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# Scenario-based recommendations for operative oil spill response in the Arctic

FateIce WP5A

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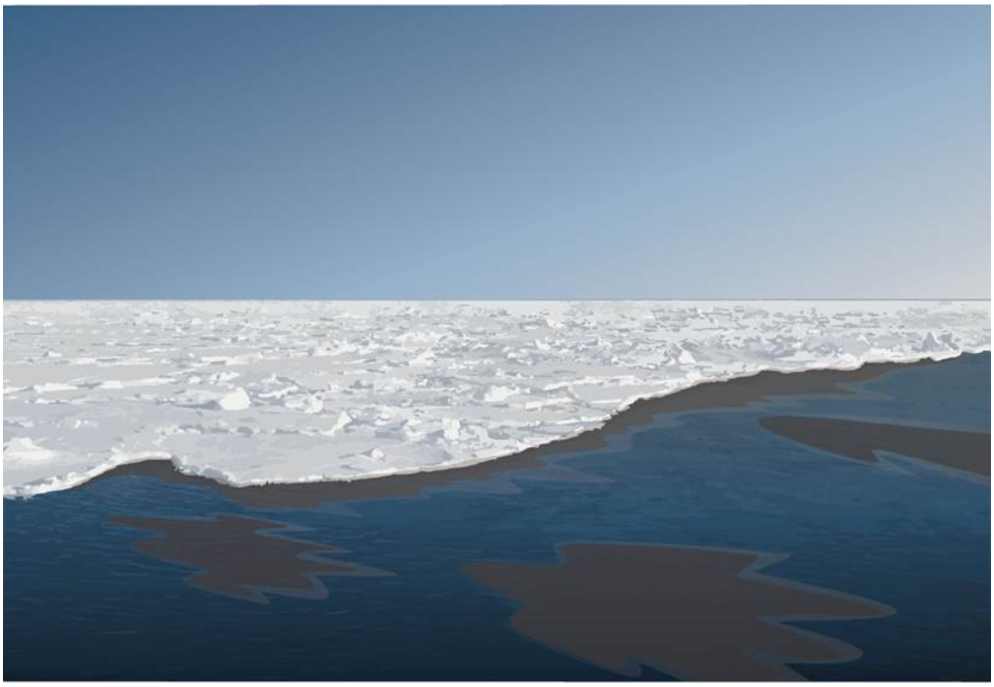

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**ABSTRACT**

On the Norwegian continental shelf, there no petroleum activities in ice-covered waters today or planned for the near future. However, future petroleum activities in Arctic waters can take place in areas free of ice most of the year, but with the possibility of occasional drifting sea ice in the winter season. Besides, there will be future increasing ships traffic in the Arctic and ice-covered waters, which demands an operational oil spill contingency for icy waters.

This report gives examples of scenario-based recommendations on potential operative oil spill response options in the Arctic given an acute oil spill in open water where the weathered oil is drifting into an ice barrier or a frazil ice field or if the oil is spilled inside an ice field. The purpose of the scenario-based recommendations is to assist in evaluation of potential oil spill response options. The different response options are evaluated with respect to expected technical achievements related to oil type and weathering properties, ice conditions and wind speed. The recommendations will present information to assist decision-makers and personnel working with oil spills to choose the most promising and best available response methods and strategies in case of an oil spill where oil may interact with ice.



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# Table of Contents

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## Abbreviations, Acronyms and Symbols

| Abbreviations, Acronyms and Symbols | Descriptions |
|---|---|
| AOSR | Arctic Oil Spill Response module |
| ECRC | Eastern Canada Response Cooperation |
| cP | Centi Poise |
| FateIce | Petromaks2 research project " *Fate, behaviour and response to oil drifting into scattered ice and ice edge in the marginal ice zone*". |
| FRB | Fire Resistant Boom |
| IOGP | International Association of Oil & Gas Producers |
| ISB | In-situ burning |
| JIP | Joint Industry Project |
| LORS | Lamor Oil Recovery System |
| MGO | Marine Gas Oil |
| NCA | Norwegian Coastal Administration |
| NOFO | The Norwegian Clean Seas Association for Operating Companies |
| OSRL | Oil Spill Response Limited |
| OWM | Oil Weathering Model |
| R&D | Research and Development |

# 1 Introduction

## 1.1 Background

At the Norwegian continental shelf, there are no petroleum activities in ice and as for now there are no plans for operation in ice either. Future petroleum activities in the Arctic waters are expected to take place in areas free of ice most of the year, but with the possibility of occasional drifting sea ice in the winter season. Recent R&D on accidental oil spills in the Arctic has contributed to increased knowledge about fate and behaviour of fresh oil released in ice covered conditions, where the oil typically has a low degree of weathering due to calm conditions compared to open water situations. However, oil drifting in open water towards a solid ice barrier or into an area with scattered ice, will to a large degree be exposed to wind and waves and hence be more weathered before meeting the ice which will influence on selection of oil spill response measures. The Petromaks2 Research Project " *Fate, behaviour and response to oil drifting into scattered ice and ice edge in the marginal ice zone*" (hereafter called FateIce project) is a 3-year R&D project (2016-2019) funded by the Research Council of Norway and industry partners (AkerBP, ConocoPhillips, Equinor, Lundin, Neptune Energy, OMV Norge, Vår Energi) aims to establish a foundation for establishment of a best possible oil spill response for the given scenarios.

This report gives examples of scenario-based recommendations on potential operative oil spill response options in the Arctic given an acute oil spill in open water where the weathered oil is drifting into an ice barrier or a frazil ice field or if the oil is spilled inside an ice field. Different scenarios with varying ice conditions and two release rates and durations have been defined. Four crude oils and a marine gas oil, all subjected to laboratory studies in the FateIce project, have been selected to represent different oil types in the recommendations. Two main ice conditions have been included as a basis for the recommendations. One is broken ice conditions with 20, 50 and 70% ice coverage and a solid ice barrier scenario, and the other one is a frazil ice scenario. The different ice conditions are illustrated in Figure 1.1.

