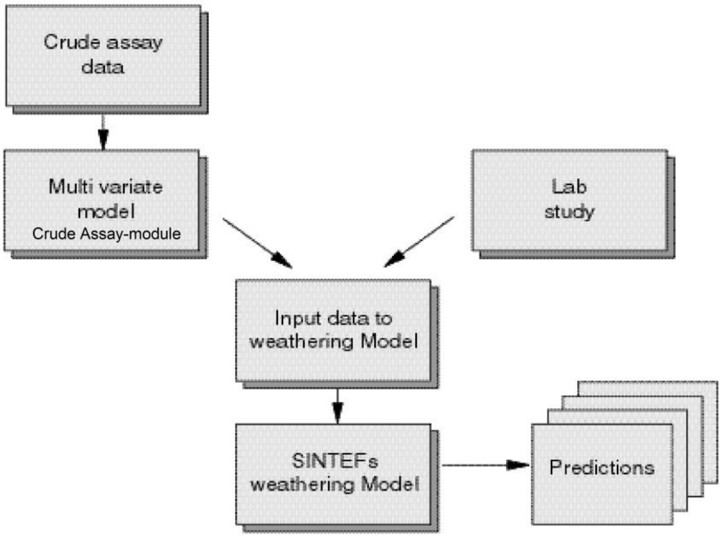


Figure A-2 Different approaches to development of oil weathering predictions.

Oil film thickness

In the SINTF OWM, the oils are categorized into condensate, emulsifying crude, low emulsifying crude, heavy bunker fuel or refined distillate based on experimental results obtained in small-scale testing. The terminal film thickness varies among these categories based on experimental field experience. TOR II and Ekofisk J and Eldfisk S are categorized as a crude oil, whilst Ekofisk J with production chemicals was categorized as low emulsifying oil.

Sea temperature

The prevailing weather conditions greatly influence the weathering rate of oil on the sea surface. Two sets of predictions are given in this report, one for average summer temperatures and one for average winter temperatures. The temperatures chosen for TOR II, Ekofisk J and Eldfisk S are 5 °C and 15 °C.

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 A-1.

Table A-10-1 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

B Predicted weathering behaviour of Eldfisk S and Ekofisk J

B.1 Eldfisk S 2021

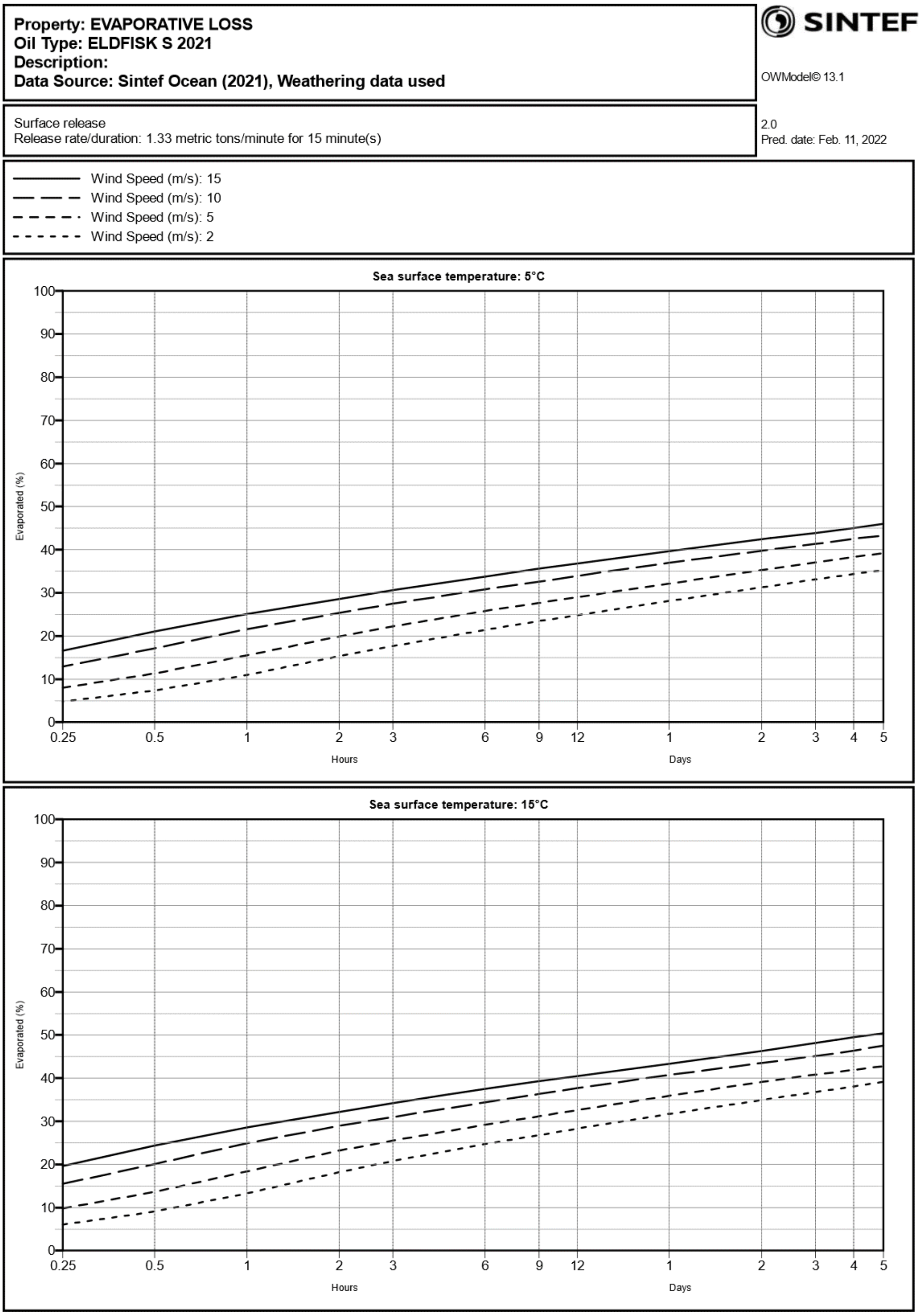


Figure B-1 Evaporative loss of Eldfisk S crude oil predicted at sea temperatures of 5 °C and 15 °C.

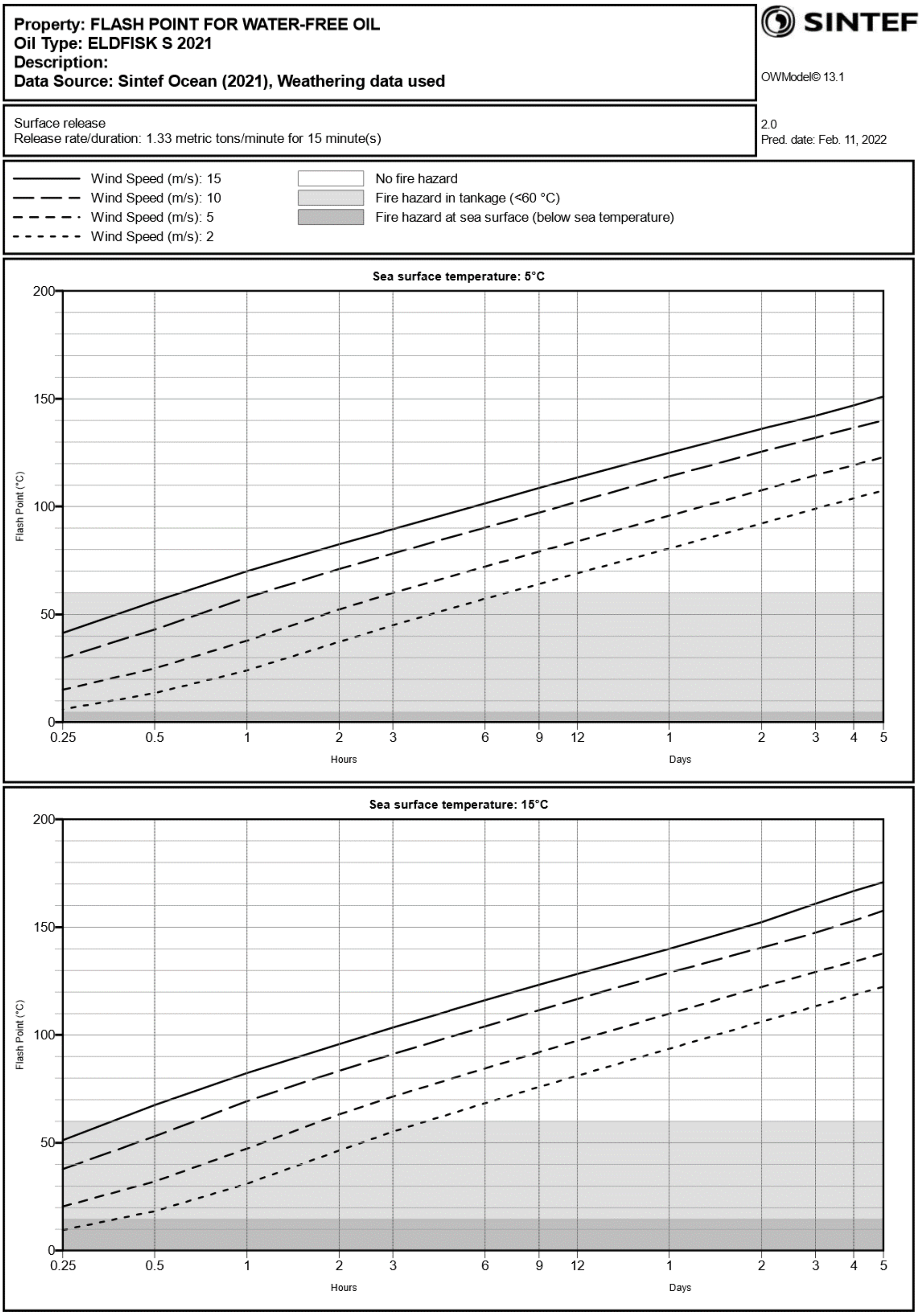


Figure B-2 Flash point of Eldfisk S crude oil predicted at sea temperatures of 5 °C and 15 °C.

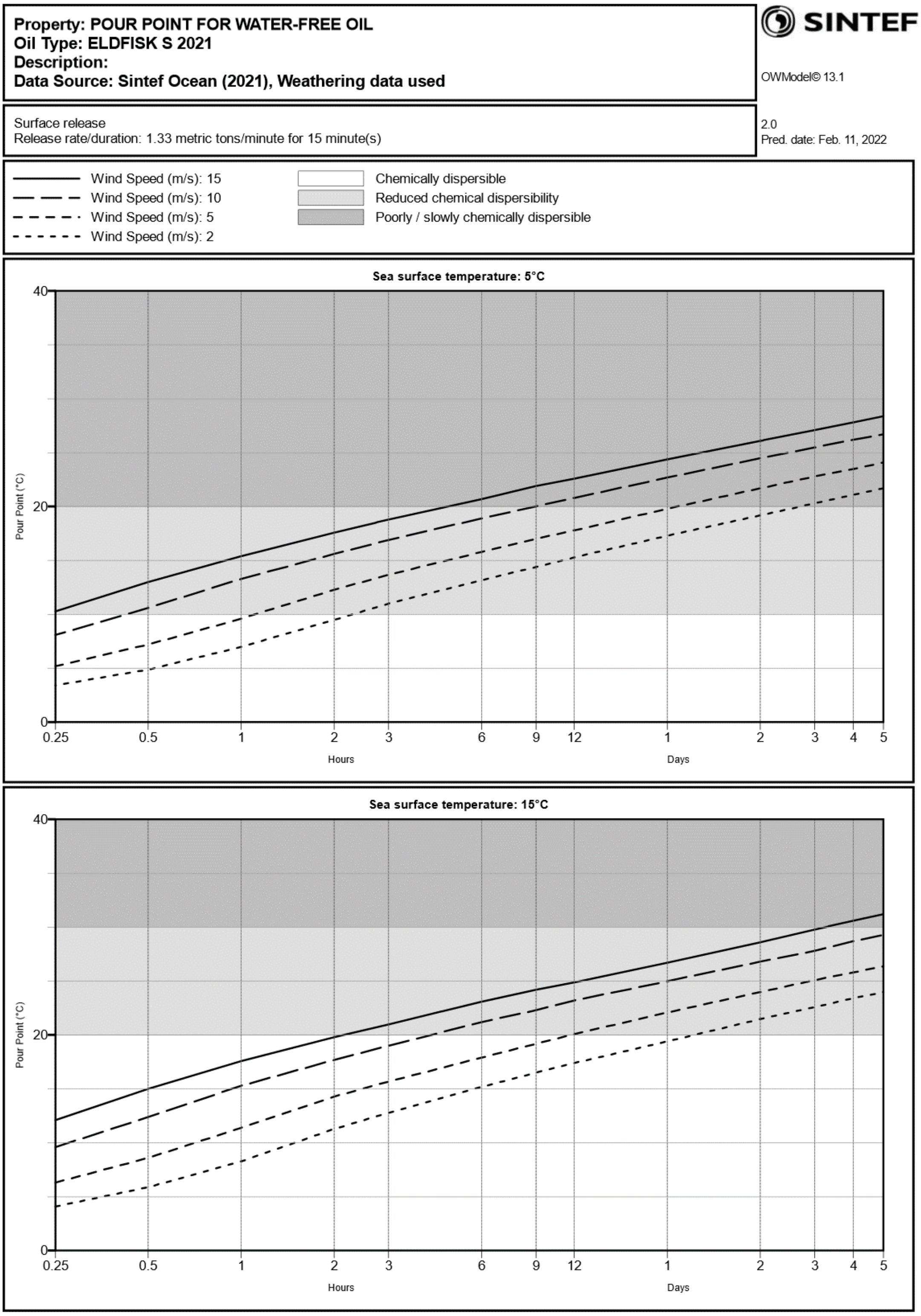


Figure B-3 *Pour point of Eldfisk S crude oil predicted at sea temperatures of 5 °C and 15 °C.*

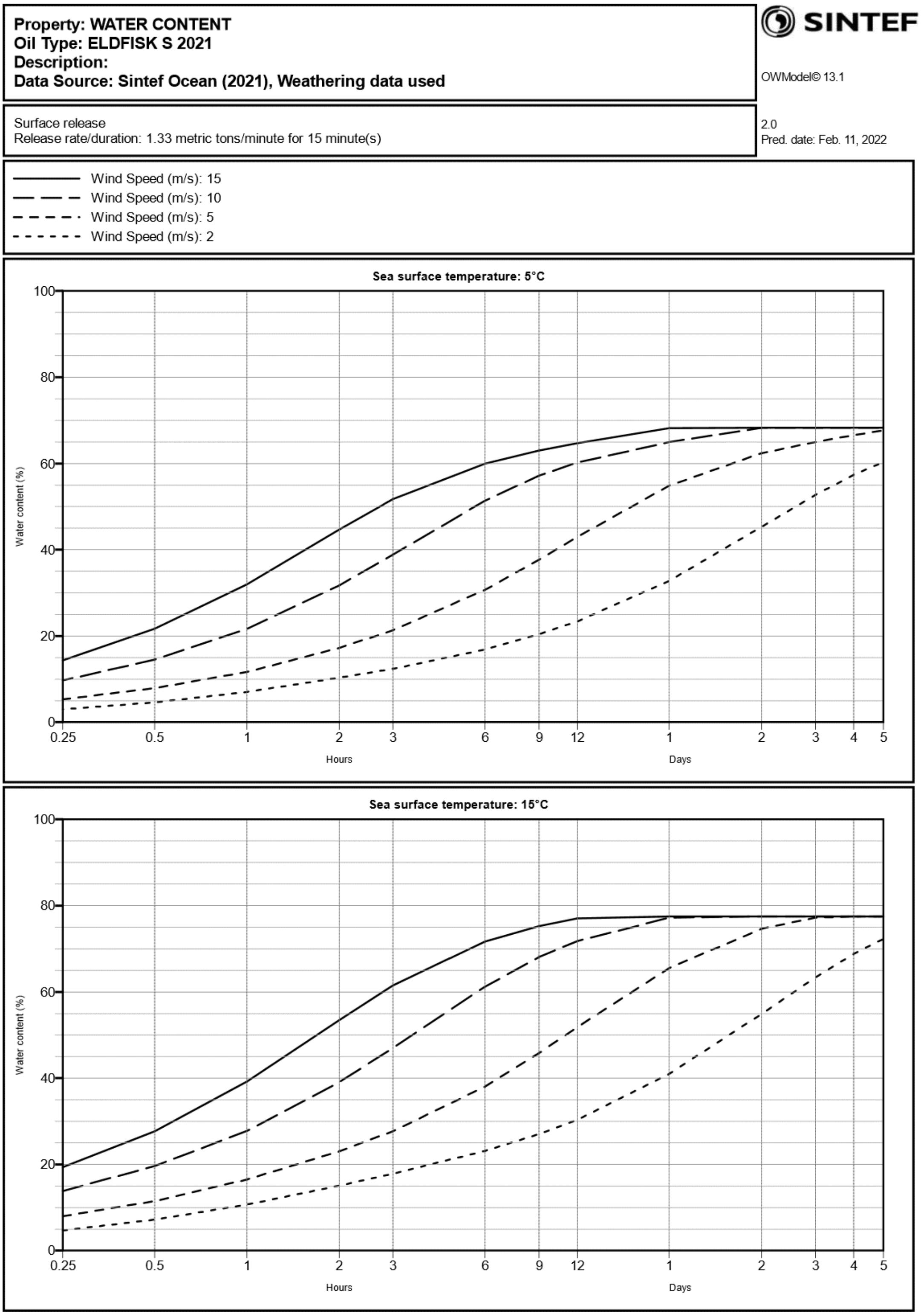


Figure B-4 Water uptake of Eldfisk S crude oil predicted at sea temperatures of 5 °C and 15 °C.