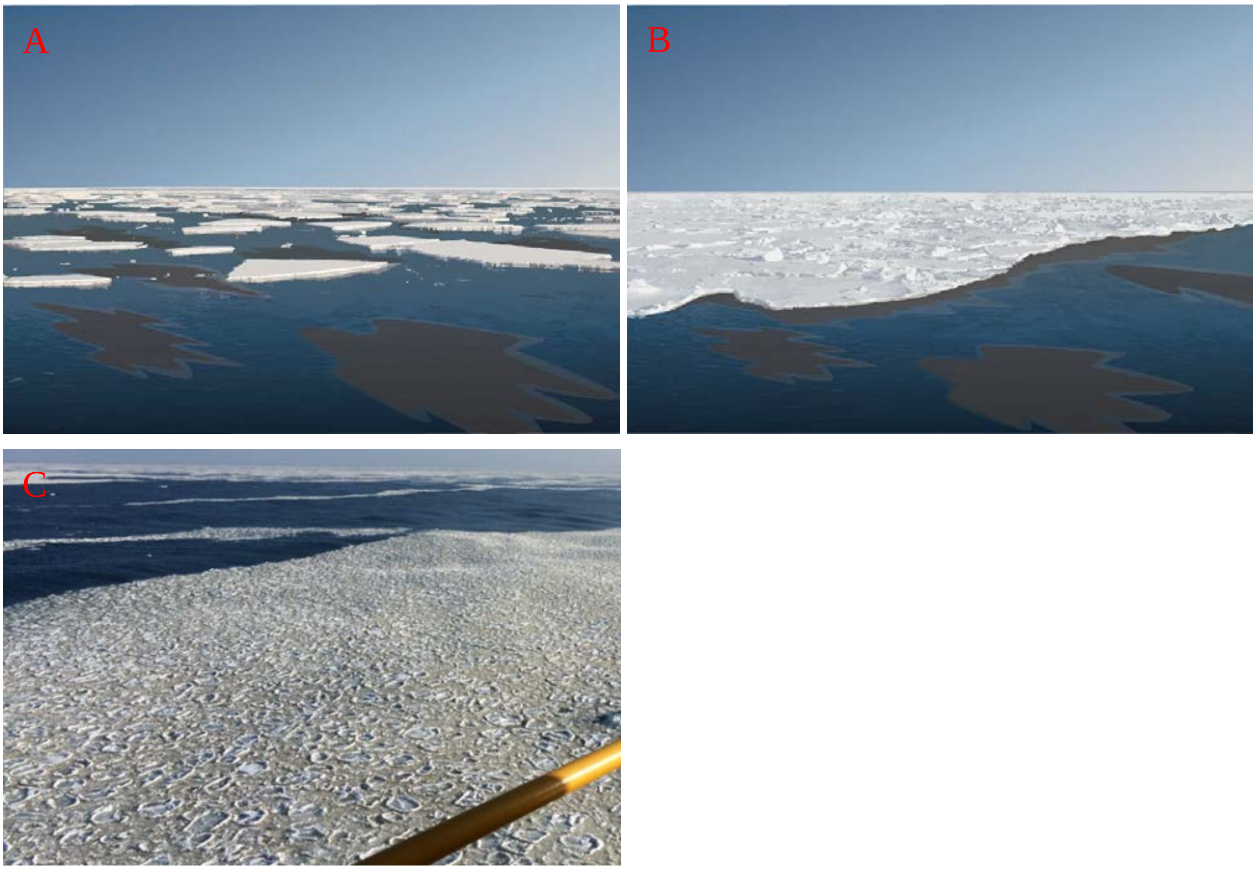



*Figure 1.1 Illustration of different ice scenarios. A: Broken ice scenario with approximately 20-50% ice coverage; B: Solid ice barrier: C: Frazil ice mixed with pancake ice (Photo: NOFO/BaSEC).*

The recommendations are based on the following reports and model tools to give the best available support and guidance to oil spill response options for different scenarios in the Arctic:

- FateIce project, 2016-2019
- Oil in ice JIP, 2006-2010
- IOGP Arctic Oil Spill Response Technology Joint Industry Program, 2012-2017
- Decision rules as implemented in the OWM/AOSR system
- OWM/AOSR system to predict applicability of the different response options given in different scenarios

As mentioned, four crude oils and one marine diesel oil (MGO), studied in the FateIce project, have been used as examples for different oil types in the recommendations. The recommendations are based on findings from the laboratory and basin experiments in the FateIce project (Singsaas and Leirvik, 2019), and physico-chemical and weathering properties of the oils combined with different wind speeds and ice conditions.

## 1.2 Purpose of the recommendations

The purpose of the scenario-based recommendations is to assist in evaluation of potential oil spill response options with respect to acute oil spills in Arctic and ice-covered waters. The different response options are evaluated with respect to expected technical achievements related to oil type and weathering properties, ice conditions and wind speed. The recommendations indicate which response option is judged to be applicable, to have reduced applicability or not to be applicable for the different scenarios.

The recommendations can be used in building up different response strategies for oil drifting in open cold waters, drifting into different ice conditions or is spilt in ice. It should contribute with documentation to companies, authorities and response organisations operating in the Arctic (e.g. Barents Sea) to reduce and mitigate the environmental impact from potential oil spills. The recommendations will present information to assist decision-makers and personnel working with oil spills to choose the most promising and best available response methods and strategies in case of an oil spill where oil may interact with ice.

## 1.3 What is not included in the recommendations

The recommendations evaluate the technical achievements of a response option in relation to oil type and weathering properties, ice conditions and wind speed only, not considering different "outside" factors that influence upon the success and efficiency of a response operation. The following are among the topics not addressed by the recommendations:

- Logistic challenges (like e.g. availability of equipment, ships and other necessary hardware) and remoteness of a spill site. For instance, helicopter application of dispersants is not available in Norway today and vessel application is the preferred application method offshore. However, helicopter application is well documented and found to have a potential in certain scenarios and the fact that it is not operational is outside the scope of the recommendations because it is based primarily on judgement of the method itself.
- Costs related to establishment and operation of a response option.
- The risk for icing of vessels, response equipment, helicopters, aircrafts etc. and efforts to avoid it. Icing of equipment can be a problem in the Arctic for all kind of equipment and in the recommendations, it is assumed that such "outside" factors are solved.
- Poor visibility, fog, darkness and other factors that can influence upon the use and efficiency of a given response option.
- HSE and people awareness regarding operations in cold weather and harsh environment.
- If a response option is not available in Norway today but is judged to have a potential, it still will be included in the recommendations. Examples are equipment for helicopter application, as mentioned above, and vessel-based spray arm for dispersant application.

The recommendations are not intended to replace oil spill response analyses as it only evaluates the usefulness of a response option given selected scenarios and not efficiency like amount of oil recovered, dispersed or burned.

## 1.4 Safety aspects in Arctic and cold climate conditions

Protection of human life and health has always the highest priority in oil spill response operations. Typically concerns in Arctic and cold climate conditions are snow, low visibility, ice and low temperatures. Remoteness and long distances to shore can also be more challenging in harsh climate conditions. The following safety aspects should be considered operating in the Arctic and cold climate conditions, but this topic is not discussed in further details in this report.

- Winterization-icing on vessels and smaller boats
- Low temperature
- Wind shifts – affect the ice leads (opening /closing)
- Ice dynamics
- Reduced or even lack of daylights - long winter period darkness
- Reduced operational efficiency of both personnel and equipment's due to ice
- Remote areas

# 2 Modelling tools

## 2.1 SINTEF Oil Weathering Model (OWM)

The SINTEF OWM (Figure 2.1) relates oil properties to a chosen set of conditions (oil/emulsion film thickness, wind speeds and seawater temperature) and predicts the change rate of the oil's properties on the sea surface with time. The model utilizes results from standardized weathering studies of oils, a stepwise laboratory study described e.g. in Daling *et al.* 1990. The oil weathering predictions obtained from the SINTEF OWM are useful tools in oil spill contingency planning related to the expected behaviour of oil on the sea surface in addition to evaluate the time window for operational response strategies in a spill operation. SINTEF OWM is described in more detail in Johansen (1991), and in the user's guide for the model.