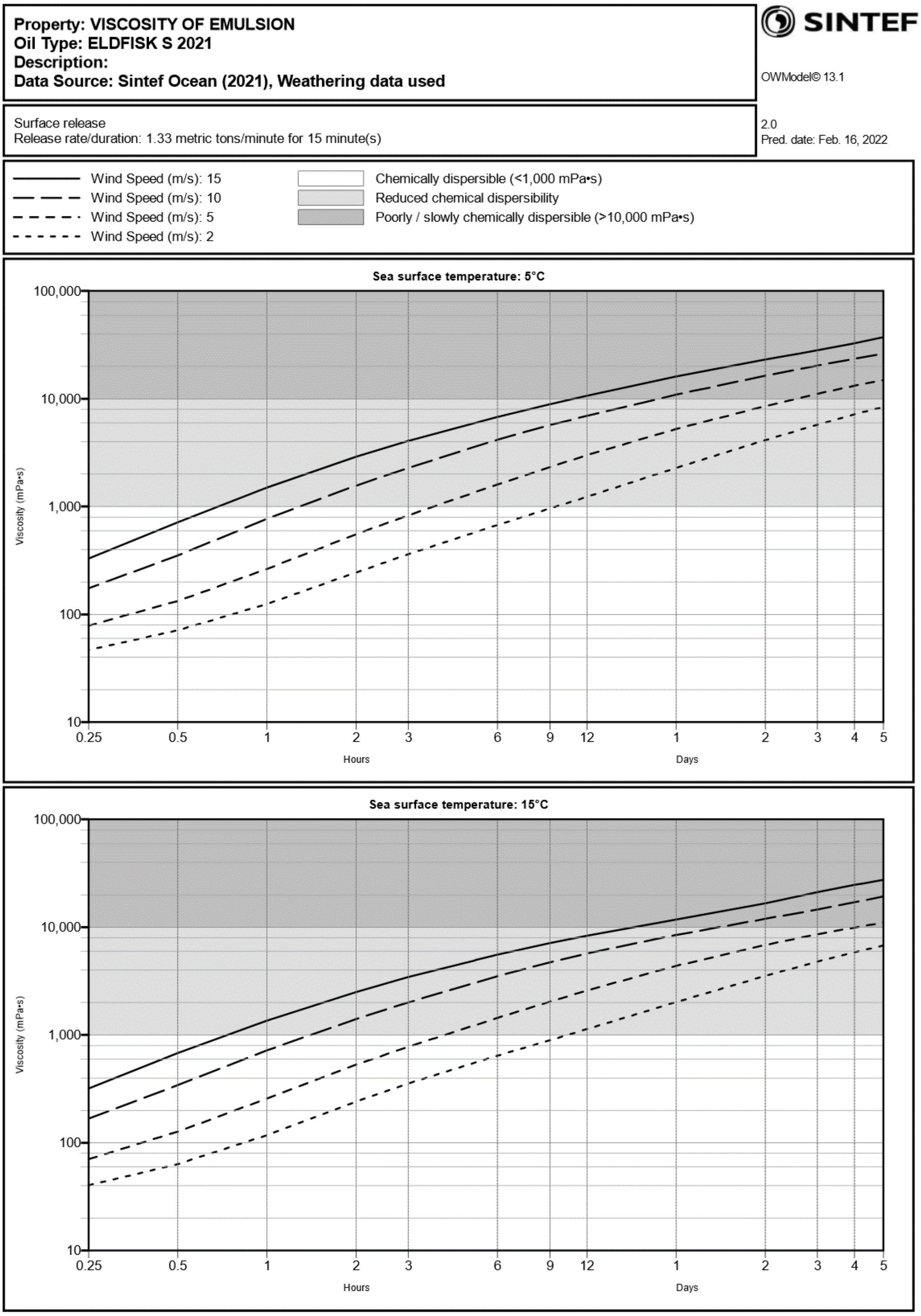


Figure B-5 Viscosity of emulsion of Eldfisk S crude oil predicted at sea temperatures of 5 °C and 15 °C.

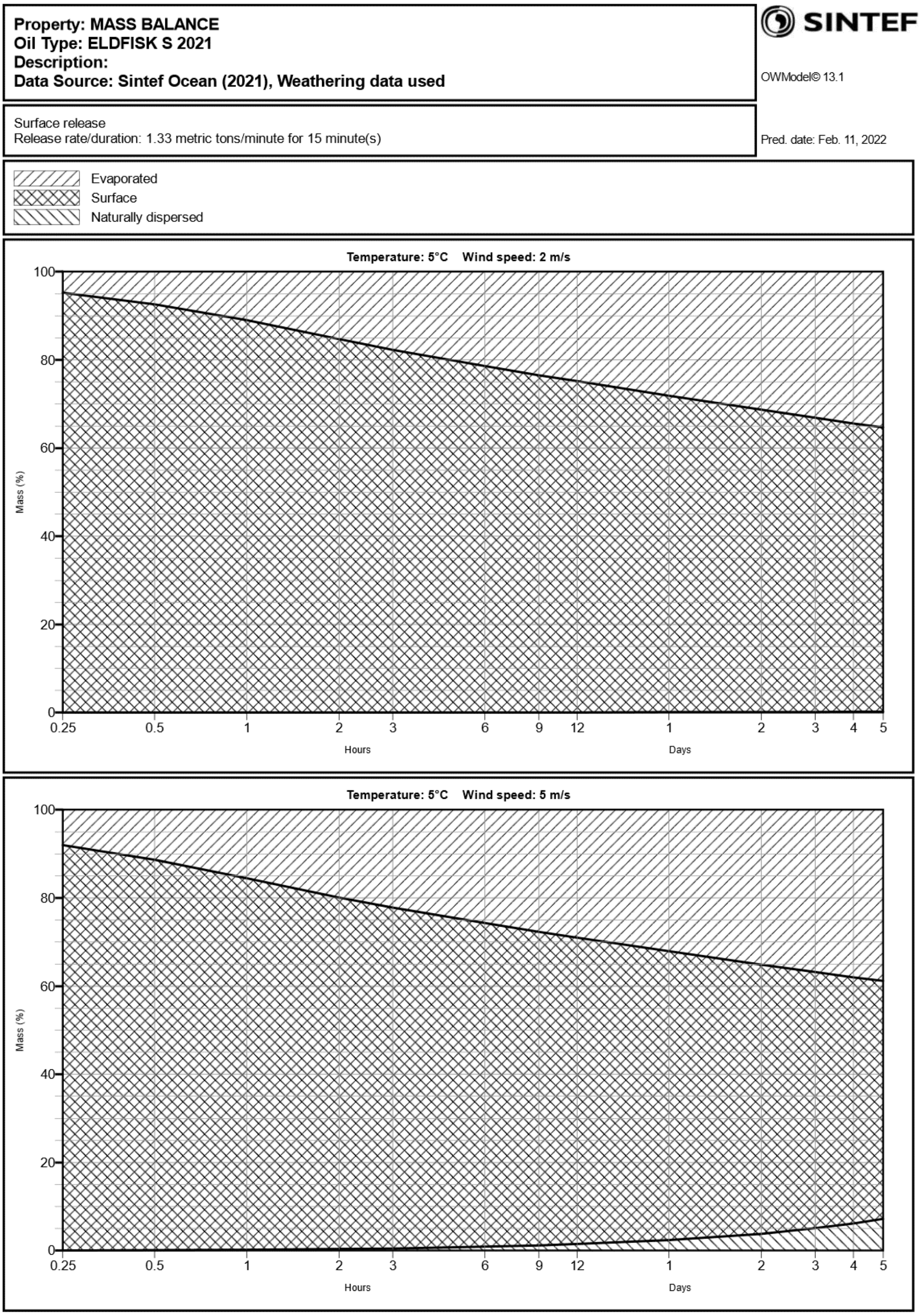


Figure B-6 Mass Balance of Eldfisk S crude oil predicted at sea temperatures of 5 °C and wind speed of 2 and 5 m/s.

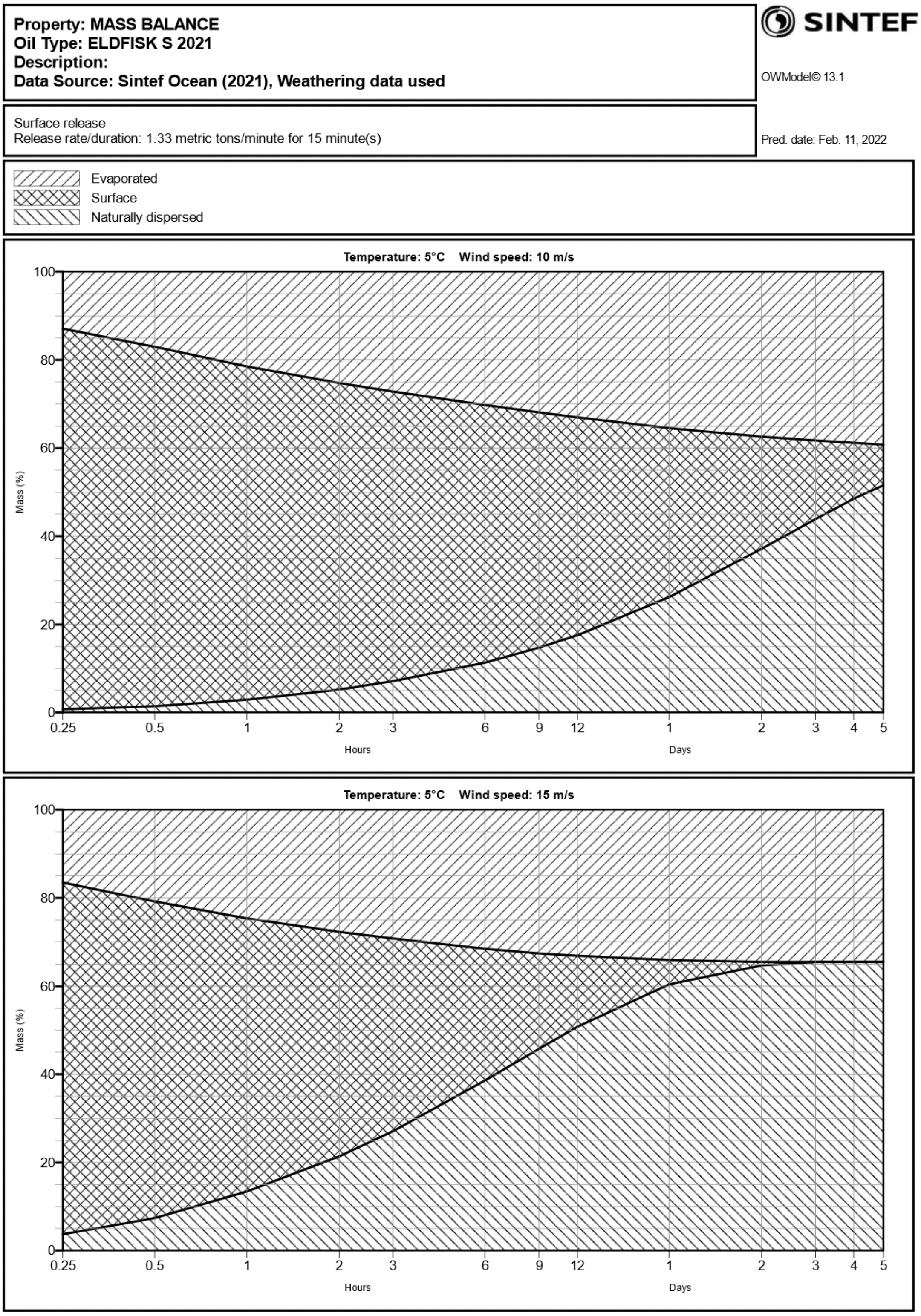


Figure B-7 Mass Balance of Eldfisk S crude oil predicted at sea temperatures of 5 °C and wind speed of 10 and 15 m/s.

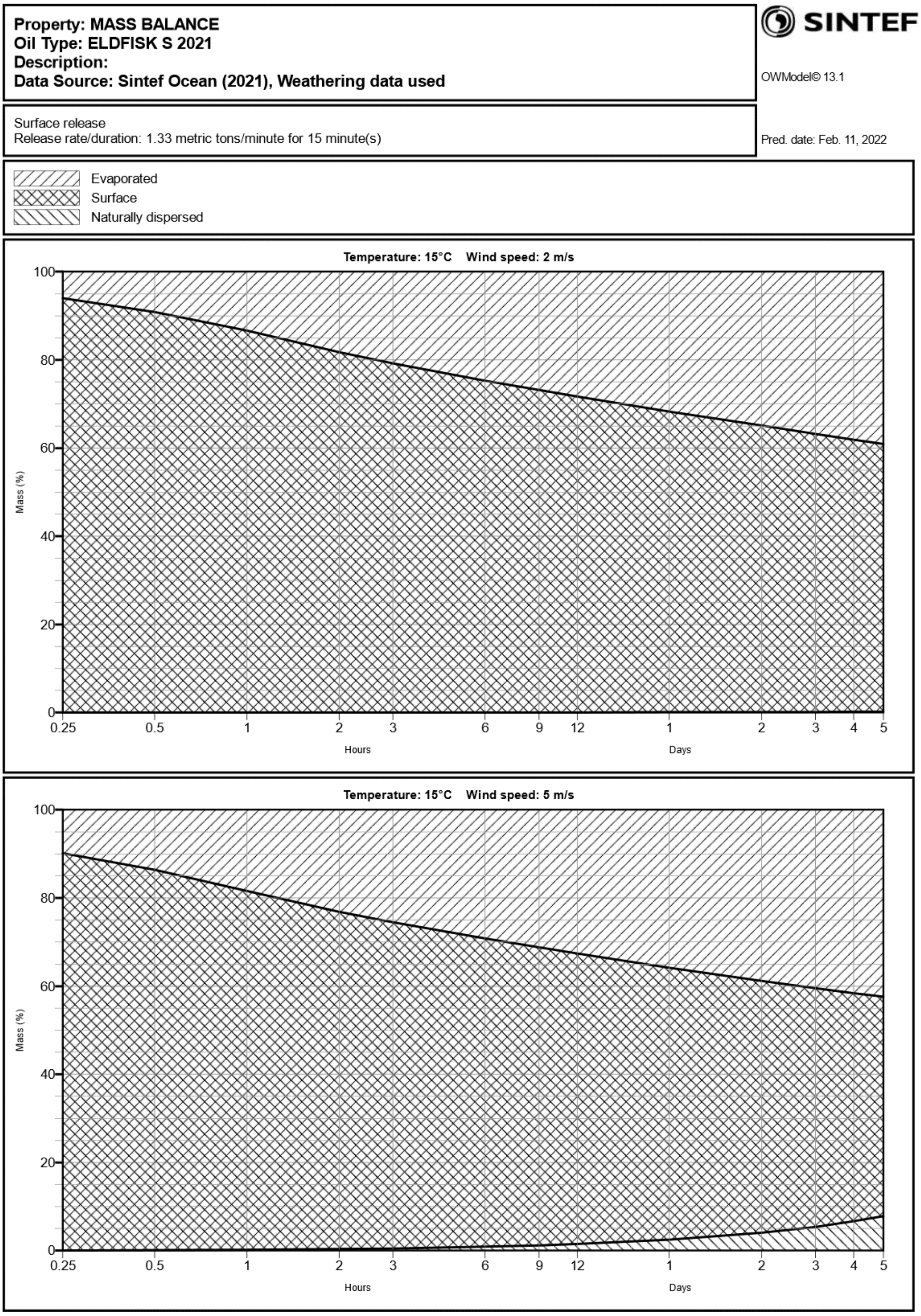


Figure B-8 Mass Balance of Eldfisk S crude oil predicted at sea temperatures of 15 °C and wind speed of 2 and 5 m/s.

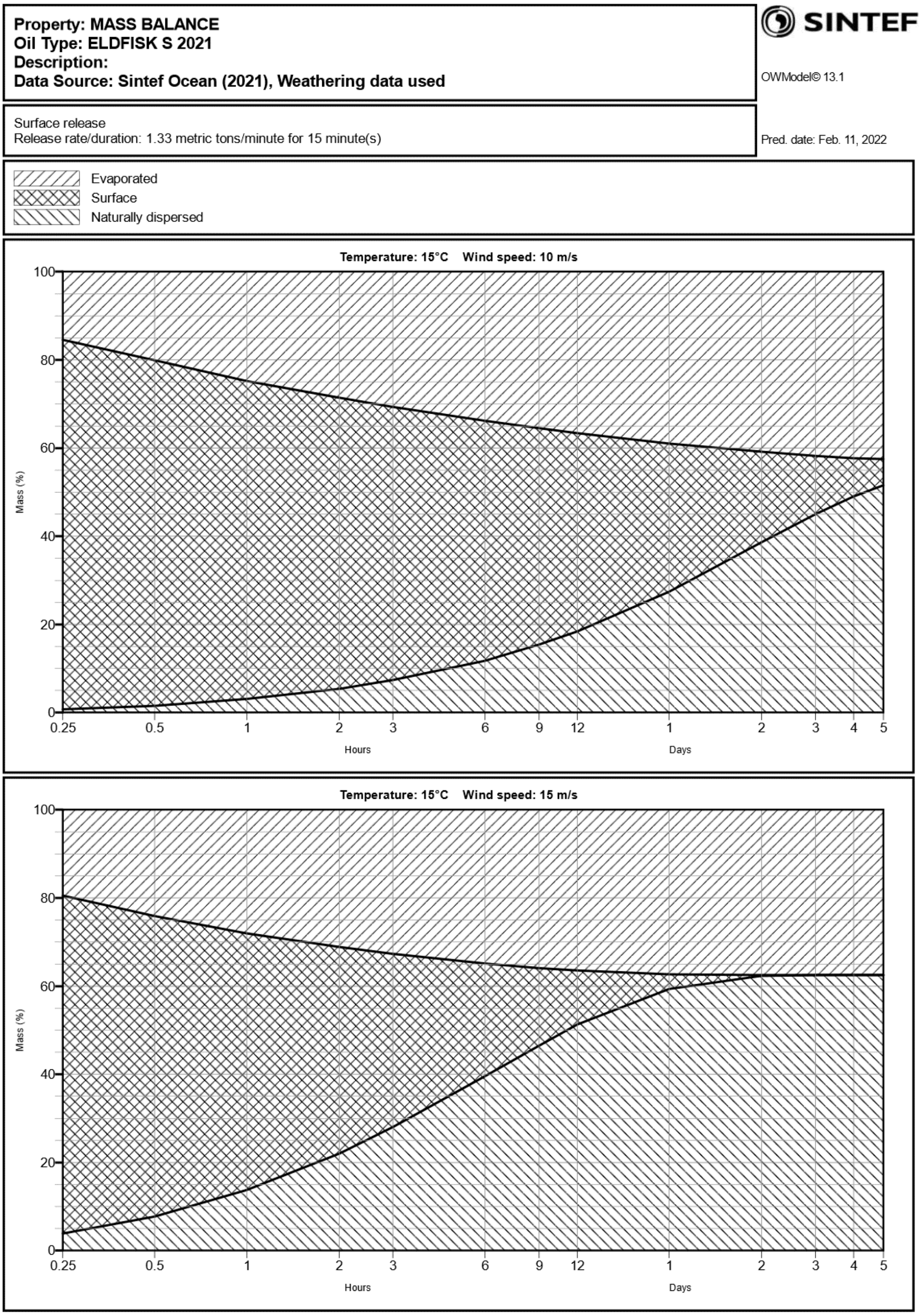


Figure B-9 *Mass Balance of Eldfisk S crude oil predicted at sea temperatures of 15 °C and wind speed of 10 and 15 m/s.*