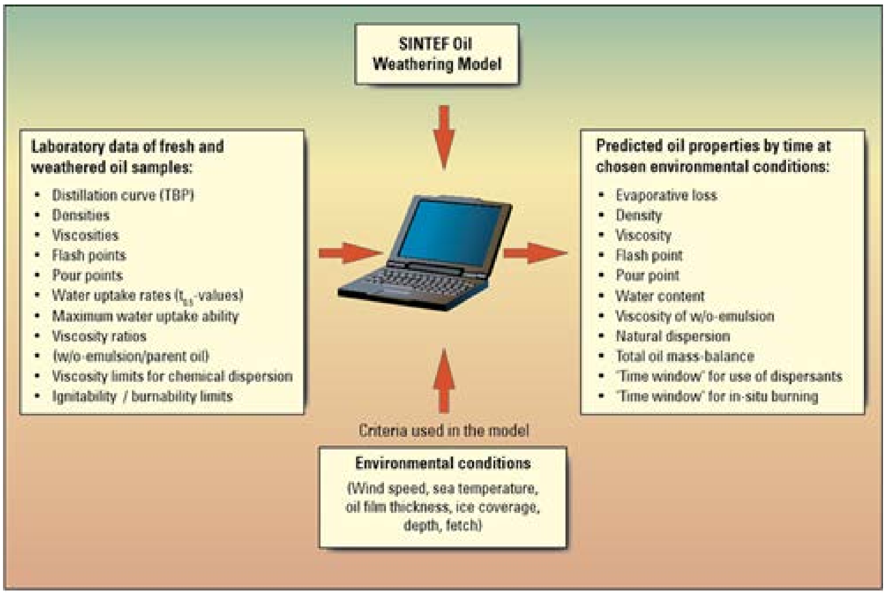



*Figure 2.1 SINTEF Oil Weathering Model*

## 2.2 Arctic Oil Spill Response (AOSR) module

An Arctic Oil Spill Response (AOSR) module was developed through the FateIce project and linked to SINTEF Oil Weathering Model (OWM) (Figure 2.2). This system combines physico-chemical data, predictions of weathering properties and dispersibility limits for a number of crude oils, condensates and oil products from the SINTEF Oil database with a set of decision rules for applicability of different oil spill response options. The decision rules implemented into the AOSR module are further discussed in chapter 3. The combined OWM/AOSR system has been used to prepare the basis for the recommendations given.

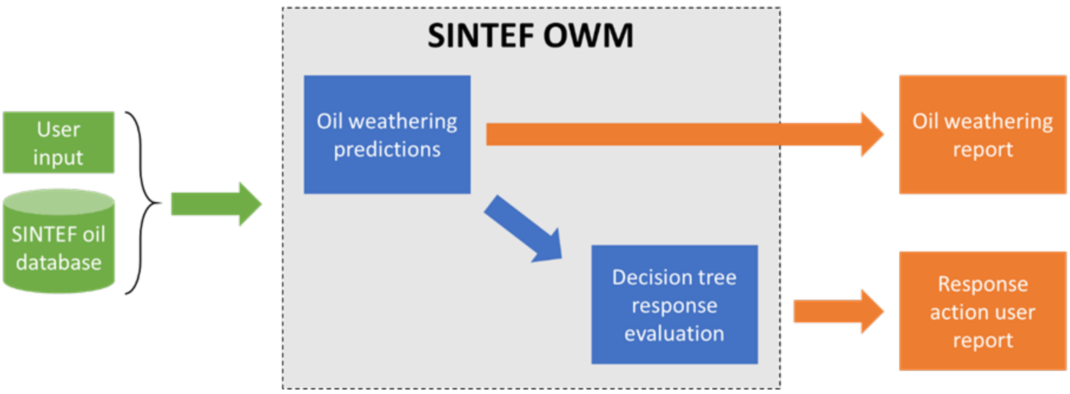



*Figure 2.2 Sketch of the AOSR module linked to SINTEF OWM*

# 3 Decision criteria

Decision criteria (also referred as decision trees) is a decision support tool that may use a flowchart or algorithms of decisions with possible consequences, outcomes and utilities. Here the decision criteria are used as a method to evaluate the usefulness or applicability of different response technologies within the three main response options (mechanical recovery, use of dispersants and in-situ burning). The defined decision criteria for each response option were further implemented in the AOSR module used as a tool when working out the recommendations given in this report.

The decision criteria have partly been documented through laboratory testing and/or verified through field testing and partly based on best available knowledge. Some of them, especially on in-situ burning, are documented in peer reviewed publications. The criteria have been discussed briefly with the reference group in the FateIce project and with DNV GL in a case study performed jointly in 2017. It should be realized that some of the decision criteria may be subjected to different opinion and discussions and changes may, in some cases, lead to different recommendations. However, it is important with transparency to better understand the outcome as presented in this report.

There are three levels of usefulness/applicability for the different response options and the various technologies within each response option: *"Applicable"*, *"Reduced applicability"* and *"Not applicable"*. The different applicability levels are colour coded:

- *"Applicable"*
- *"Reduced applicability"*
- *"Not applicable"*

The efficiency of a response technology, measured in amount of oil treated per time unit, is not part of the assessment. The recommendations estimate whether a response option can be used, based on the oil weathering properties combines with the decision criteria, and when it can be used along a time axis (time window). As an example, a response option in ice can be evaluated as *"Applicable"* even if it is assumed to recover or treat less oil than in open water.

## 3.1 Mechanical recovery

Decision rules for mechanical recovery estimate the combined usefulness/applicability of boom and skimmer (also including skimmer only) given different oil parameters and conditions – <u>not</u> how effective it is to recover oil (e.g. amount oil recovered per time unit). The table below gives the decision criteria defined for mechanical recovery. The Norwegian Coastal Administration has previously used a grab to recover oil in slush ice and a skimmer called Sandvik band to recover heavy bunker oils. Both methods may have a potential to recover solidified oil or oil with high viscosities and have been used in more near-shore operations. They are not further evaluated in this report.

| Guide input parameters | Variables | MR, Booms and low visc skimmer | MR, Booms and HighVisc skimmer | MR, Flexible one vessel systems | MR, Uncontained recovery |
|---|---|---|---|---|---|
| **OIL:** | | | | | |
| Oil/emulsion viscosity | < 10 000 cP | | | | |
| | 10 000 – 20 000 cP | | | | |
| | 20 000 – 50 000 cP | | | | |
| | 50 000 – 500 000 cP | | | | |
| | 500 000 – 1 000 000 cP | | | | |
| | > 1 000 000 cP | | | | |
| Pour point above sea water temp. | < 10ºC above | | | | |
| | 10 - 15ºC above | | | | |
| | 16 - 25ºC above | | | | |
| | > 25ºC above | | | | |
| Film thickness | < 0.1 mm | | | | |
| | 0.1 – 0.2 mm | | | | |
| | 0.3 – 20 mm | | | | |
| | > 20 mm | | | | |
| **ICE:** | | | | | |
| Ice coverage | < 5% | | | | |
| | 5 - 15% | | | | |
| | 16 - 30% | | | | |
| | 31 - 50% | | | | |
| | > 50% | | | | |
| **WEATHER:** | | | | | |
| Wind speed | <10 m/s | | | | |
| | 10-15 m/s | | | | |
| | > 15 m/s | | | | |

**Mechanical recovery, Booms and low viscosity skimmer:** Examples are booms in J-configuration used by e.g. NOFO, MOS Sweeper and other similar boom systems using a wear skimmer, "octopus" skimmer or other skimmers designed for recovery of oil with low to medium viscosity (tentatively < 20.000 cP).

**Mechanical recovery, Booms and HighVisc skimmer:** Examples are booms in J-configuration or other similar boom systems using a skimmer designed for recovery of oil with high viscosity (tentatively up to 1.000.000 cP) and high pour points (up to 25°C).

**Mechanical recovery, Flexible one vessel systems:** Examples are Current Buster and Lamor Oil Recovery System (LORS), representing flexible systems that are assumed to be able to operate between larger ice floes in up to 50% ice coverage.

**Mechanical recovery, Uncontained:** Examples are Lamor Arctic Sternmax, Brush skimmers, Foxtail skimmer and other skimmers that are assumed to be able to operate in relatively high ice coverage (> 30-50%) without use of booms.

## 3.2 Use of dispersants

Decision rules for use of dispersants estimate the combined usefulness/applicability of dispersant application and dispersibility of the oil given different oil parameters and conditions – not how effective the dispersant action is (e.g. amount oil dispersed per time unit).

| **Guide input parameters** | **Variables** | **Helicopter applation** | **Fixed-wing application** | **Vessel application *** | **SprayArm + Agitation** |
|---|---|---|---|---|---|
| **OIL:** | | | | | |
| Dispersibility limits, OWM | Dispersible | Green | Green | Green | Green |
| | NOT dispersible | Red | Red | Red | Red |
| Pour point above sea water temp. | Temp: < 5°C above | Green | Green | Green | Green |
| | Temp: 5 - 15°C above | Yellow | Yellow | Yellow | Yellow |
| | Temp: > 15°C above | Red | Red | Red | Red |
| Film thickness | Thickness > 10 mm | Red | Red | Red | Red |
| | Thickness > 0.2 mm | Green | Green | Green | Green |
| | Thickness 0.1-0.2 mm | Yellow | Yellow | Yellow | Yellow |
| | Thickness < 0.1 mm | Red | Red | Red | Red |
| **ICE:** | | | | | |
| Ice coverage | < 30% | Green | Green | Green | Yellow |
| | 30 – 50% | Green | Yellow | Yellow | Yellow |
| | 50 – 60% | Yellow | Red | Yellow | Green |
| | 60 – 70% | Yellow | Red | Red | Green |
| | 70 – 90% | Yellow | Red | Red | Green |
| | > 90% | Red | Red | Red | Green |
| **WEATHER:** | | | | | |
| Wind speed | < 12 m/s | Green | Green | Green | Green |
| | 12 - 15 m/s | Yellow | Yellow | Green | Green |
| | 15 – 20 m/s | Red | Red | Yellow | Yellow |
| | > 20 m/s | Red | Red | Red | Red |

**Helicopter application:** In the 1990's an underslung helicopter dispersion bucket (Response 3000 D) was developed. It proved to be challenging to operate and is not in operation today. However, the principle of using dispersant application by helicopter is well documented and, in some scenarios (e.g. oil in frazil ice), it may be one of few options to apply dispersants. Potential development of new systems for helicopter application is under evaluation in Norway, primarily for use near-shore (need for quick response) and in the Arctic (for instance increased ship traffic in the Spitzbergen area. Artificial energy (agitation) may be needed in ice.

**Fixed-wing aircraft application:** Example is a Boeing 727 equipped with a Tersus System for spraying of dispersants, operated by ORSL. NOFO has performed an evaluation for use of aircraft application in Norwegian waters and has revealed a danger for icing large parts of the time during winter conditions. High speed and low accuracy have also been mentioned as a drawback using fixed-wing aircraft for dispersant application. However, in this context the usefulness of fixed-wing aircraft application has been evaluated in relation to a few oil parameters, ice coverage and wind speed (table above), not discussing all the factors that may contribute reducing the efficiency.

**Vessel application:** Example is spray booms mounted in the bow of a vessel, as is installed on a number of supply-vessels which is part of the NOFO pool of oil spill response vessels. They can spray with high or low dosage dependent on the thickness of the oil film.

**Spray arm application:** Example is the prototype of a flexible spray arm developed through the Oil-in-ice JIP (2006-2010). Such a spray arm will have reduced effectiveness as the application rate is lower that other application systems. However, it can be used in most ice coverages between ice floes, but the applicability is judged to be reduced at ice coverages below 50% because it is relatively slow in covering large areas of open water. Artificial energy (agitation) may be needed in ice.

## 3.3 *In-situ* burning (ISB)

Decision rules for in-situ burning (ISB) estimate the combined usefulness/applicability of ISB as a method to respond to an oil slick - not how effective the burn is (e.g. amount oil burned per time unit). The possibility to ignite the oil (ignitability) is a key element when using this response method. Burn efficiency estimates the volume-fraction of the oil assumed to be burned. It can vary widely between different oil types and different ice and weather conditions. It has not been included in these evaluations as basis for the recommendations. Flash Point of the oil is a parameter important for ignitability. According to burn experiments carried out by SINTEF recently on behalf of the Norwegian Coastal Administration the following limit values can be suggested for flash point:

Flash point < 100°C: Ignitable

Flash point 100-190°C: Reduced ignitability

Flash point > 190°C: Difficult to ignite

Prediction of flash point for the oils included in this report shows that it is not a limiting factor for the recommendations given and has not been included in the decision criteria for ISB.

The following "Rules of Thumb" have been used as a guidance in preparation of decision rules for ISB:

**Residue Rules of Thumb**

- For pools of unemulsified crude oil up to roughly 40-mm in thickness the residue thickness is on the order of 1-mm;
- For thicker crude slicks the residue is thicker; for example, 3 to 5-mm for 50-mm thick oil and 6-mm for 100-mm thick oil;
- For emulsified slicks the residue thickness can be much greater (see below); and,
- For light and middle-distillate fuels the residue thickness is 1-mm, regardless of slick thickness.

**Ignition Rules of Thumb**

- The minimum ignitable thickness for fresh crude oil on water is about 1-mm;
- The minimum ignitable thickness for aged, unemulsified crude oil and diesel fuels is about 2 to 5-mm;
- The minimum ignitable thickness for residual fuel oils, such as IFO 380 (aka Bunker "C" or No. 6 fuel oil) is about 10-mm; and,
- Once 1-m2 of burning slick has been established, the fire can sustain itself without an external heat source.