B.2 Ekofisk J 2021

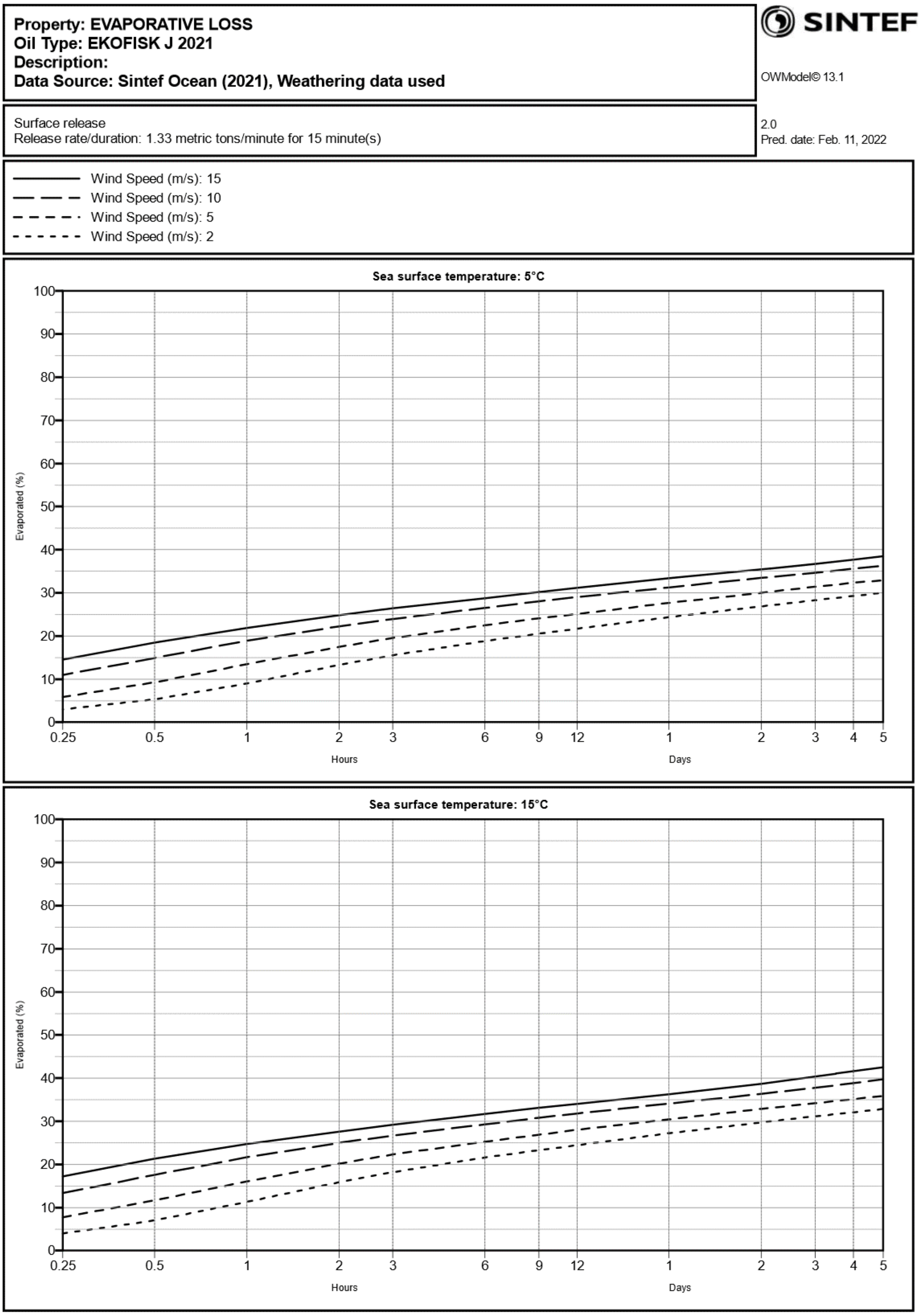
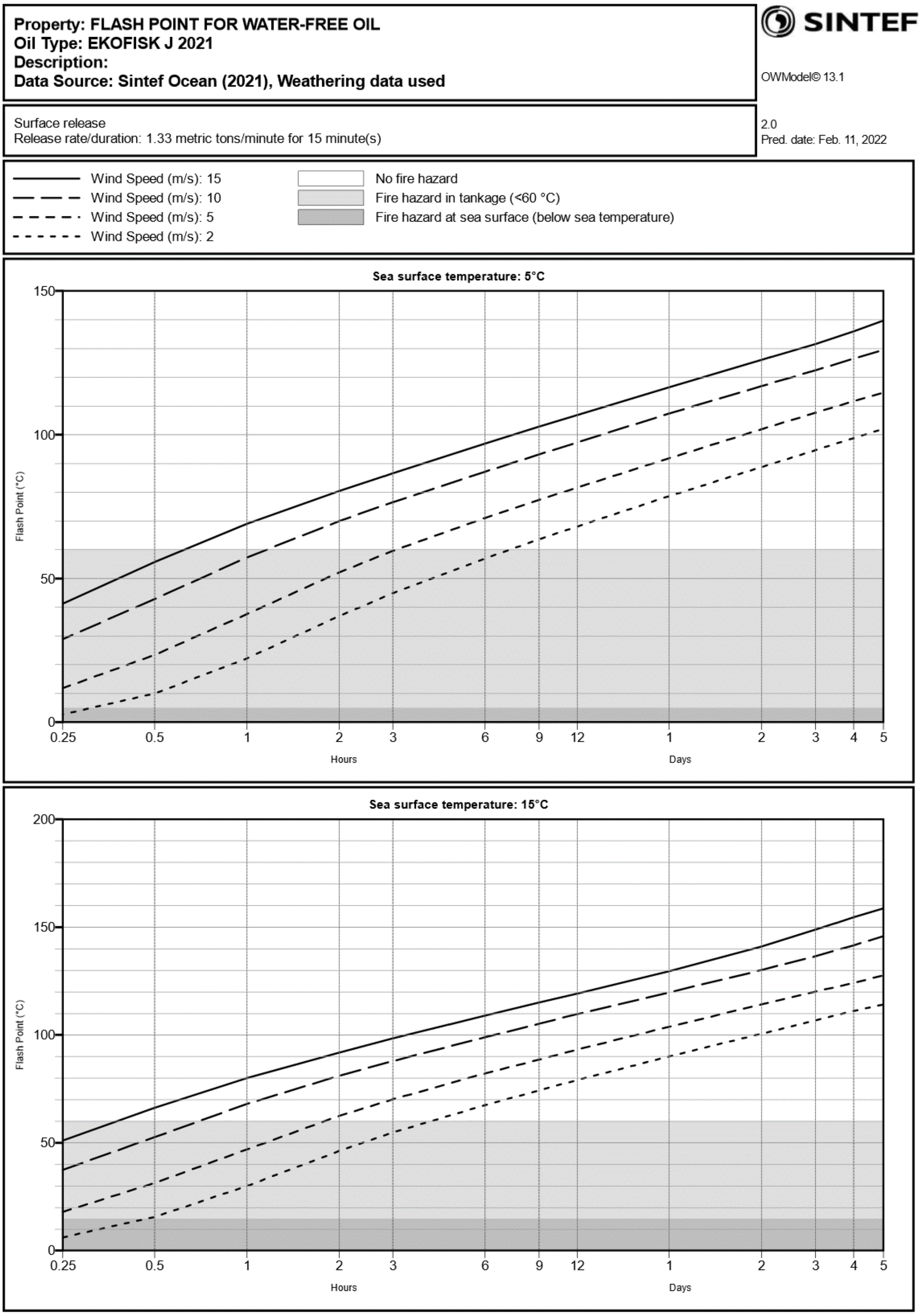


Figure B-10 Evaporative loss of Ekofisk J 2021 crude oil predicted at sea temperatures of 5 °C and 15 °C. Based on physio-chemical properties from lab. study combined with synthetic data set produced by the crude assay (CA)-module in OWM.



Property: FLASH POINT FOR WATER-FREE OIL
Oil Type: EKOFISK J 2021
Description:
Data Source: Sintef Ocean (2021), Weathering data used

OWModel© 13.1

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

2.0
Pred. date: Feb. 11, 2022

Figure B-11 Flash point of Ekofisk J 2021 crude oil predicted at sea temperatures of 5 °C and 15 °C. Based on physio-chemical properties from lab. study combined with synthetic data set produced by the crude assay (CA)-module in OWM.

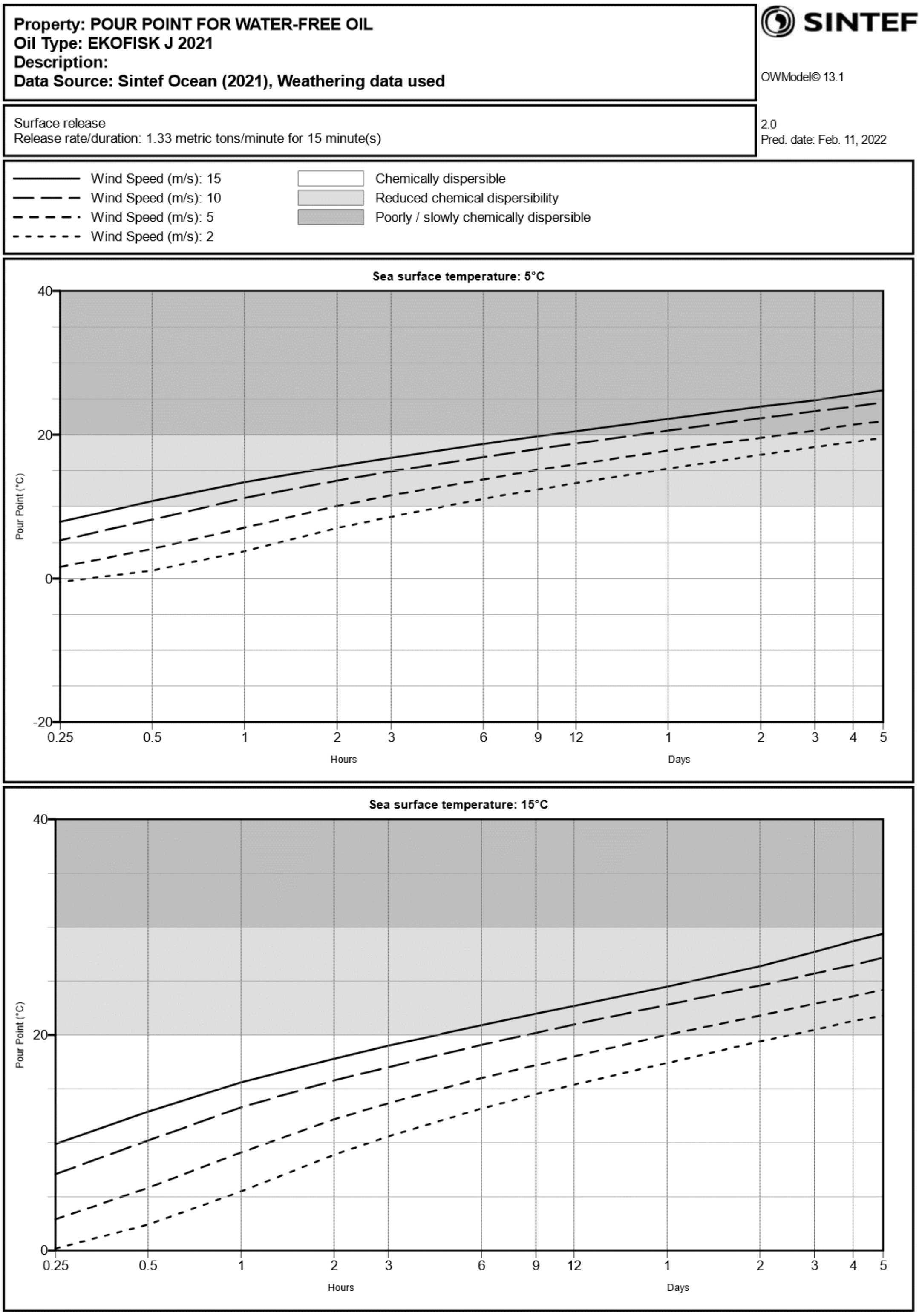


Figure B-12 Pour point of Ekofisk J 2021 crude oil predicted at sea temperatures of 5 °C and 15 °C. Based on physio-chemical properties from lab. study combined with synthetic data set produced by the crude assay (CA)-module in OWM.

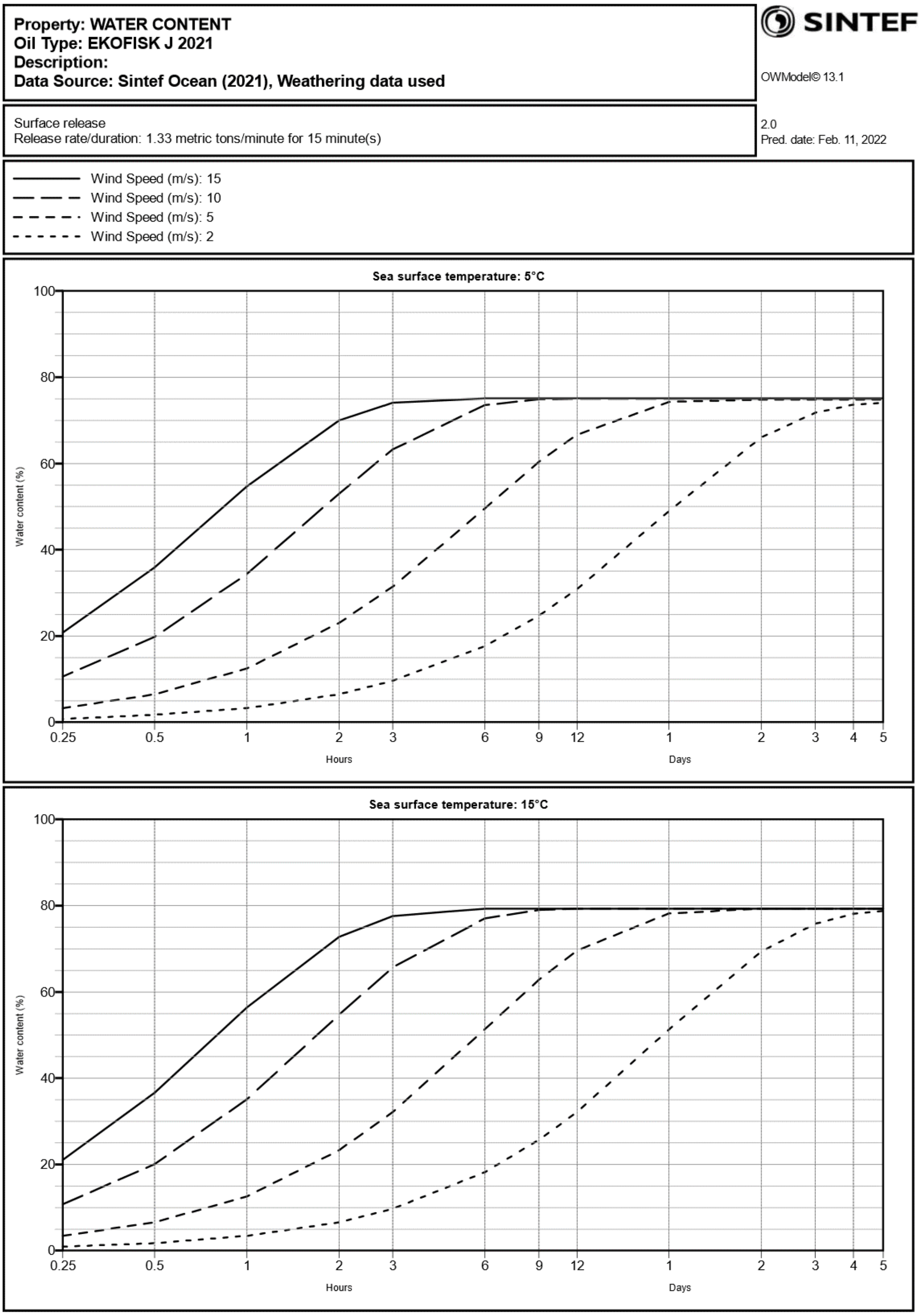


Figure B-13 *Water uptake of Ekofisk J 2021 crude oil predicted at sea temperatures of 5 °C and 15 °C. Based on physio-chemical properties from lab. study combined with synthetic data set produced by the crude assay (CA)-module in OWM.*

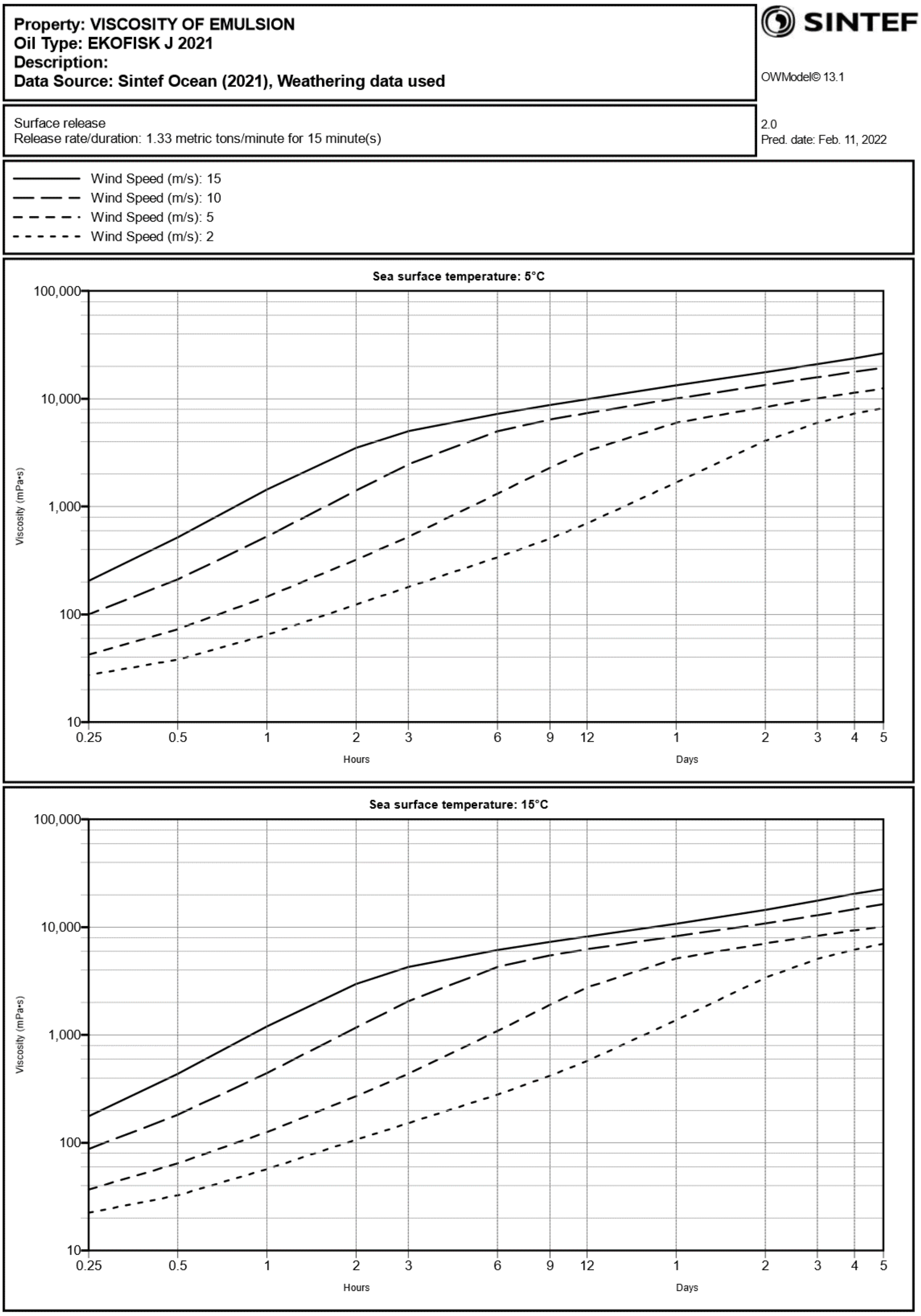


Figure B-14 Viscosity of emulsion of Ekofisk J 2021 crude oil predicted at sea temperatures of 5 °C and 15 °C. Based on physio-chemical properties from lab. study combined with synthetic data set produced by the crude assay (CA)-module in OWM.

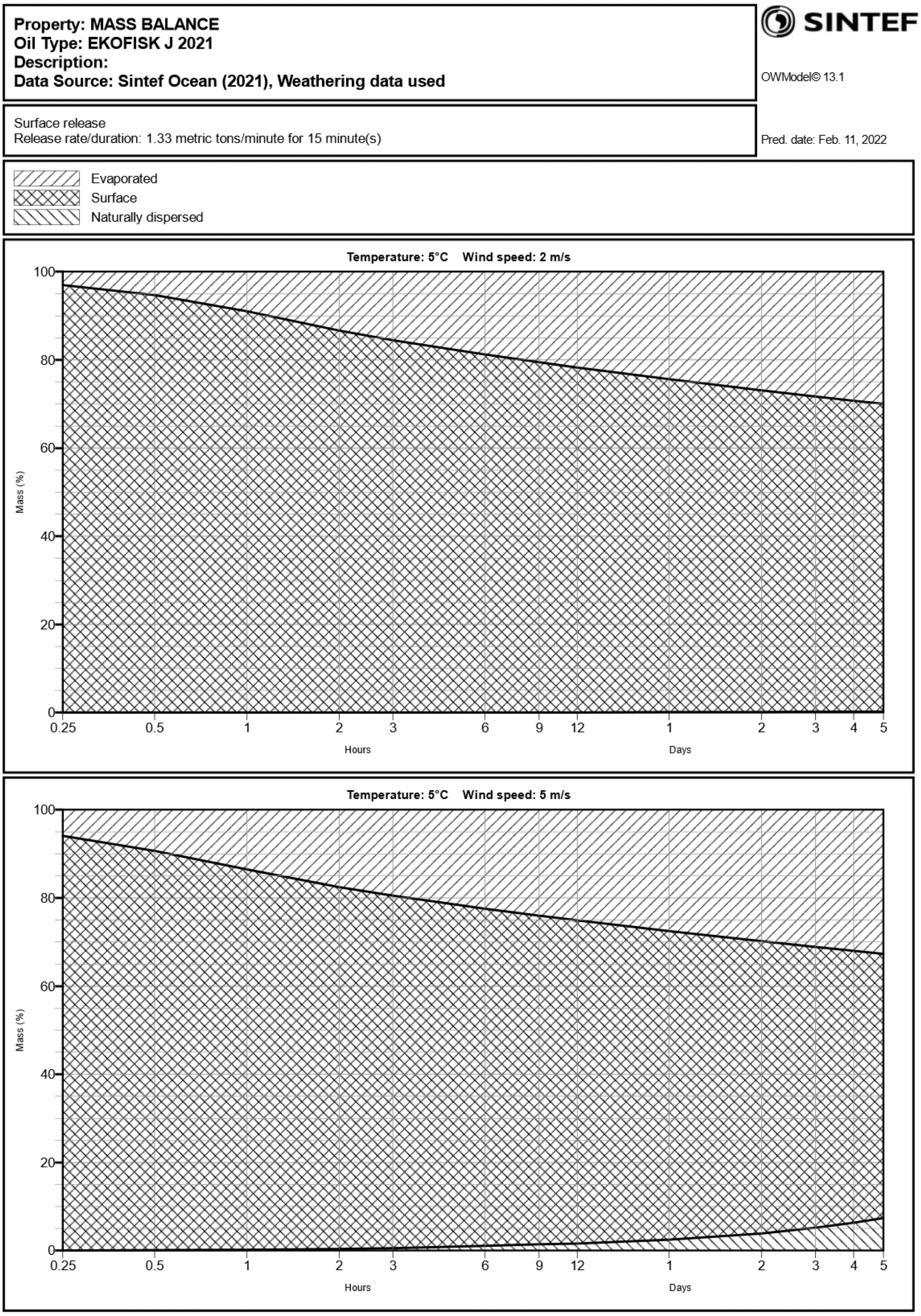
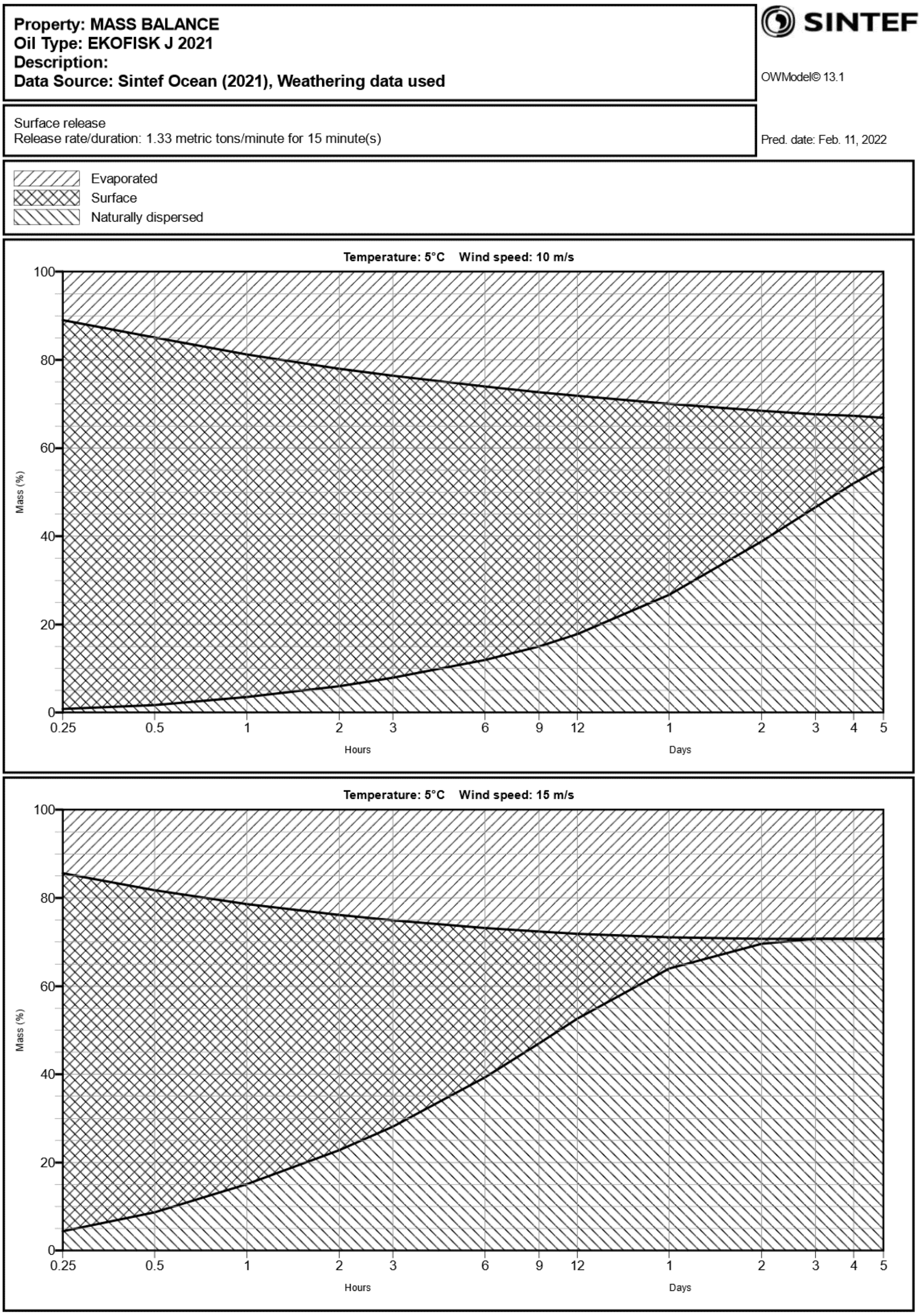


Figure B-15 Mass balance of Ekofisk J 2021 crude oil predicted at sea temperatures of 5 °C and 2 and 5 m/s wind speeds. Based on physio-chemical properties from lab. study combined with synthetic data set produced by the crude assay (CA)-module in OWM.



Property: MASS BALANCE
Oil Type: EKOFISK J 2021
Description:
Data Source: Sintef Ocean (2021), Weathering data used

SINTEF
OWModel© 13.1

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

Pred. date: Feb. 11, 2022

▨ Evaporated
▨ Surface
▨ Naturally dispersed

Figure B-16 *Mass balance of Ekofisk J 2021 crude oil predicted at sea temperatures of 5 °C and 10 and 15 m/s wind speeds. Based on physio-chemical properties from lab. study combined with synthetic data set produced by the crude assay (CA)-module in OWM.*

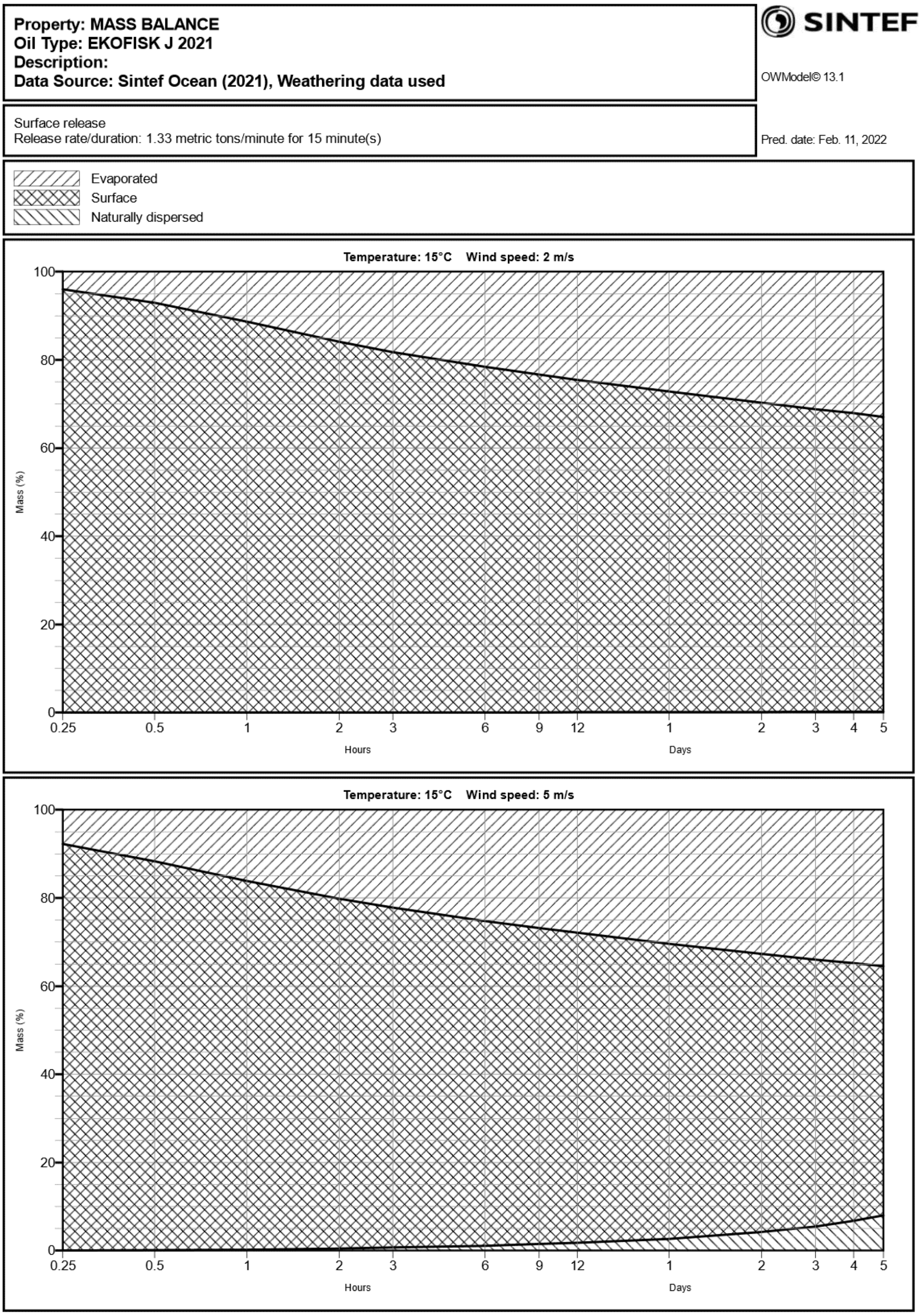


Figure B-17 *Mass balance of Ekofisk J 2021 crude oil predicted at sea temperatures of 15 °C and 2 and 5 m/s wind speeds. Based on physio-chemical properties from lab. study combined with synthetic data set produced by the crude assay (CA)-module in OWM.*

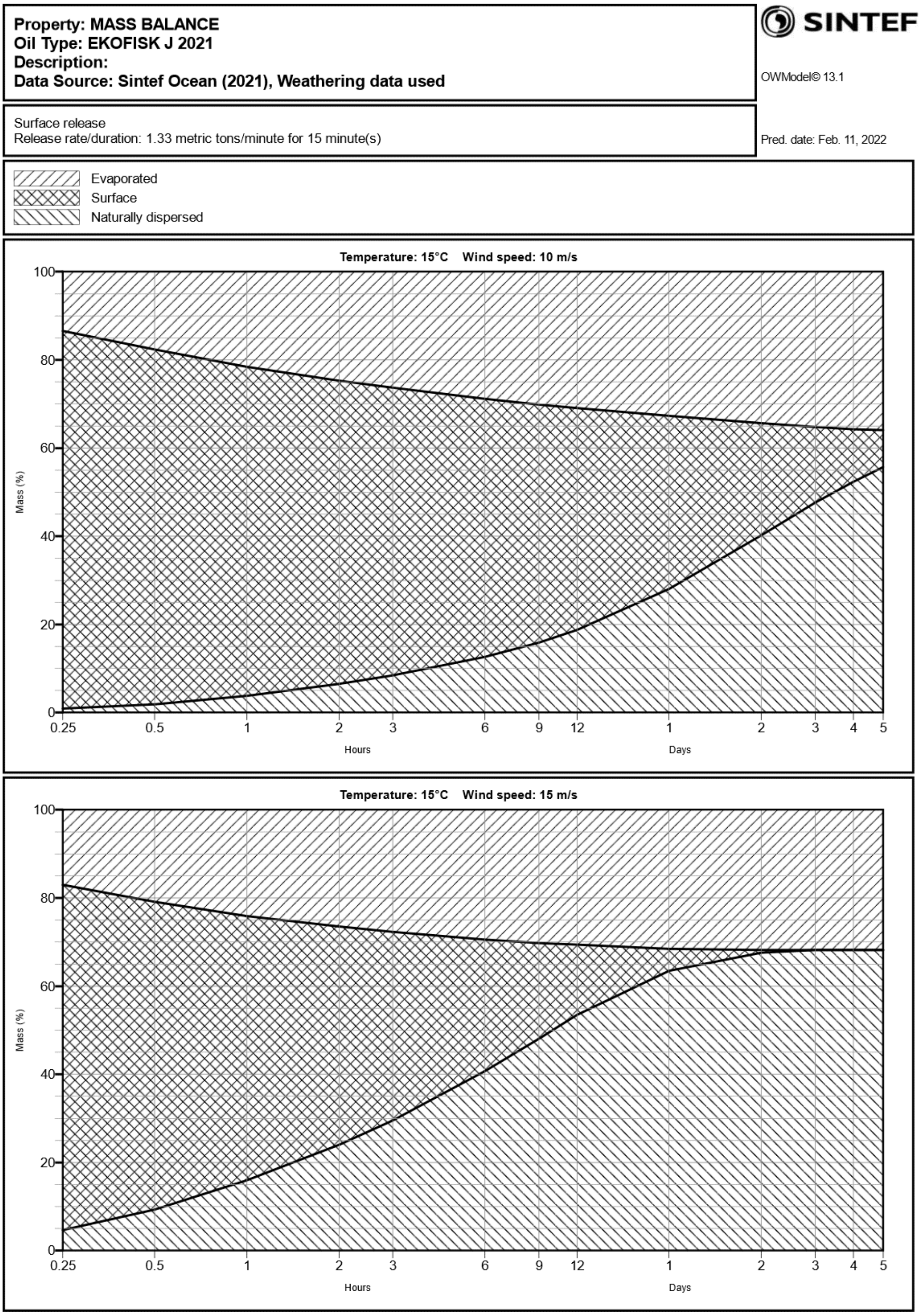


Figure B-18 Mass balance of Ekofisk J 2021 crude oil predicted at sea temperatures of 15 °C and 10 and 15 m/s wind speeds. Based on physio-chemical properties from lab. study combined with synthetic data set produced by the crude assay (CA)-module in OWM.

C Comparison of OWM predictions of TOR II and Ekofisk oils

Weathering predictions of TOR II and other Ekofisk oils are compared, as listed in Table 3-1. The presented comparisons are based on predictions limited to summer conditions (15 °C) and wind speeds of 10 m/s. Oils for comparison:

- TOR II: Full weathering study of oil received 2021
- Eldfisk S 2021: Received 2021. The same blend previously named Eldfisk Kompleks in 2015. The original names have been kept, while the same colour is used (full and stapled line respectively) for the oils (based on lab study results)
- Ekofisk J 2021: Based on physio-chemical properties from lab. study combined with synthetic data set produced by the crude assay (CA)-module in OWM.
- Ekofisk J 2021 Prod.chem: The same physio-chemical properties as Ekofisk J 2021, plus limited data from emulsion testing. Registered as "Low emulsifying crude oil" in OWM, which predicts thinner oil films as expected due to presence of production chemicals.
- Ekofisk Blend 2000: Reference model oil
- Ekofisk J 2015: Oil analysed in 2015. Based lab study results combined with synthetic data set
- Eldfisk Kompleks 2015: oil analysed in 2015. Later renamed to Eldfisk S. Based lab study results combined with synthetic data set
- Eldfisk B 2015: oil analysed in 2015. Based lab study results combined with synthetic data set

C.1 Evaporative loss

Evaporation is one of the natural process that helps removing spilled oil from the sea surface. Among these oils, Eldfisk S (2021) reaches the highest evaporative loss. Ekofisk Blend 2000, Eldfisk B (2015) and Ekofisk J (2021) exhibit the lowest evaporative loss, whilst TOR II, Ekofisk J (2015) and Eldfisk Kompleks (2015) are in between, as shown in Figure C-2.