**Rules of Thumb for the Effects of Emulsification**

- Little effect on oil removal efficiency (i.e., residue thickness) for low water contents up to about 12.5% by volume;
- A noticeable decrease in burn efficiency with water contents above 12.5%, the decrease being more pronounced with weathered oils; and
- Zero burn efficiency for emulsion slicks having stable water contents of 25% or more. Some crudes form meso-stable emulsions that can be burned efficiently at much higher water contents. Paraffinic crudes appear to fall into this category.

| Guide input parameters | Variables | ISB Uncontained | ISB FR booms | ISB Herders |
|---|---|---|---|---|
| **OIL:** | | | | |
| Emulsion water content | Water content <30% | | | |
| | Water content 30-50% | | | |
| | Water content >50% | | | |
| Pour point above sea water temp. | Temp: <8°C above | | | |
| | Temp: 8-10°C above | | | |
| | Temp: >10°C above | | | |
| Film thickness | > 5 mm | | | |
| | 2 – 5 mm | | | |
| | 1 – 2 mm | | | |
| | 0.5 – 1 mm | | | |
| | 0.2 – 0.5 mm | | | |
| | 0.1 – 0.2 mm | | | |
| | < 0.1 mm | | | |
| **ICE:** | | | | |
| Ice coverage | < 10% | | | |
| | 10 - 30% | | | |
| | 30 – 40% | | | |
| | 40 – 60% | | | |
| | 60 – 80% | | | |
| | > 80% | | | |
| Wind speed | <5 m/s | | | |
| | 5-8 m/s | | | |
| | 8-12 m/s | | | |
| | > 12 m/s | | | |

**ISB uncontained:** Provided that the oil film thickness is high enough, oil can be ignited and burned without prior containment, for instance in high ice coverage.

**ISB Fire-resistant booms:** Specially designed booms used to confine the oil to achieve sufficient oil film thickness for ignition and burning and to withstand a fire.

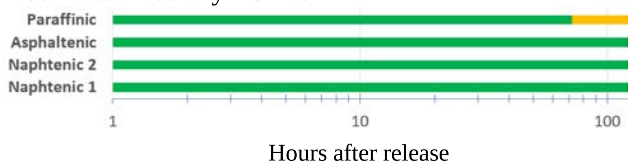
**ISB by use of herders:** Herders are surface-active chemicals used to confine and thicken a thin oil film for ignition and burning.

# 4 Explanation in use of tables and symbols

For each scenario the usefulness of the response options: mechanical recovery, use of dispersants and in-situ burning is discussed in relation to different wind speeds (5, 10 and 15 m/s). A sea water temperature of 0°C is assumed in all scenarios.

Below is an example of how the different results are presented and discussed. On the left side is an overall evaluation of the response option (e.g. mechanical recovery in this example). It predicts the potential of the response option given oil weathering properties predicted by the OWM combined with the decision criteria defined earlier in this report. Typically, physicochemical data like viscosity and pour point can be decisive for a successful or not successful response. The output of the assessment is given in three colours as indicated in chapter 3. The x-axis gives prediction time in hours (logarithmic scale) and the y-axis the different oil types that are evaluated (see chapter 5 for definition of oil types).

On the right side of the example below, different techniques within a response option are presented and discussed. Each method/technique, judged to be the best for each response option and scenario, is visualized by a picture given a coloured frame: green frame: the method is judged to be applicable; yellow frame: the method is judged to have reduced applicability. A given method can be judged to be applicable even if the evaluation on the left side says, "reduced applicability". Then it is not the method itself that is the limiting factor, but for instance some physicochemical property of the oil.

| **Applicability** | **Response in open water** |
|---|---|
| Mechanical recovery – 5 m/s   |   <br>NOFO system, mechanical: *"applicable"*.<br>Flexible one-vessel system: *"applicable"*.<br>High viscosity skimmer: *"applicable"*.<br>Oil can be recovered by usual offshore mechanical recovery equipment. Skimmer for high viscous oils may be necessary for asphaltenic and paraffinic oils. |

### Symbols used for techniques/methods within each response option:

Different symbols have been selected to represent and visualize different techniques/methods within each response option. The techniques/methods are briefly described under the decision criteria for each response option in 3.1 through 3.3. As described above, each symbol is given a coloured frame to indicate whether the technique/method is applicable or have reduced applicability. Missing symbols indicate that the technique/method is found "not applicable" for the scenario in question.

| **Symbol** | **Use of dispersants** |
|---|---|
|  | Vessel application of dispersants. |
|  | Helicopter application of dispersants. |
|  | Fixed-wing aircraft application of dispersants. |
|  | Flexible spray arm application of dispersants.<br>In high ice concentration above 50-70%. Artificial agitation may be needed. |
| **Symbol** | **Mechanical recovery** |
|  | Mechanical recovery with boom using low viscous skimmer, like e.g. weir skimmer. |
|  | Mechanical recovery with boom using high viscous skimmer, like e.g. HiVisc skimmer, brush skimmer etc. |
|  | Mechanical recovery with flexible one vessel system, like e.g. current buster, LORS etc. |
|  | Mechanical recovery uncontained in high ice concentration above 30-50% or at a solid ice barrier. |
| **Symbol** | **In-situ burning** |
|  | Fire-resistant boom for in-situ burning. |
|  | Herders for in-situ burning. |
|  | Uncontained in-situ burning. The oil is not contained by any artificial means, only by the presence of ice. |

# 5 Response recommendations

A total of 8 scenarios (Table 5.1) have been evaluated with respect to relevant oil spill response options for an acute oil spill in the Arctic. In scenarios 2, 3, 4, 5 and 6 the oils have been allowed to drift in open water before hitting the ice which means that the oils have weathered before reaching the ice field. In scenarios 6 and 7 the oils are released inside the ice field. An overview of the oil types used for the response recommendations are given in Table 5.2.

*Table 5.1 Overview of scenarios used in the response recommendations*

| Scenarios | Description |
|---|---|
| Scenario 1 | Oil drifting in open Arctic waters |
| Scenario 2 | Oil drifting into a solid ice barrier |
| Scenario 3 | Oil drifting into 20% broken ice |
| Scenario 4 | Oil drifting into 50% broken ice |
| Scenario 5 | Oil drifting into 70% broken ice |
| Scenario 6 | Oil drifting into frazil ice |
| Scenario 7 | Oil released in 50% broken ice |
| Scenario 8 | Oil released in 70% broken ice |

*Table 5.2 Overview of oil types used in the response recommendations*

| Oil type | Name |
|---|---|
| Paraffinic crude oil | Oseberg Blend |
| Asphaltenic crude oil | Grane |
| Naphtenic crude oil 2 | Wisting Central |
| Naphtenic crude oil 1 | Troll B |
| Marine gas oil | MGO 500 ppm S |

Prediction using the OWM combined with AOSR module have been used as a basis for the recommendations. Two release scenarios have been used as basis for the recommendations, one for the crude oils and one for the MGO (table 5.3). The four crude oil types were included in all scenarios, while MGO was included in scenarios 6, 7 and 8. It was included in scenario 6 because experiments performed in the FateIce project have shown that MGO migrated more rapidly to the top of a frazil ice layer than weathered crude oils, making it more accessible to dispersant application. At 5 m/s wind approximately 90% of the MGO would still be on the surface when meeting the ice after 9 hours. At 10 m/s wind approximately 15-20% would be on the surface while at 15 m/s wind the MGO would have been evaporated or naturally dispersed before reaching the ice.