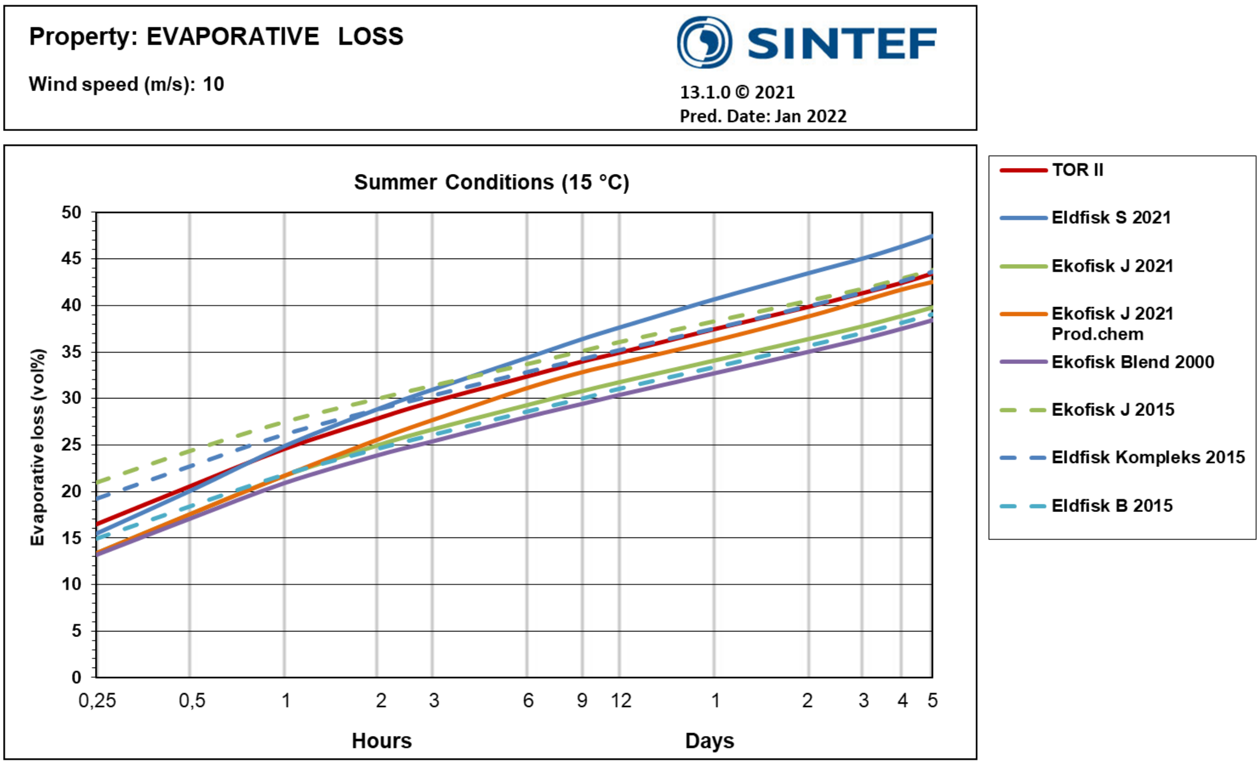


Figure C-2 Predicted evaporative loss at 15 °C and 10 m/s for TOR II and Ekofisk oils.

C.2 Pour point

Pour point depends on the oil's wax content and the amounts of light components that can keep the waxes dissolved in the oil. In addition, high asphaltene content prevents precipitation and lattice formation and lowers the pour point. The pour point of oil may influence the dispersant effectiveness as a high pour point may prevent the dispersant to soak into the oil slick.

TOR II has higher predicted pour point than the other Ekofisk oils, due to higher wax content. Eldfisk Kompleks and Eldfisk B from 2015 have the lowest pour points.

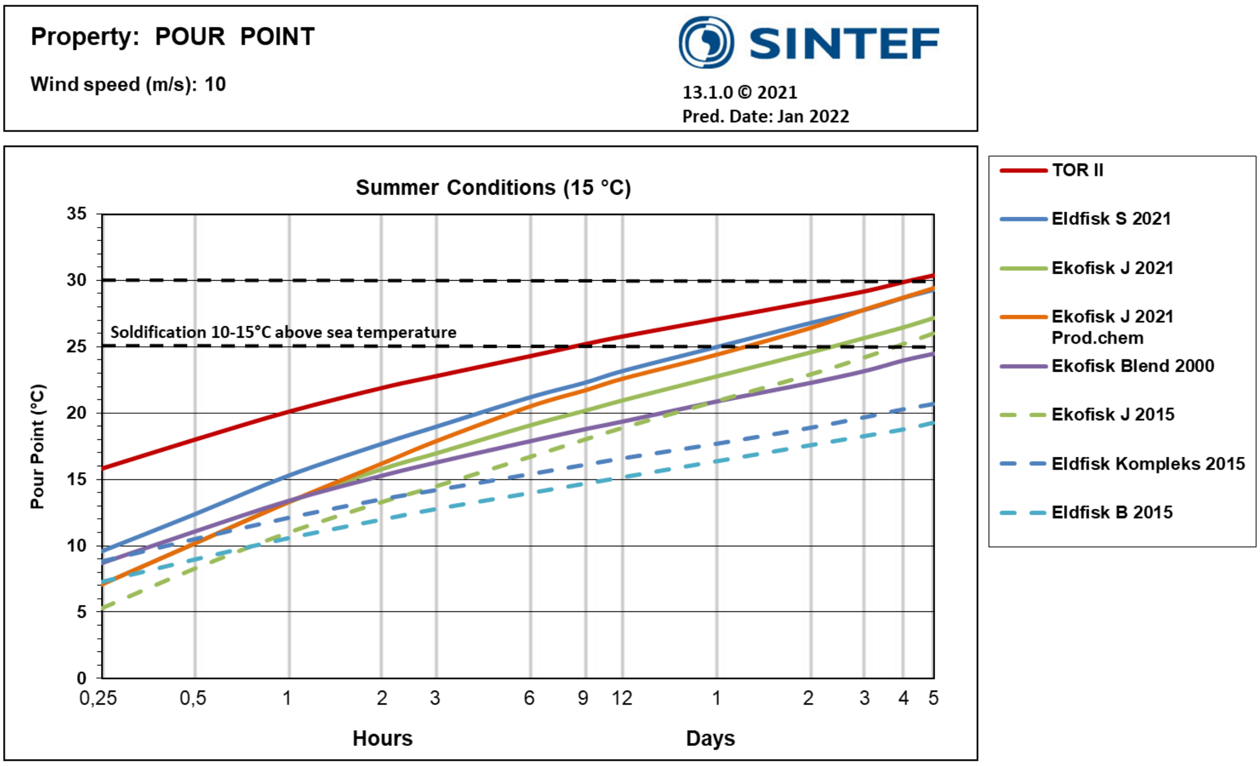


Figure C-3 Predicted pour point at 15 °C and 10 m/s for TOR II compared to other Ekofisk oils.

C.3 Water content

The maximum water uptake of the TOR II and the other Ekofisk oils are shown in Figure C-4, and several of the oils reach a maximum water content of 80 vol.% after 9-12 hours. Ekofisk J from 2015 has, however, a slightly lower water uptake of 75 vol.%. Eldfisk S (2021) has a slower rate of water uptake and reach 80 vol. % after 1 day of weathering.

In addition, Ekofisk J (2021) with production chemicals are also included with input data from the emulsification testing that show a clearly lower maximum water-uptake of about 42 vol.%.

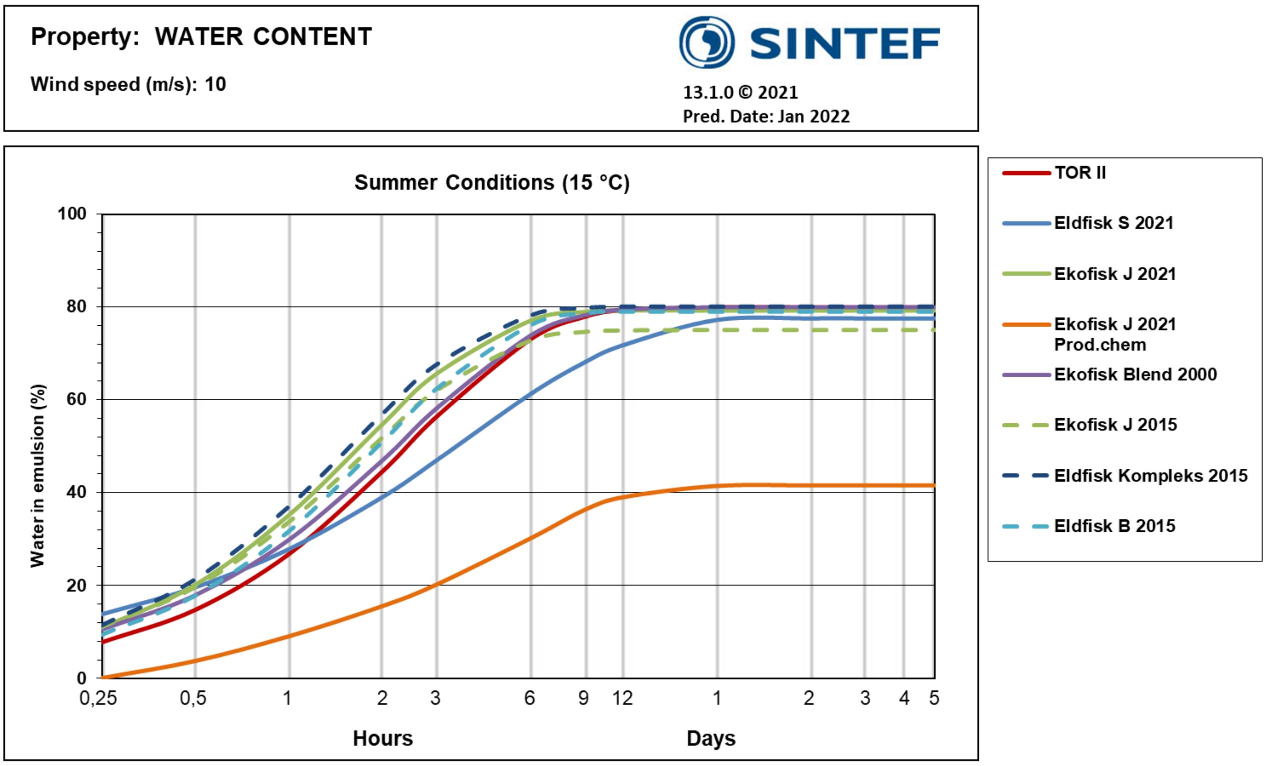


Figure C-4 Predicted water content at 15 °C and 10 m/s for TOR II compared to other Ekofisk oils.

C.4 Emulsion viscosity

Figure C-5 shows the predicted (emulsion) viscosities of TOR II in comparison with the other Ekofisk oils. TOR II has intermediate emulsion viscosity among these oils. Ekofisk J (2021), Eldfisk S (2021) and Ekofisk Blend 2000 reach the highest emulsion viscosities, whilst the Ekofisk oils from 2015 have the lowest viscosities. Overall, the emulsion viscosities are within the expected range for medium paraffinic crude oils.

In addition, Ekofisk J (2021) production chemicals are also included with input data from the emulsification testing that show low emulsion viscosity as a low emulsifying oil.

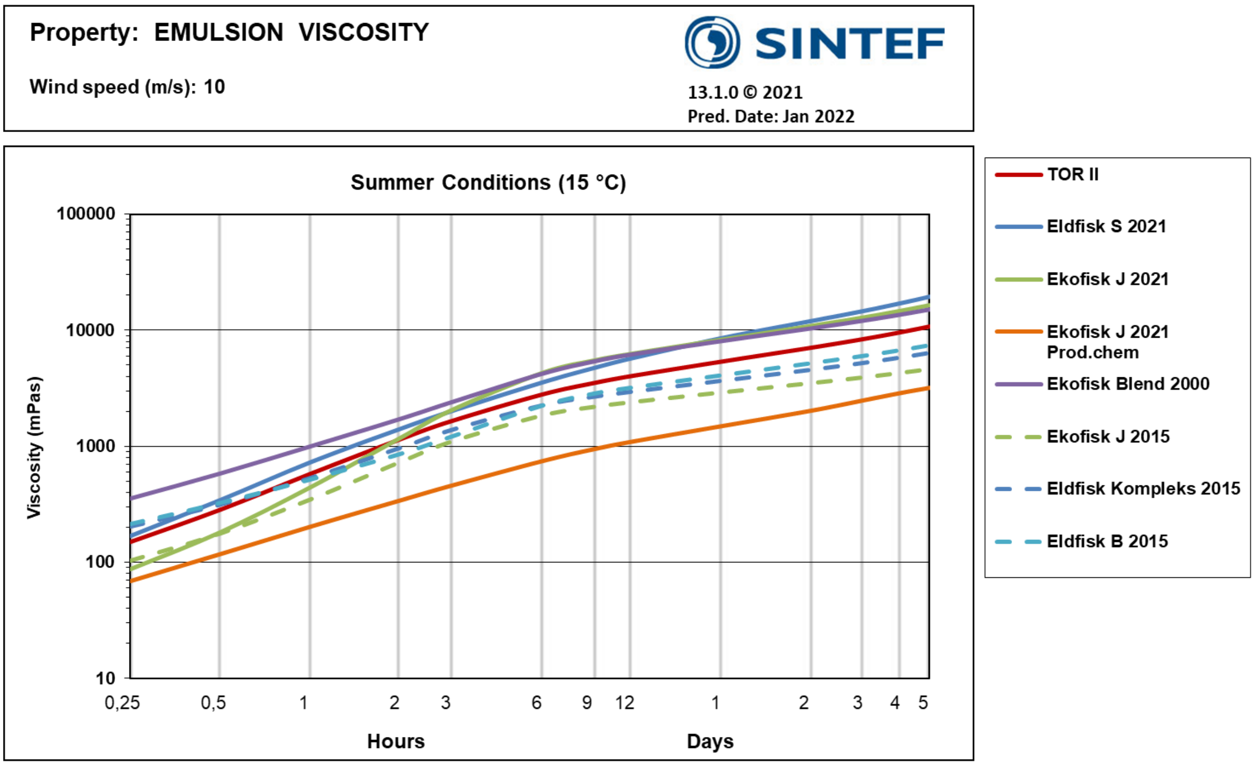


Figure C-5 Predicted emulsion viscosity at 15 °C and 10 m/s for TOR II and other Ekofisk oils.

C.5 Surface oil

Due to evaporative loss and natural dispersion the oil on the sea surface will gradually be reduced. Figure C-6 illustrates the predicted mass balance of TOR II and the Ekofisk oils. Figure C-6 shows very high degree of similarities among these oils, and the oils are persistent on the sea surface with predicted lifetime >5 days for this scenario.

In addition, Ekofisk J (2021) with production chemicals are also included with input data from the emulsification testing that exhibit lower persistence on the sea surface.

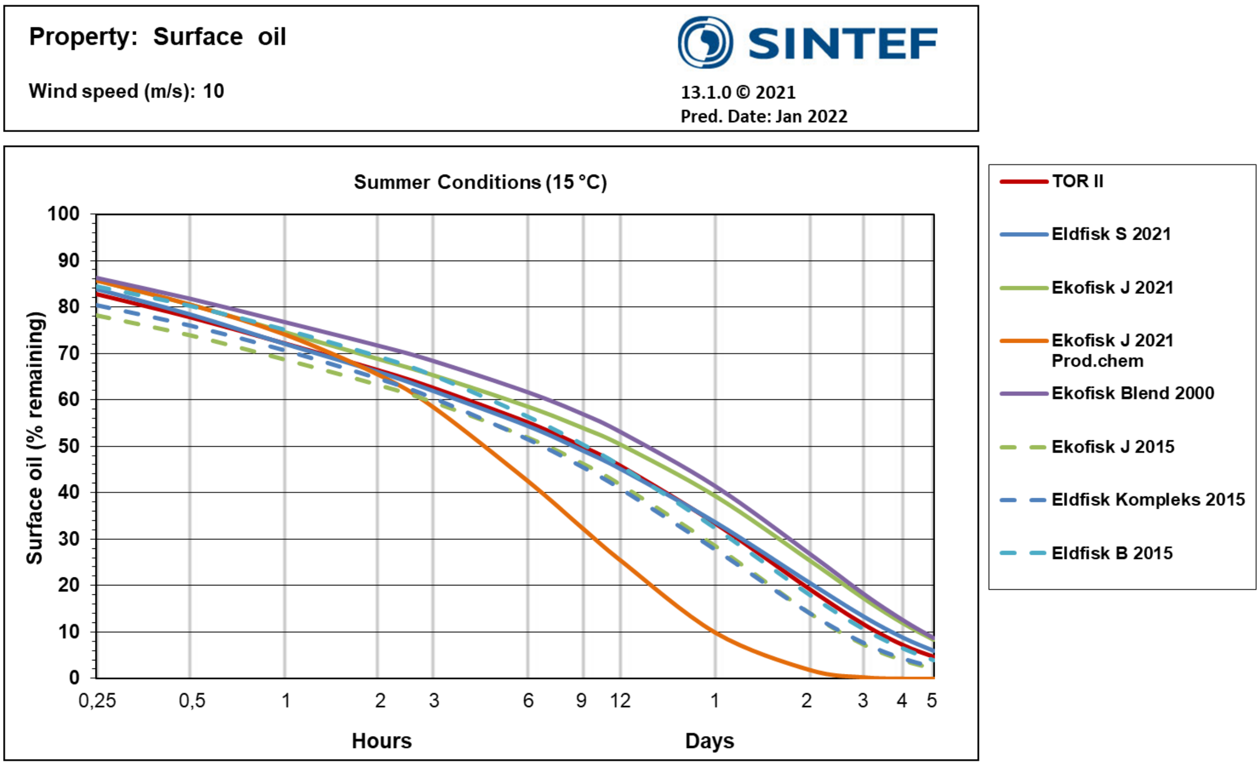


Figure C-6 Predicted remaining surface oil at 15 °C and 10 m/s for TOR II and other Ekofisk oils.

D The behaviour of crude oil on the sea surface

D.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 heteroatomic organics see Figure D-1.

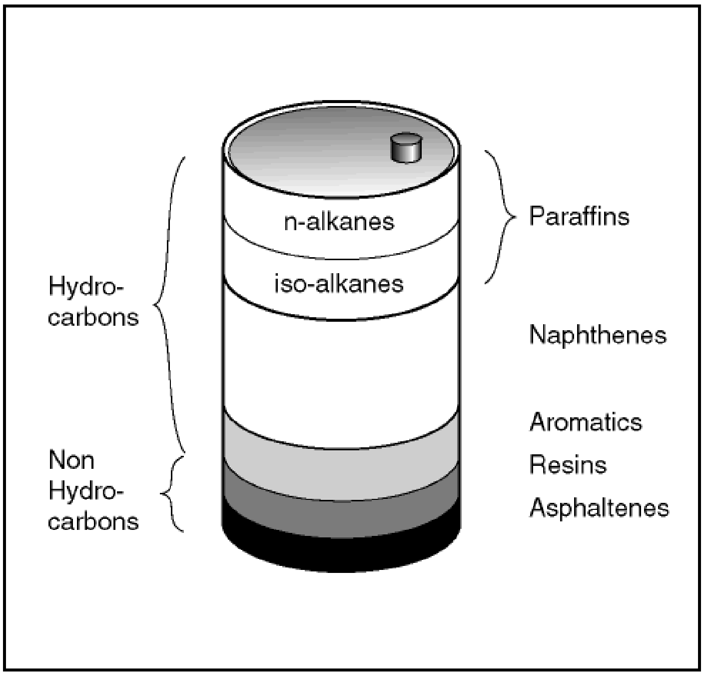


Figure D-1 *The chemical composition of crude oils.*

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.

D.2 Main oil categories related to weathering

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

- Crude oils
- Light oils
- Condensates

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

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

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

D.3 Physical properties of crude oils

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

Density
The density of a crude oil is dependent on the density of all of its components. The density of the hydrocarbons increases with increasing molecular weight. Furthermore, paraffinic oils have lower density than those containing large amounts of high molecular weight aromatics, naphthenes and asphaltenes.
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:

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

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).

D.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.html.The industry often uses centipoise, as the *Poise* is normally too large, 1 Poise = 100 cP and 1 cP = 0.001 N s/m^2= 1 mPa s. 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 in the area of typically 0.9 – 1 g/ml, the units cSt and cP will often have similar values. The 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 quite 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 D-2.

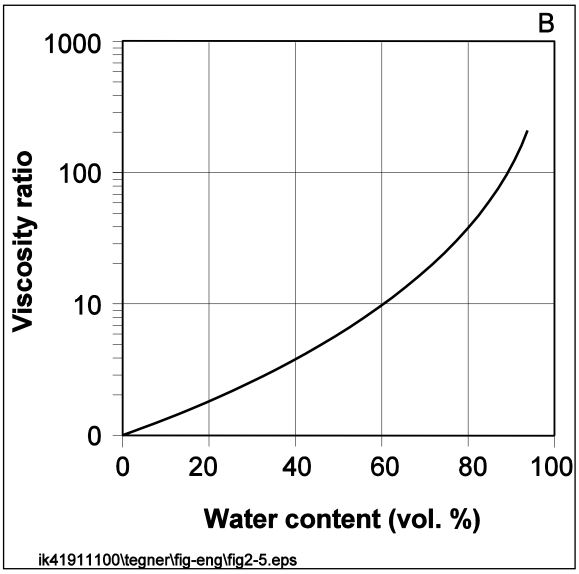


Figure D-2 Example of viscosity ratio as a function of water content.

D.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.

D.3.3 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:
Moving in an oil slick where the oil's flash point is close to or lower than the sea temperature implies a fire and/or explosion hazard.

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.

D.4 The behaviour of crude oil spilled at sea

This chapter gives a general description of the main weathering processes when oil is spilled at sea. There is a number of 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 and the release of oil components into the water column, 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 D-3 illustrates the various weathering processes, and Figure D-4 shows their relative importance over time.

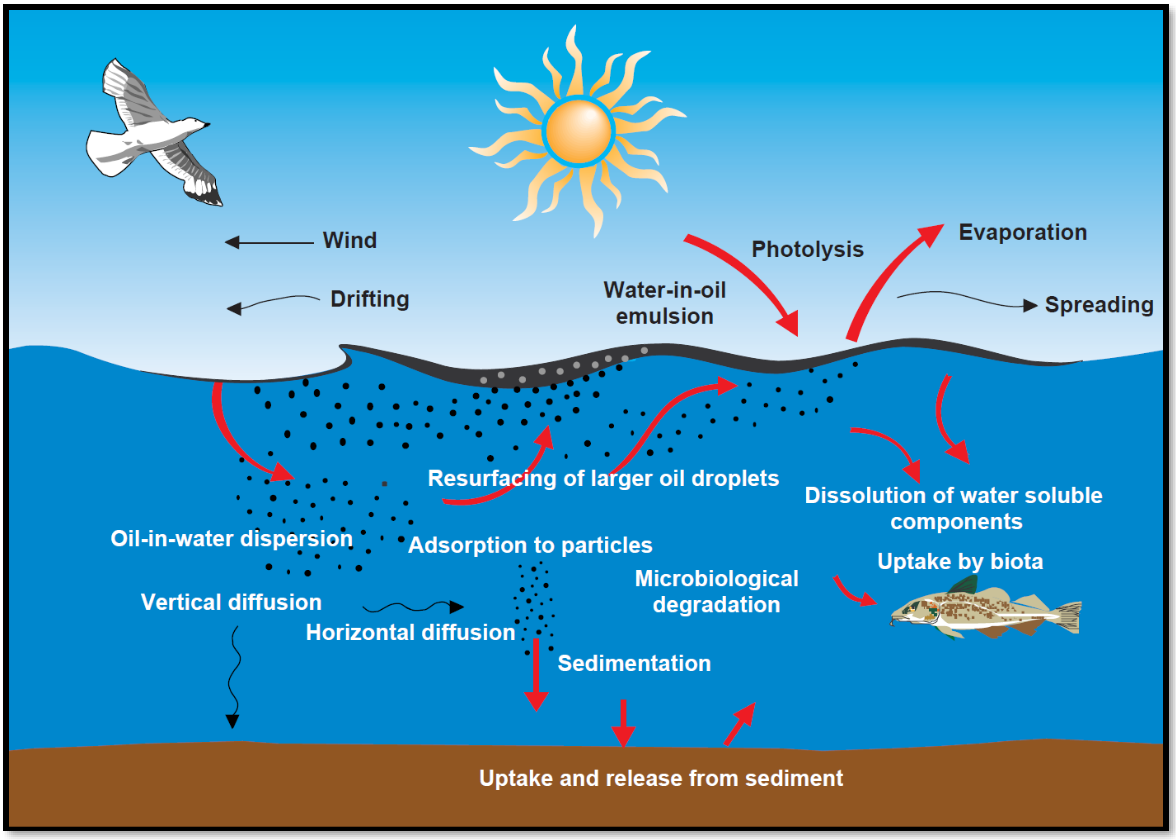


Figure D-3 Illustrating the weathering processes that take place when oil is spilled on the sea surface.

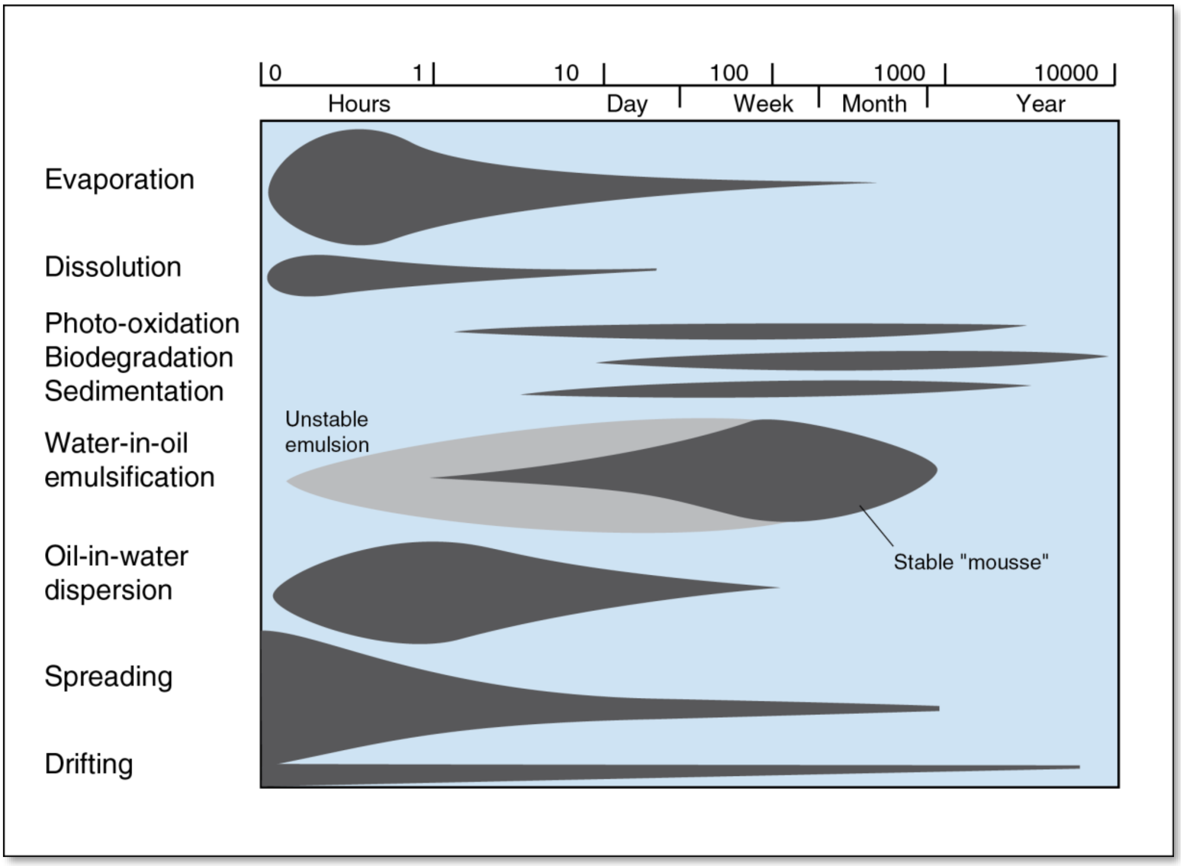


Figure D-4 Weathering processes' relative importance over time. Note: logarithmic scale.

D.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.

D.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 retarded if the oil's pour point is 10-15°C below the sea temperature.

Oceanographic conditions (e.g., wind, waves and currents) affect the spreading process. The oil slick will be broken into windrows aligned in the direction of the wind, see Figure D-5. The thickness of the oil slick varies, often differing by a factor of several thousand. Experience has shown that e.g., 90 vol.% of the oil spilled may consist of patches of w/o emulsion with a film thickness of 1 to 5 mm, which often constitutes less than 10%

of the total oil slick area. The remaining 5-10 vol. % usually covers 90% of the spill area in the form of a sheen (<1 µm oil thickness).

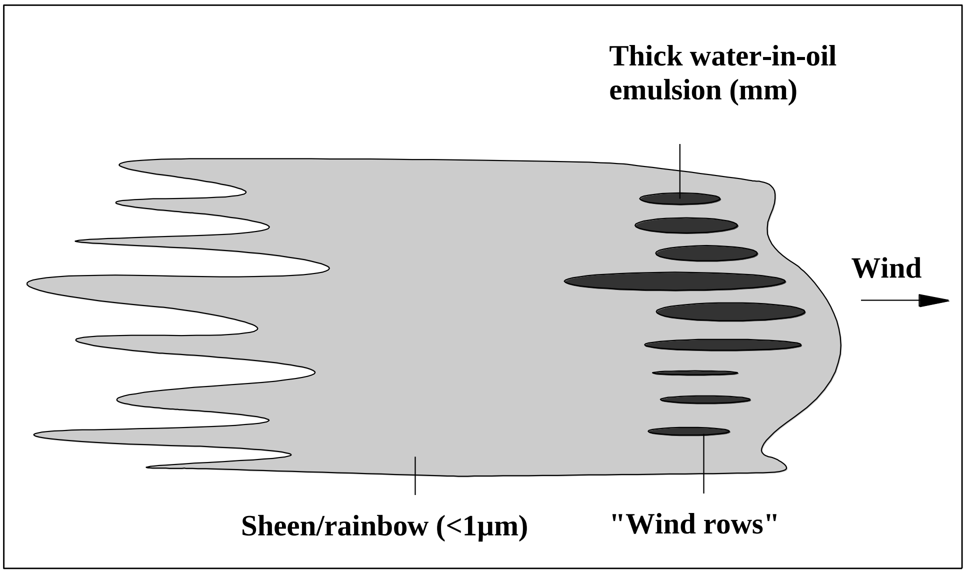


Figure D-5 *The spreading of oil spilled on the sea surface and the distribution within the oil slick.*

D.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 D-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.

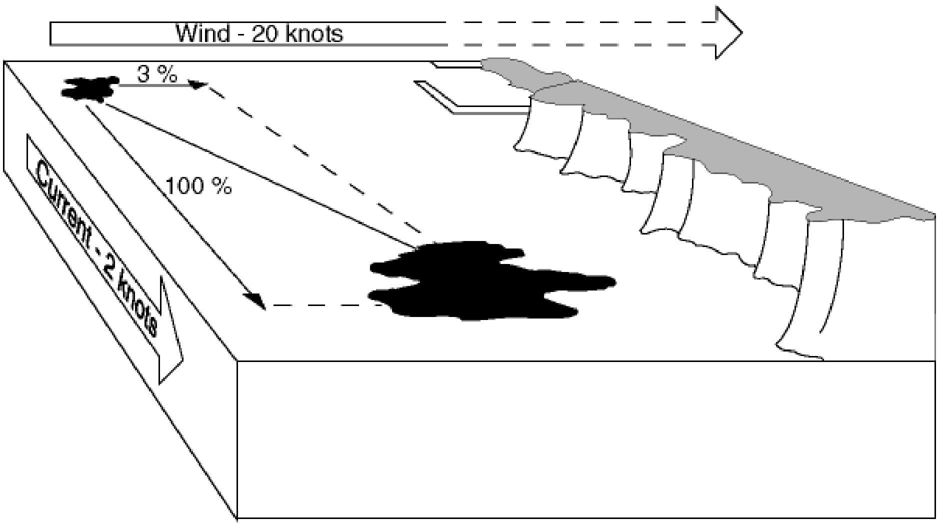


Figure D-6 *An illustration showing how wind and current can influence the drifting of an oil slick*

D.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 D-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.

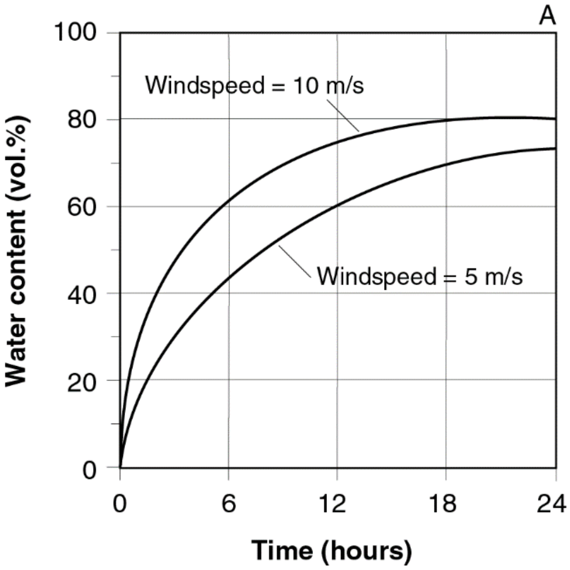


Figure D-7 Example of how weather conditions influence the w/o emulsion formation for typical oils.

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 of time, the emulsion may only contain small water droplets with diameters of 1 to 10 µm, yielding a more stable emulsion.

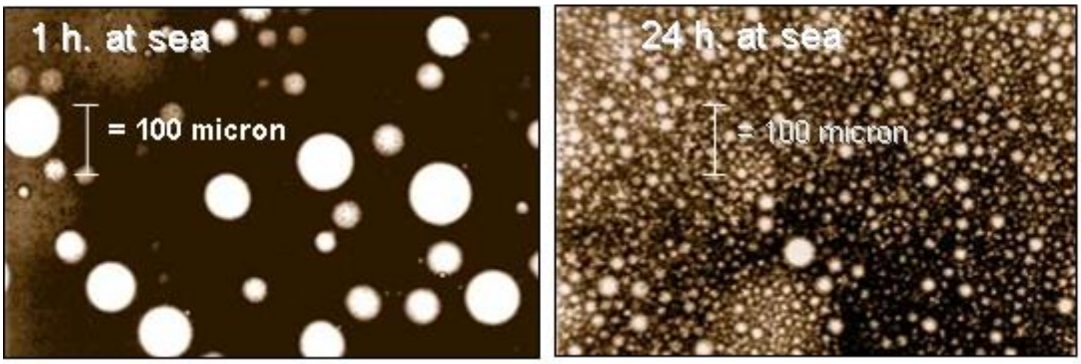


Figure D-8 Microscope pictures of w/o emulsion after (A) 1 h. and (B) 24 h. in a rotating cylinder.

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 D-9.

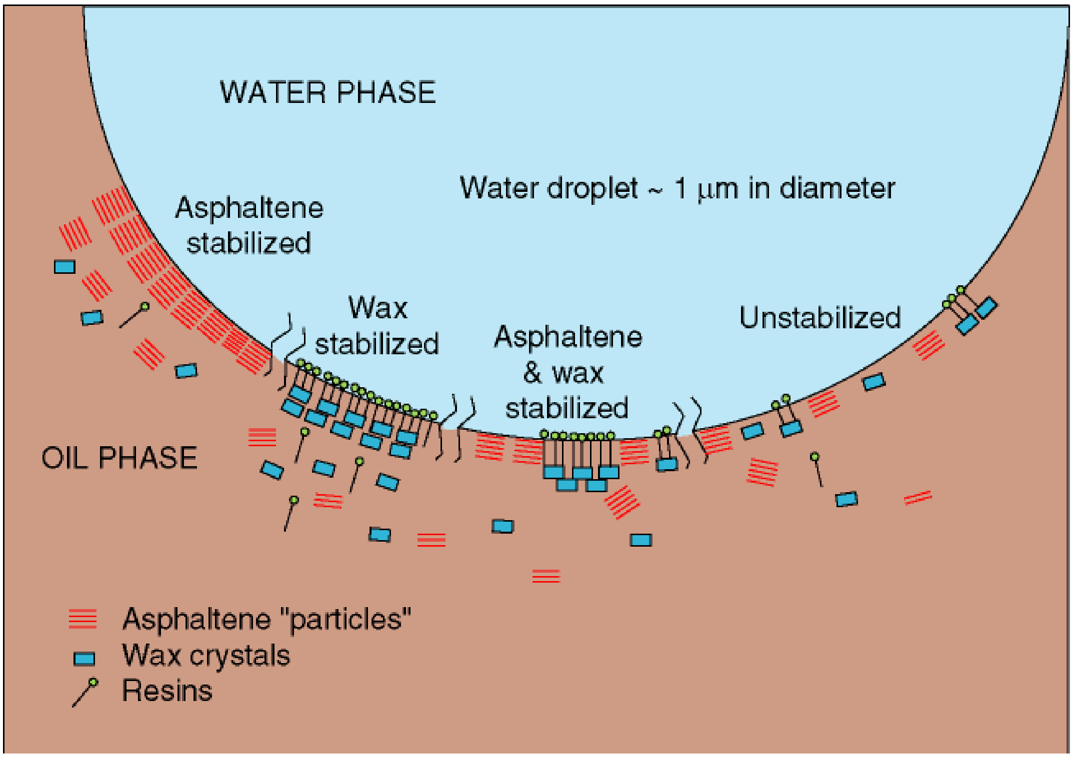


Figure D-9 Interfacial layer stabilized by wax and asphaltenes in w/o emulsion.