*Table 5.3 Release scenarios*

| Parameter | Crude oil scenario | MGO scenario |
|---|---|---|
| Release rate | 4000 metric tons/day | 167 $m^3$/hour |
| Release duration | 2 days | 6 hours |
| Total release | 8000 metric tons | 1000 $m^3$ |
| Sea water temperature | 0°C | 0°C |
| Wind speed | 5, 10, 15 m/s | 5, 10, 15 m/s |
| Ice conditions | Variable (table 5.1) | Variable (table 5.1) |

## 5.1 Scenario 1: Oil drifting in open Arctic waters

Scenario 1 is given the following input parameters:

| Parameter | Values |
|---|---|
| Oil types | Paraffinic oil (represented by Oseberg Blend)<br>Asphaltenic oil (represented by Grane)<br>Naphtenic 2 oil (represented by Wisting Central)<br>Naphtenic 1 oil (represented by Troll B)<br>Marine Gas Oil (MGO) |
| Release rate | Crude oils: 4000 metric tons/day; MGO: 167 m3/hour |
| Release duration | Crude oils: 2 days; MGO: 6 hrs |
| Total release | Crude oils: 8000 metric tons; MGO: 1000 m3 |
| Sea surface temperature | 0°C |
| Wind speed | 5, 10 and 15 m/s |
| Ice conditions | No ice |

**SUMMARY**

In this scenario the oil drifts in open water during the entire simulation period of 5 days. There is no interaction between oil and ice, but the sea water temperature is 0°C. MGO is predicted to have short living time on the sea surface in 15 m/s wind speed, but in these predictions it is treated as it remains on the surface for the entire prediction period of 5 days.

**Mechanical recovery:** Usual NOFO offshore mechanical recovery equipment can be used including also one-vessel systems like current buster, MOS sweeper, LORS etc. Among the oil types used in these simulations, the asphaltenic oil reaches high viscosities (above 10000 cP) where weir skimmers may have *"reduced applicability"* and use of skimmers for high viscous oils may be necessary. The paraffinic oil will get high pour point and may tend to solidify. At pour point 10°C above sea water temperature low viscous skimmers, like weir skimmers, are judged to have *"reduced applicability"*. Skimmer for high viscous oils will then be necessary when recovering the paraffinic oil.

**Dispersant use:** Dispersant application by vessel, helicopter and fixed-wing aircraft is *"applicable"*. For the paraffinic oil there are reductions in the applicability due to increasing pour point and risk for solidification by weathering. For the asphaltenic and naphtenic 1 oils dispersant use is judged to have *"reduced applicability"* when the weathered oil reaches the lower viscosity limit for dispersibility, as established during dispersibility testing as part of laboratory weathering studies. When the weathered oil reaches the upper viscosity limit for dispersibility, dispersant use is judged to be *"not applicable"*. Aerial application (helicopter and aircraft) is more sensitive to wind than vessel application, and at 15 m/s wind vessel application should be prioritised before aerial application, even if it is assumed that aerial application still can be used, with *"reduced applicability"*.

**In-situ burning:** Both fire-resistant booms (FRB) and herders can be used to confine the oil into required thicknesses for ignition in this scenario, but use of herders is judged to be *"not applicable"* at wind speeds above 8 m/s. Ignition and burnability varies between the different oils based on water uptake and pour point (paraffinic oil). At 30% water content ISB is judged to have *"reduced applicability"* and at 50% water content ISB is judged to be *"not applicable"*.

## Mechanical recovery

Figure 5.1 shows the predicted time window (in hours) for mechanical recovery on the 4 different groups of crude oils and MGO at 3 selected wind speeds, when drifting in open Arctic waters. MGO is predicted at 5 and 10 m/s wind speed. At 15 m/s wind the lifetime at the sea surface is predicted to be less than 9 hours (when meeting the ice) for the MGO.

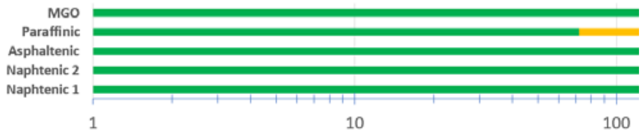
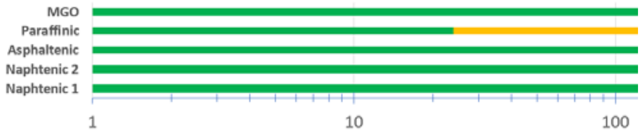
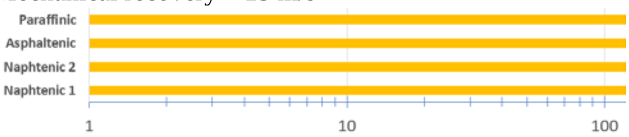
| **Applicability** | **Response in open water** |
|---|---|
| Mechanical recovery – 5 m/s<br> | <br>NOFO system, mechanical: *"applicable"*.<br>Flexible one-vessel system: *"applicable"*.<br>High viscosity skimmer: *"applicable"*.<br>Oil can be recovered by usual offshore mechanical recovery equipment. Skimmer for high viscous oils may be necessary for asphaltenic and paraffinic oils. |
| Mechanical recovery – 10 m/s<br> | <br>NOFO system, mechanical: *"applicable"*.<br>Flexible one-vessel system: *"applicable"*.<br>High viscosity skimmer: *"applicable"*.<br>Time window is green for the entire simulation period (5 days) for 3 of the oils. Somewhat reduced for the paraffinic oil due to increasing pour point, |
| Mechanical recovery – 15 m/s<br> | <br>NOFO system, mechanical: *"reduced applicability"*.<br>Flexible one-vessel system: *"reduced applicability"*.<br>High viscosity skimmer: *"reduced applicability"*.<br>Oil recovered by same equipment as above, but with *"reduced applicability"* due to high wind speed. |

*Figure 5.1 Predicted time window for use of dispersants at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed "usual" NOFO systems for mechanical recovery offshore can be used in open water. Use of high viscosity skimmer may be necessary for the asphaltenic and paraffinic oil after some time on the sea surface. One-vessel systems, like e.g. current buster, MOS sweeper, LORS etc. are also judged to be *"applicable"* in this scenario. The asphaltenic oil reaches a viscosity above 10000 cP after 12 hours where weir skimmers may start to have *"reduced applicability"* and use of skimmers for high viscous oils may be necessary. Paraffinic oils may get high pour point and may tend to solidify. At pour point 10°C above sea water temperature low viscous skimmers, like weir skimmers, are judged to have *"reduced applicability"*. Skimmers for high viscous oils are judged to have *"reduced applicability"* if the pour point of the oil is 15 - 25°C above sea water temperature, which in this case happens after 3 days for the paraffinic oil.

At 10 m/s wind speed the same systems as for 5 m/s can be used. For the asphaltenic oil(s) a viscosity of 10000 cP is reached after 6 hours, and weir skimmer may have *"reduced applicability"* and use of skimmers for high viscous oils may be necessary. For the paraffinic oil(s) the time before the oil reaches a pour point 10°C above sea water temperature is shorter than at 5 m/s (9 hours), and weir skimmers are judged to have *"reduced applicability"*. After 1 day the pour point will be above 15°C and use of skimmers for high viscosity oils are judged to have *"reduced applicability"*.