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.

D.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 droplets of diameters, typically 1 µm - 1 mm, which are then mixed into the water mass. The largest oil droplets will resurface and form a thin oil film (typically <50 µm) behind the oil slick. 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 the 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 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. The dispersant reduces the interfacial tension between water and oil and thus promotes dispersion. When effective chemical dispersion is achieved, small oil droplets are formed with diameters typical from 5 to 100 µm. These are retained in the upper layers of the water column by the prevailing turbulence of wave action.

D.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.

D.4.7 Photo-oxidation

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

D.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.

D.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.

D.4.10Deep 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 D-10. This was observed both during the "DeepSpill" experiments in 2000 (Figure D-11) and the DWH oil spill in 2010 (Figure D-12). This emulsification will be dependent on oil properties and environmental conditions, such as temperature and sea state.

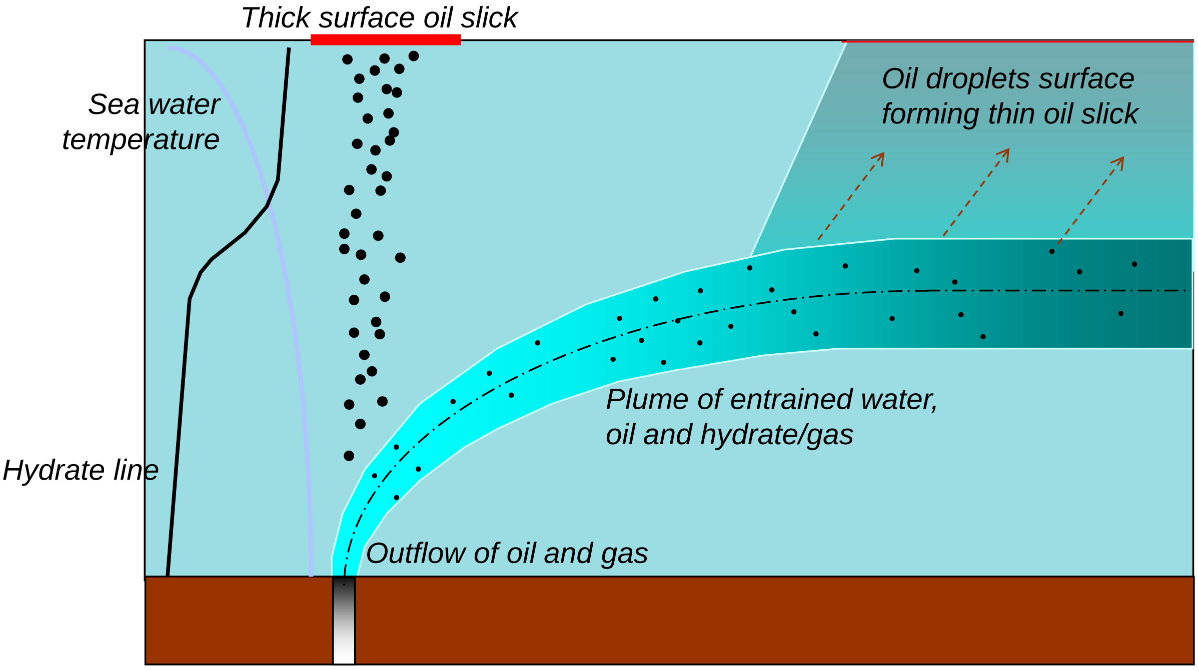


Figure D-10 Illustration of possible creation of thick surface oil slick (> 200 µm) from deep water release of oil.

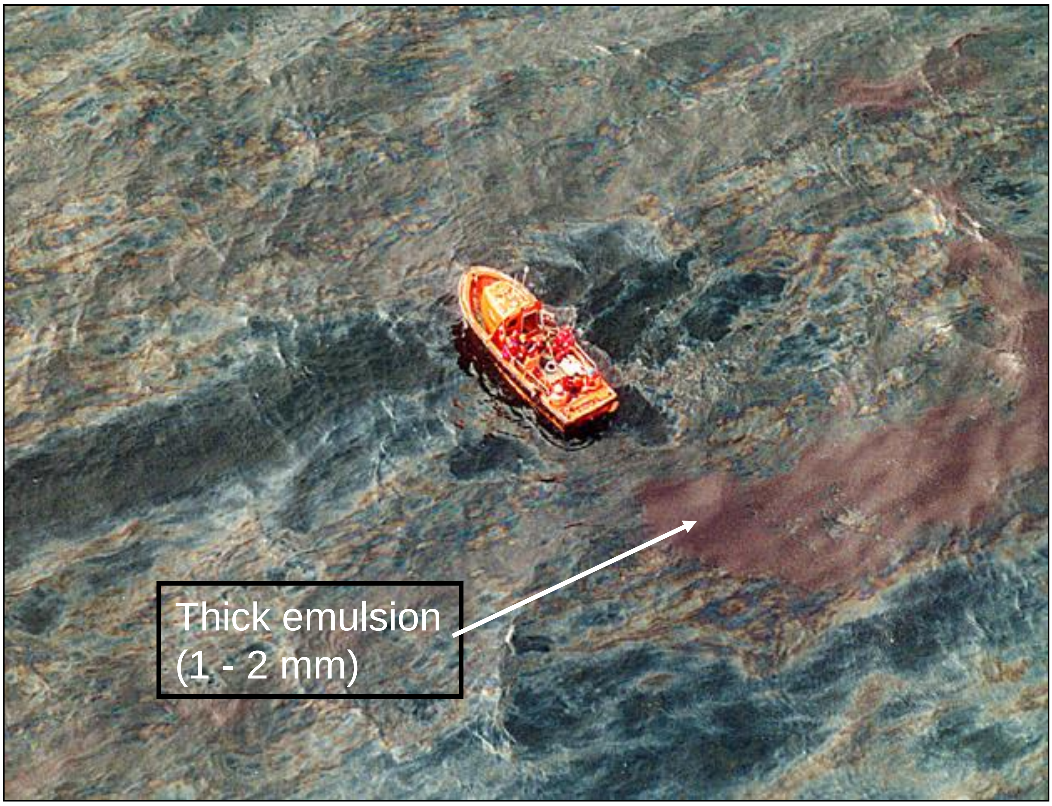


Figure D-11 Surface oil slick (initial thickness > 200 µm) from the experimental deep-water release DeepSpill in 2000. Surface oil is emulsifying similar to an oil slick from a surface batch release (from Leirvik et al., 2011).

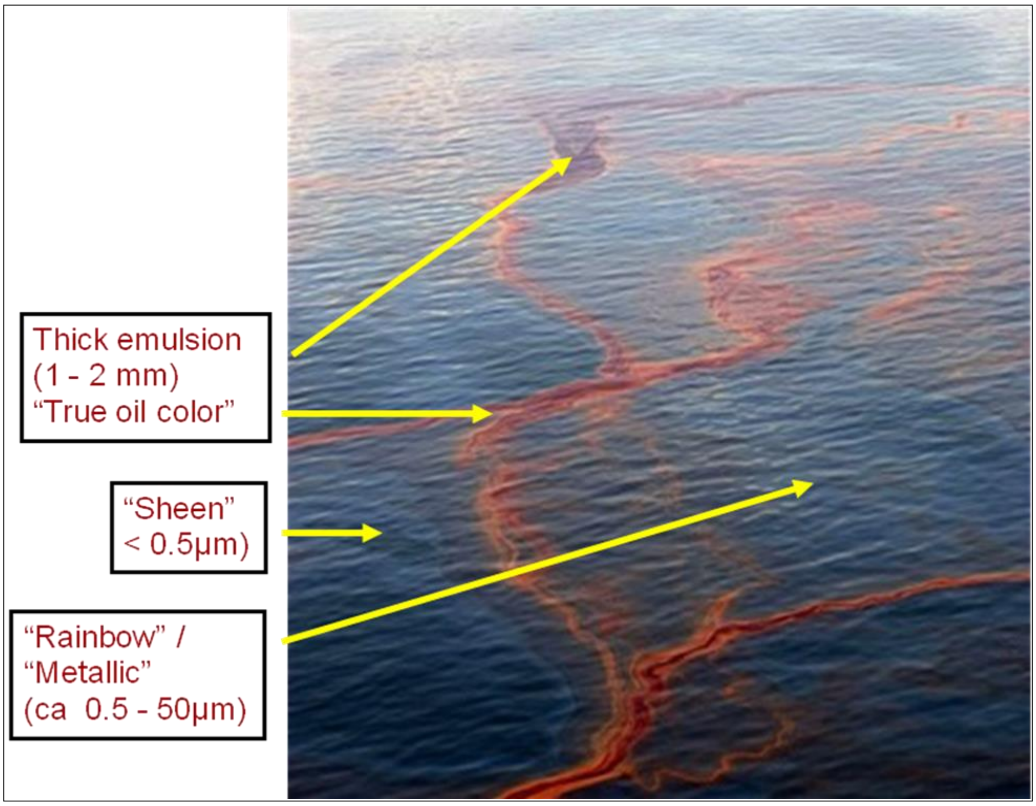


Figure D-12 Surface oil slick (initial thickness > 200 µm) from the DWH deep water release. Surface oil is emulsifying similar to an oil slick from a surface batch release.

D.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 D-13, Figure D-14 and Rye et al, 1997). This surface oil slick will in many cases be too thin to emulsify (< 200 microns) and evaporation and natural dispersion will be the predominant weathering processes.

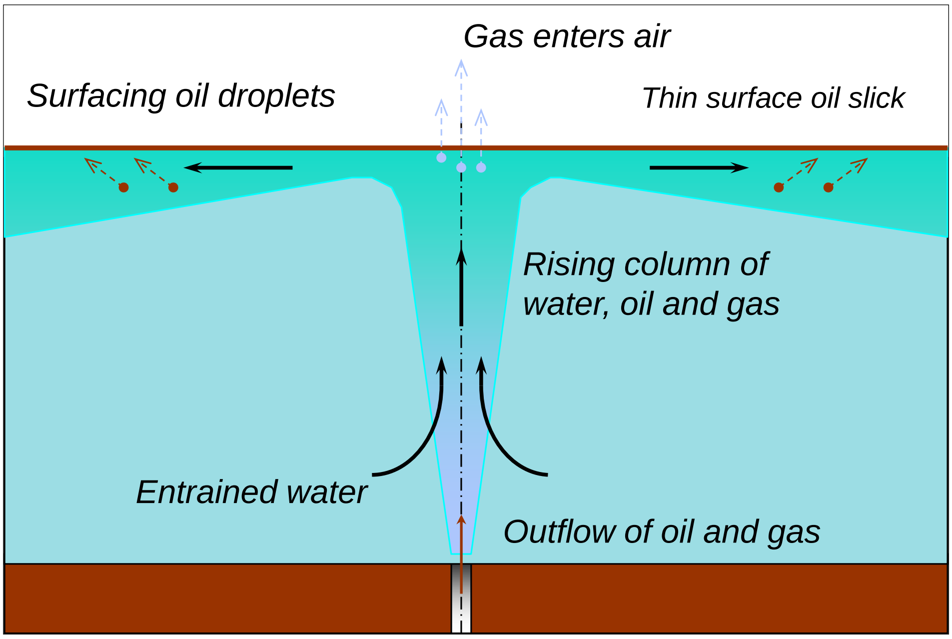


Figure D-13 Illustration of possible creation of thin surface oil slick (< 200 μm) from a shallow subsurface release (<500 m).

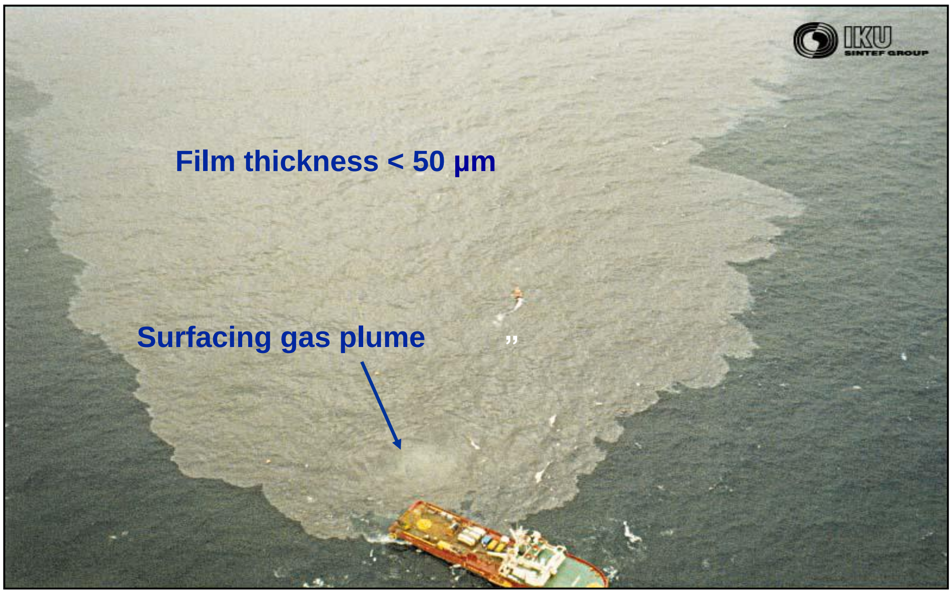


Figure D-14 Surface oil slick (< 50 μm) from experimental subsurface release at 106 m in 1996. The surface oil did not emulsify and had a very limited lifetime (hours) due to the low film thickness and high rate of natural dispersion (even at < 10 m/s wind).

E Experimental setup

E.1 Oil samples and test temperature

SINTEF Ocean received 27.09.2021 Jerry cans of TOR II , Eldfisk S and Ekofisk J. The oil samples were registered in LIMS and given unique SINTEF ID, as given in Table D-1.

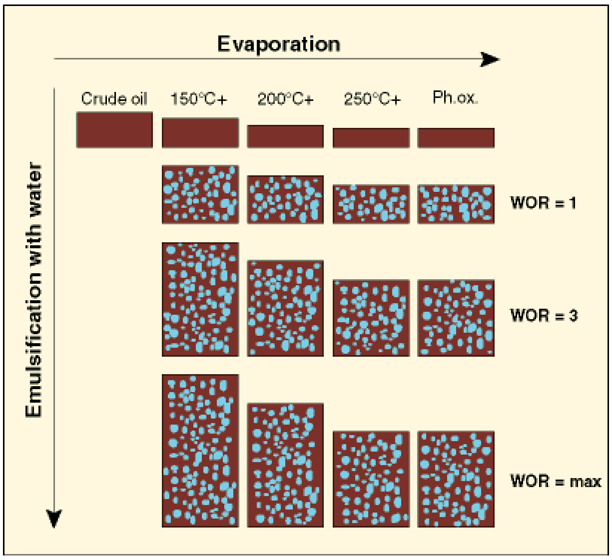
Check of free-water in the cans and water content in the oil phase (Karl Fisher titration). Important for HSE and risk assessment prior to the topping/distillation step (water limit < 2 vol. %) to simulate evaporative loss at sea by topping/distillation. The studies were performed at 13 °C for all the three oils.

Table E-1 Oil samples received 27.09.2021

Oil type	**SINTEF ID**	**Type of barrel**	**Total volume. (L)**
TOR II	2021-6958	Jerry,20L	40
Eldfisk S	2021-6959	Jerry,20L	20
Ekofisk J	2021-6960	Jerry,10L	20

E.2 Small-scale laboratory testing

To isolate and map the various weathering processes at sea, the oils were exposed to a systematic, stepwise procedure developed at SINTEF (Daling et al., 1990). The general procedure is illustrated in Figure E-1.



WOR: Water to Oil Ratio

WOR=1: 50 vol.% water
WOR=3: 75 vol.% water
WOR=max: the maximum water content

Figure E-1 Small-scale laboratory weathering flow chart of oil.

E.2.1 Evaporation

The evaporation procedure used is described in Stiver and Mackay (1984). Evaporation of the lighter compounds from the fresh oil were 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.

E.2.2 Physical and chemical analysis

The viscosity, density, pour point and flash point 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 *E-2* and Table E-3.

Table E-2 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
Interfacial tension (IFT)	-	-

Table E-3 Analytical methods used to determine the chemical properties.

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

Chemical characterization by GC/FID and GC/MS

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

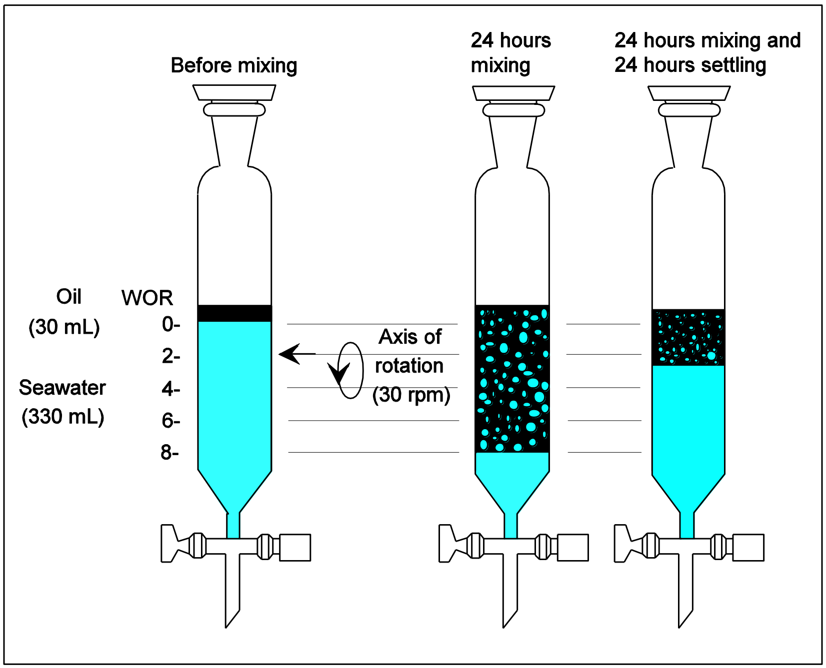
The volatile components were in the range of nC_5-nC_{10} and were quantified by use of PT-GC-MS (Purge and Trap Gas chromatograph Mass Spectrometer operating in full-scan mode, and using a modified version of the EPA 8260 analysis method)

E.2.3 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 E-2. 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.



6621/handbøker/grafisk/fig-eng/3skilletrakter.eps

Figure E-2 Principle of the rotating cylinder method.

E.2.4 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 (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 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, produces a circular wave motion. The sample of the oily water is taken under dynamic conditions after a mixing period of 5 min.

Both IFP and MNS test apparatus is shown in Figure E-3.

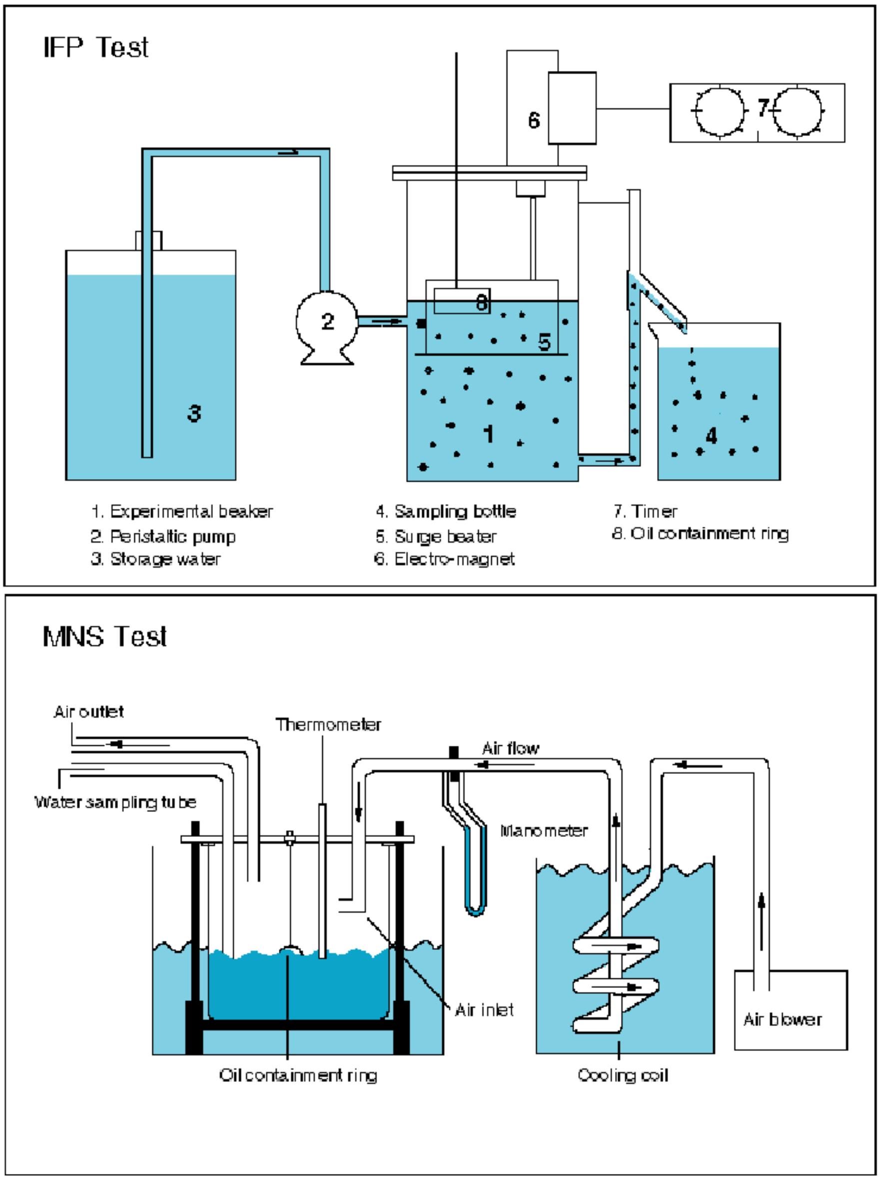


Figure E-3 *IFP and MNS test apparatus.*

F Input data to SINTEF Oil Weathering Model (OWM)

The laboratory data at 13 °C for TOR II, Ekofisk J 2021, Ekofisk J 2021 Prod.chem and Eldfisk S 2021 used as input to the SINTEF OWM are given in tables in subchapters below.

F.1 TOR II

Table F-1 Physico-chemical properties for TOR II at 13 °C.

Properties of fresh oil	**Value**
Density (g/ml)	0.8344
Pour point (°C)	6
Reference temperature (°C)	13
Viscosity at ref. temp. (mPa·s = cP) *	20
Asphaltenes (wt. %)	0.06
Flash Point (°C)	-
Wax Content (wt. %)	7.07
Dispersible for visc. <**	-
Not dispersible for visc. >	9000
Maximum water uptake (%)	-

** Measured at shear rate 10s^{-1}*

*** Not determined*

- No data available

Table F-2 True boiling point (TBP) curve for TOR II. The TBP is based on results simulated distillation analysis performed by Intertek Sunbury (report no. 4359075), converted from mass % to vol. % by SINTEF Ocean. No further adjustment of TBP was necessary.

Temperature (°C)	**Volume (%)**
28	1.6
72	6.7
101	12.6
158	23.6
265	44.2
365	63.6
488	82.1
583	91.0
668	95.4
730	97.1

Table F-3 Lab weathering data for TOR II at 13 °C.

Property	**Fresh**	**150°C+**	**200°C+**	**250°C+**
Boiling Point Temp. (°C)	-	194.95	266.85	310.65
Vol. Topped (%)	0	19.4	33.8	43.3
Weight Residue (wt. %)	100	83	69.4	60.2
Density (g/ml)	0.834	0.858	0.875	0.885
Pour point (°C)	6	18	24	27
Flash Point (°C)	-	43.5	92	123
Viscosity of water-free residue (mPa·s =cP)	20	144	576	2458
Viscosity of 50% emulsion (mPa·s = cP)	-	694	1673	3353
Viscosity of 75% emulsion (mPa·s = cP)	-	778	2936	5774
Viscosity of max water (mPa·s = cP)	-	859	2223	5143
Max. water cont. (vol. %)	-	79.5	84.2	78.1
(T1/2) Halftime for water uptake (hrs)	-	0.23	0.35	0.27
Stability ratio	-	0.95	0.94	0.96

** Measured at shear rate 10 s^{-1}*

- No data

F.2 Eldfisk S

Table F-4 Physico-chemical properties for Eldfisk S at 13 °C.

Properties of fresh oil	**Value**
Density (g/ml)	0.842
Pour point (°C)	0
Reference temperature (°C)	13
Viscosity at ref. temp. (mPa·s = cP) *	18
Asphaltenes (wt. %)	0.1
Flash Point (°C)	-
Wax Content (wt. %)	3.99
Dispersible for visc. <**	1000
Not dispersible for visc. >**	10000
Maximum water uptake (%)	-

** Measured at shear rate 10s^{-1}*

*** Estimated based on laboratory results*

- No data available

The true boiling point curve of Eldfisk S 2021 is based on an extended cut distribution provided by Intertek WestLab from pressurised oil sample. The data have been adjusted compensate for a higher content of light components compared to the non-pressurised oil sample SINTEF Ocean received, and to match topping results from the testing. The Intertek WestLab oil sample had a lower density compared to the SINTEF Ocean sample, verifying a higher content of lighter components.

Table F-5 True boiling point (TBP) curve for Eldfisk S.

Temperature (°C)	Volume (%)
47	4.5
69	7
93	10
125	16
173	27
213.3	36
257.7	47
297.2	55
337	62.43
370	67.65
450	76.58

Table F-6 Lab weathering data for Eldfisk S (20219 at 13 °C.

Property	Fresh	150°C+	200°C+	250°C+
Boiling Point Temp. (°C)	-	193.53	261.35	321.6
Vol. Topped (%)	0	19	32.5	44.1
Weight Residue (wt. %)	100	83.8	71.2	60
Density (g/ml)	0.84204	0.87216	0.88851	0.90595
Pour point (°C)	0	11**	18**	24
Flash Point (°C)	-	40.5	82.5	126.5
Viscosity of water-free residue (mPa·s =cP)	18	116	566	2493
Viscosity of 50% emulsion (mPa·s = cP)	-	415	1528	3787
Viscosity of 75% emulsion (mPa·s = cP)	-	759	2765	7227
Viscosity of max water (mPa·s = cP)	-	549	1900	6723
Max. water cont. (vol. %)	-	41.2	59.5	75.8
(T1/2) Halftime for water uptake (hrs)	-	0.14	0.51	0.37
Stability ratio	-	1.0	1.0	1.0

** Measured at shear rate 10 s^{-1}*

***Estimated based on density and pour point of fresh and 250°C+*

- *No data*

F.3 Ekofisk J

Three different profiles have been entered in OWM for Ekofisk J received in 2021. One is based on the Crude Assay in data only (TBP, fresh oil data for density, viscosity, pour point and wax- and asphaltene content), and is called Ekofisk J 2021 CA. This profile has been used to generate a synthetic profile used for the second profile.

The second profile is called Ekofisk J 2021 and consist of a combination of synthetic data profile and laboratory results. Ekofisk J 2021 predicts the behaviour of chemical-free oil and is classified as a regular crude oil in OWM.

The third profile is based on only available laboratory data and is called Ekofisk J 2021 Prod.chem. Due to the presence of production chemicals in the received oil, this profile is classified as a low-emulsifying crude oil in OWM.

Table F-7 Physical and chemical properties for Ekofisk J 2021 CA, Ekofisk J 2021 and Ekofisk J 2021 Prod.chem at 13 °C.

Properties of fresh oil	**Value**
Density (g/ml)	0.8539
Pour point (°C)	-3
Reference temperature (°C)	13
Viscosity at ref. temp. (mPa·s = cP) *	17
Asphaltenes (wt. %)	0.07
Flash Point (°C)	-
Wax Content (wt. %)	4.27
Dispersible for visc. <**	-
Not dispersible for visc. > **	-
Maximum water uptake (%)	-

* *Measured at shear rate* $10s^{-1}$

*** Estimated*

- *No data available*

Table F-8 True boiling point (TBP) curve for Ekofisk J 2021 CA, Ekofisk J 2021 and Ekofisk J 2021 Prod.chem, used as input in the oil weathering model. The TBP is based on results simulated distillation analysis performed by Intertek Sunbury (report no. 4359075), converted from mass % to vol. % by SINTEF. No further adjustment of TBP was necessary.

Temperature (°C)	**Volume (%)**
36	1.5
69	2.8
119	12.4
173	23.5
283	44.3
391	63.9
513	82.7
604	91.7
672	96.2
729	98.8

Table F-9 Lab weathering data for Ekofisk J 2021 crude oil at 13 °C.

Property	**Fresh**	**150°C+**	**200°C+**	**250°C+**
Boiling Point Temp. (°C)	-	210	248.05	304.15
Vol. Topped (%)	0	19.3	26.4	36.2
Weight Residue (wt. %)	100	83.2	76.7	67.4
Density (g/ml)	0.854	0.880	0.889	0.901
Pour point (°C)	-3	10**	15**	21
Flash Point (°C)	-	49.5	74.5	113
Viscosity of water-free residue (mPa·s =cP)	17	90	205	1051
Viscosity of 50% emulsion (mPa·s = cP)	-	622	969	1639
Viscosity of 75% emulsion (mPa·s = cP)	-	1717	2565	3921
Viscosity of max water (mPa·s = cP)	-	1294	2352	4508
Max. water cont. (vol. %)	-	80	80	78
(T1/2) Halftime for water uptake (hrs)	-	0.2	0.2	0.2
Stability ratio	-	1	1	1

* *Measured at shear rate* $10\ s^{-1}$

***Estimated based on density and pour point of fresh and 250°C+*

- *No data*

Table F-10 Lab weathering data for Ekofisk J 2021 Prod.chem crude oil at 13 °C.

Property	**Fresh**	**150°C+**	**200°C+**	**250°C+**
Boiling Point Temp. (°C)	-	210	248.05	304.15
Vol. Topped (%)	0	19.3	26.4	36.2
Weight Residue (wt. %)	100	83.2	76.7	67.4
Density (g/ml)	0.854	0.880	0.889	0.901
Pour point (°C)	-3	10**	15**	21
Flash Point (°C)	-	49.5	74.5	113
Viscosity of water-free residue (mPa·s =cP)	17	90	205	1051
Viscosity of 50% emulsion (mPa·s = cP)	-	-	-	-
Viscosity of 75% emulsion (mPa·s = cP)	-	-	-	-
Viscosity of max water (mPa·s = cP)	-	-	-	1442
Max. water cont. (vol. %)	-	6	19	41
(T1/2) Halftime for water uptake (hrs)	-	0.01	0.05	1.4
Stability ratio	-	1.0	0.57	0.89

** Measured at shear rate 10 s^{-1}*

***Estimated based on density and pour point of fresh and 250°C+*

\- *No data*

G Chemical characterisation of the fresh oil on GC/MS on TOR II

Table G-1 Chemical composition of TOR II crude oil based on GC/MS analysis of fresh oil.

Group no.	Composition	TOR II wt.%
1	C1-C4 gasses (dissolved in oil)	1.500
2	C5-saturates (n-/iso-/cyclo)	2.500
3	C6-saturates (n-/iso-/cyclo)	1.530
4	Benzene	0.470
5	C7-saturates (n-/iso-/cyclo)	4.000
6	C1-Benzene (Toluene) et. B	1.559
7	C8-saturates (n-/iso-/cyclo)	5.441
8	C2-Benzene (xylenes; using O-xylene)	2.031
9	C9-saturates (n-/iso-/cyclo)	2.054
10	C3-Benzene	1.415
11	C10-saturates (n-/iso-/cyclo)	3.500
12	C4 and C5 Benzenes	0.147
13	C11-C12 (total sat + aro)	5.853
14	Phenols (C0-C4 alkylated)	0.000
15	Naphthalenes 1 (C0-C1-alkylated)	0.258
16	C13-C14 (total sat + aro)	7.042
17	Unresolved Chromatographic Materials (UCM: C10 to C36)	-
18	Naphthalenes 2 (C2-C3-alkylated)	0.431
19	C15-C16 (total sat + aro)	5.269
20	PAH 1 (Medium soluble polyaromatic hydrocarbons (3 rings-non-alkylated;<4 rings)	0.253
21	C17-C18 (total sat + aro)	5.247
22	C19-C20 (total sat + aro)	6.500
23	C21-C25 (total sat + aro)	8.651
24	PAH 2 (Low soluble polyaromatic hydrocarbons (3 rings-alkylated; 4-5+ rings)	0.349
25	C25+ (total)	34.000

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

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 25 pseudo-components, changes in the oil composition due to evaporation, dissolution and degradation are accounted for. OSCAR may compute oil weathering from crude assay data, although the most reliable results are produced if the target oil has been through a standardized set of laboratory weathering procedures established by the SINTEF laboratories. Alternatively, the model may use oil weathering properties from oils for which data already exist, selecting the oil in the oil database that most closely matches the composition of the oil of concern.

H Categorization of TOR II, Ekofisk J and Eldfisk S from 2021

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 by 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.

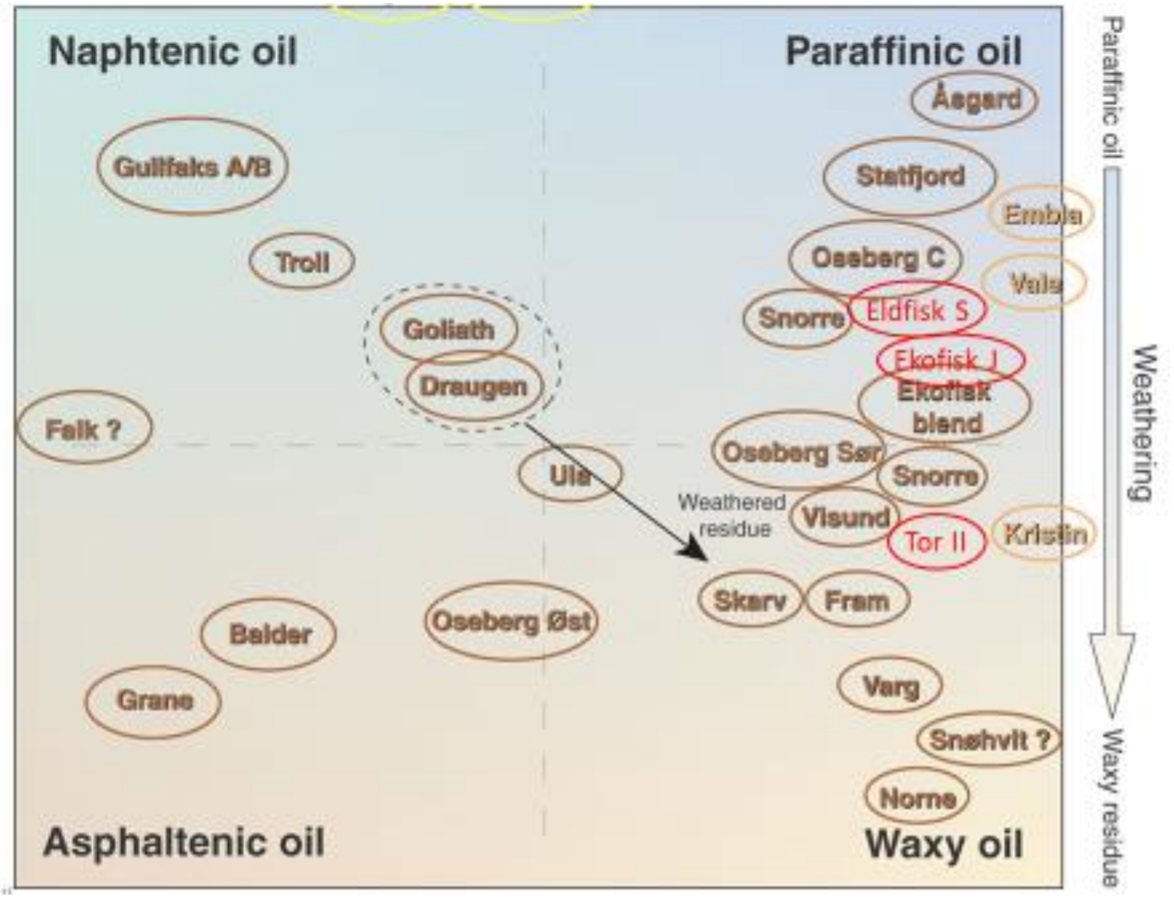


Figure H-1 Shows TOR II, Eldfisk S and Ekofisk J from 2021 in comparison to some other Norwegian crude oils.