At 15 m/s wind speed *"reduced applicability"* should be expected for all oil types due to the high wind speed and expected high waves leading to reduced booming performance (boom leakage). Due to high viscosity (> 20000 cP after 6 hours) skimmer for high viscous oil should be used after that for the asphaltenic oil

## Dispersant use

Figure 5.2 shows the predicted time window (in hours) for use of dispersants on the 4 different groups of crude oils and MGO at 3 selected wind speeds, when drifting in open Arctic waters. MGO is predicted at 5 and 10 m/s wind speed. At 15 m/s wind the lifetime at the sea surface is predicted to be less than 9 hours (when meeting the ice) for the MGO.

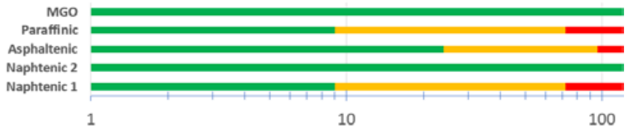
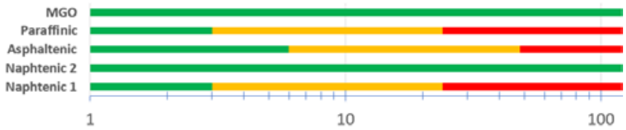
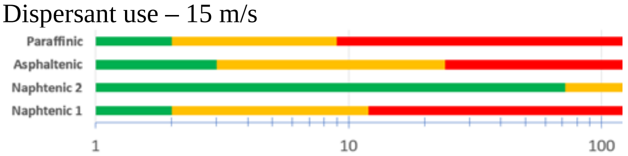
| Applicability | Response, open water |
|---|---|
| Dispersant use – 5 m/s<br><br> | <br>Vessel spraying: *"applicable"*.<br>Helicopter spraying: "*applicable*".<br>Fixed-wing aircraft spraying: "*applicable*".<br>All three application methods can be used. Limitations in dispersibility due to increase in pour point (paraffinic oil) and viscosity (asphaltenic and naphtenic 1 oils). |
| Dispersant use – 10 m/s<br><br> | <br>Vessel spraying: *"applicable"*.<br>Helicopter spraying: "*applicable*".<br>Fixed-wing aircraft spraying: "*applicable*".<br>All three application methods can be used, but further reduction in time window for 3 of the oils, due to more rapid weathering at increased wind speed. |
| Dispersant use – 15 m/s<br><br> | <br>Vessel spraying: *"applicable"*.<br>Helicopter spraying: *"reduced applicability"*.<br>Fixed-wing aircraft spraying: *"reduced applicability"*.<br>Helicopter and aircraft application is judged to have *"reduced applicability"* due to strong winds. |

*Figure 5.2 Predicted time window for use of dispersants at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed dispersant application by vessel, helicopter and aircraft is *"applicable"*. For the paraffinic oil reduced dispersibility should be expected after 9 hours and after 3 days the oil is judged not to be dispersible due to increased pour point (5°C and 15°C above sea water temperature respectively). For the asphaltenic and naphtenic oils reduced dispersibility should be expected when the weathered oil reaches the lower viscosity limit for dispersibility (3000 cP for the naphtenic 1 oil and 12000 for the asphaltenic oil). When the weathered oil reaches the upper viscosity limit for dispersibility (7000 cP after 3 days for the naphtenic 1 oil and 30000 after 4 days for the asphaltenic oil), dispersant use is judged to be *"not applicable"*.

At 10 m/s wind speed the same application methods as for 5 m/s can be used. However, the time window is shorter due to increased weathering speed for the different oils. This means that *"reduced applicability"* for the paraffinic oil (pour point) and naphtenic 1 oil (viscosity) comes after 3 hours and *"not applicable"* after 1 day. The asphaltenic oil has a somewhat longer time window with 6 hours (*"reduced applicability"*) and 2 days (*"not applicable"*) based on viscosity limits.

At 15 m/s wind speed vessel application should be the main strategy for application of dispersants in open water. Helicopter and aircraft can still be used, but with expected *"reduced applicability"* in such strong winds. The time window for dispersant use is further reduced compared to 10 m/s wind, due to increased weathering speed for the different oils. Again, it is the same limiting factors as mentioned above, pour point and viscosity.

### *In-situ* burning

Figure 5.3 shows the predicted time window (in hours) for *in-situ* burning (ISB) on the 4 different groups of crude oils and MGO at 3 selected wind speeds, when drifting in open Arctic waters.

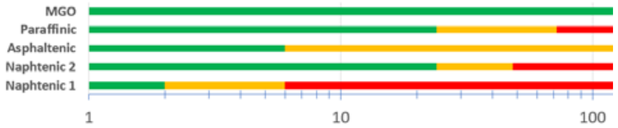
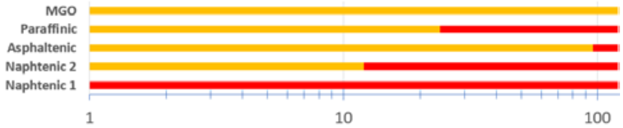
| Applicability | Response, open water |
|---|---|
| *In-situ* burning – 5 m/s<br> |  <br>Use of fire-resistant boom (FRB): *"applicable"*.<br>Use of herders: *"applicable"*.<br>Both fire-resistant booms and herders can be used to thicken the oil. Ignition and burnability varies between the different oils based on water uptake and pour point (paraffinic oil). |
| *In-situ* burning – 10 m/s<br> | <br>Use of fire-resistant boom (FRB): *"applicable"*.<br>Use of herders is judged to be *"not applicable"* at wind speeds above 8 m/s, and FRB should be used to thicken the emulsion. Ignition is judged to have *"reduced applicability"* at wind speeds above 8 m/s. |
| *In-situ* burning – 15 m/s | ISB is judged to be *"not applicable"* at wind speeds above 12 m/s, because it is extremely difficult to ignite the emulsion and sustain a burn at such high wind speeds. |

*Figure 5.3 Predicted time window for in-situ burning at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed both fire-resistant booms (FRB) and herders can be used to confine the oil into required thicknesses for ignition. ISB is judged to be *"applicable"* for the paraffinic oil for one day before the water content in the emulsion exceeds 30% and ISB is judged to have *"reduced applicability"*. After 3 days of weathering the water content have reached 50% where ISB is judged to be *"not applicable"*. After 1 day the pour point has increased to 10°C above sea water temperature and herders cannot be used anymore for the paraffinic oil and FRB should be used to confine the oil. For the other oil types, it is the water content in the emulsion that is the limiting factor. At 30% water content ISB is judged to have *"reduced applicability"* and at 50% water content ISB is judged to be *"not applicable"*. The time window varies based on oil type and predicted water uptake.

At 10 m/s wind speed herders cannot be used to thicken the oil (*"not applicable"* at wind speed > 8 m/s), but FRB can still be used. In open water 10 m/s wind gives relatively high waves which can cause a risk for boom leakage. Ignition of weathered oil is sensitive to wind speed and is judged to have *"reduced applicability"* when the wind speed increases to above 8 m/s. The naphtenic 1 oil has a very fast water uptake at 10 m/s wind speed and reaches a water content of 50% already after 1 hour. The other oils have shorter time windows at 10 m/s wind than at 5 m/s before they reach 50% water content, the asphaltenic oil having the longest time window of 4 days.

At 15 m/s wind speed ISB is judged to be *"not applicable"* because according to literature it is extremely difficult to ignite and burn an emulsion at wind speeds above 12 m/s.

## 5.2 Scenario 2: Oil drifting into a solid ice barrier

Scenario 2 is given the following input parameters:

| Parameter | Values |
|---|---|
| Oil types | Paraffinic oil (represented by Oseberg Blend)<br>Asphaltenic oil (represented by Grane)<br>Naphtenic 2 oil (represented by Wisting Central)<br>Naphtenic 1 oil (represented by Troll B)<br>Marine Gas Oil (MGO) |
| Release rate | Crude oils: 4000 metric tons/day; MGO: 167 m3/hour |
| Release duration | Crude oils: 2 days; MGO: 6 hrs |
| Total release | Crude oils: 8000 metric tons; MGO: 1000 m3 |
| Sea surface temperature | 0°C |
| Wind speed | 5, 10 and 15 m/s |
| Ice conditions | The weathered oil meets a solid ice barrier after 9 hours drifting time |

### SUMMARY

In this scenario it is assumed that the oil is trapped at the ice barrier and is subjected to approximately the same wave energy input as if it was drifting on open water. Because the oil will be thickened against the ice barrier further evaporation may be slowed down. Emulsification and viscosity increase may be slightly higher compared to if the oil was still drifting at sea. For simplicity, we assume that the weathering processes take place at approximately the same speed as in open water after the oil is trapped at the ice barrier.

**Mechanical recovery:** When the oil has reached the ice barrier it is assumed that the oil is "trapped" and increases in thickness at the ice barrier. Uncontained recovery by use of rotating brush drum skimmers operated from an excavator crane onboard a vessel, floating brush skimmers connected to a vessel by an umbilical or vessel stern mounted brush drums are examples of techniques that can be used in this scenario. Flexible one-vessel systems may have a potential to confine oil that is up-concentrated against the ice but is judged to have *"reduced applicability"* due to the difficulty in operating booms this close to the ice barrier. As the paraffinic oil weathers, it may reach high pour points which reduces the applicability of mechanical recovery. It is primarily the ability to pump the solidified oil that is the problem which can be overcome by using a skimmer capable of pumping high-viscous, semi-solid or solidified oils. But confinement of the weathered oil at the ice barrier may also be more challenging if the oil is semi-solid or have solidified.

**Dispersant use:** At the ice barrier vessel application and flexible spray arm can be used for application of dispersants. Among the 4 oil types included in this study, viscosity limits decide the time window for use of dispersants at all wind speeds simulated for the naphtenic 1 and asphaltenic oils. For the paraffinic oil, increasing pour point, giving a possibility for solidification of the weathered oil, is a limiting factor. The naphtenic 2 oil has a wide time window at all wind speeds, only with *"reduced applicability"* after 3 days for the 15 m/s wind speed scenario. Aerial application (aircraft and helicopter) is not recommended to be used in this ice condition because it is more inaccurate in hitting the oil. However, helicopter may have a potential in more broken ice conditions.

**In-situ burning:** It is assumed that the weathered oil is trapped at the ice and that the thickness of the oil layer increases. Provided emulsion thickness of approximately 5 mm and above it should be possible to ignite and burn the oil without any further confinement and thickening of the oil. Fire-proof booms are judged to be difficult to use close to a solid ice barrier. Because the oil already has thickened, use of herders is judged unnecessary and will only work on thinner oil thickness. The time window for the paraffinic and naphtenic 2 oils after they have reached the ice barrier is 15 hours, before ISB is judged to have *"reduced applicability"*. The asphaltenic oil has *"reduced applicability"* when it meets the ice and the naphtenic 1 oil is no longer ignitable and burnable. For all the oils, the individual time window is decided by the water uptake and the water content in the emulsion. At 30% water content ISB is judged to have *"reduced applicability"* and at 50% water content it is judged to be *"not applicable"*.

## Mechanical recovery

Figure 5.4 shows the predicted time window (in hours) for mechanical recovery on the 4 different groups of crude oils and MGO at 3 selected wind speeds, before and after the drifting oil reaches the solid ice barrier. MGO is predicted at 5 and 10 m/s wind speed. At 15 m/s wind the lifetime at the sea surface is predicted to be less than 9 hours (when meeting the ice) for the MGO.

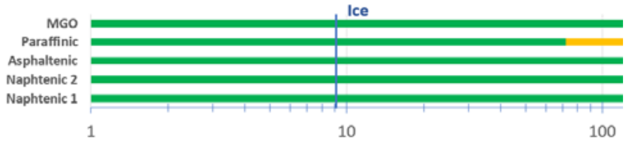
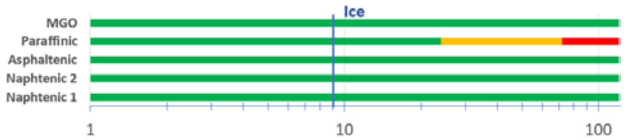
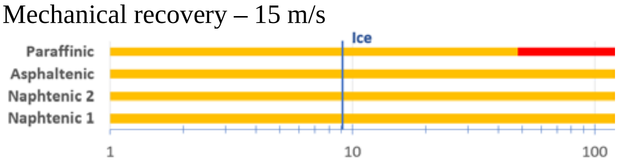
| Applicability | Response at solid ice barrier |
|---|---|
| Mechanical recovery – 5 m/s<br><br> |  <br>Uncontained recovery: *"applicable"*.<br>Flexible one-vessel system: *"reduced applicability"*.<br>The paraffinic oil reaches a pour point > 10°C above sea water temp. after 3 days giving *"reduced applicability"*. |
| Mechanical recovery – 10 m/s<br><br> |  <br>Uncontained recovery: *"applicable"*.<br>Flexible one-vessel system: *"reduced applicability"*.<br>Uncontained recovery for oil thickened against the ice barrier. One-vessel system may potentially be used. Pour point issue for paraffinic oil. |
| Mechanical recovery – 15 m/s<br><br> |  <br>Uncontained recovery: *"reduced applicability"*.<br>Flexible one-vessel system: *"reduced applicability"*.<br>Due to high wind speed and high waves at the ice barrier, mechanical recovery is judged to be less effective. Pour point issue for paraffinic oil. |

*Figure 5.4 Predicted time window for use of dispersants at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed the oil may be confined and thickened against the ice barrier. No further use of booms to confine the oil should be necessary, and besides it is very difficult to operate booms in such a scenario. Uncontained recovery by use of rotating brush drum skimmers operated from an excavator crane onboard a vessel, floating brush skimmers connected to a vessel by an umbilical, skimmers with thrusters or vessel stern mounted brush drums are examples of techniques that can be used in this scenario. Flexible one-vessel systems may have a potential to confine oil that is up-concentrated against the ice but is judged to have *"reduced applicability"*. The paraffinic oil reach high pour points as it weathers, with a risk for solidification and challenges with recovery by a brush drum type of skimmer. However, a HiVisc skimmer with thrusters can recover the solidified oil at the ice barrier.

At 10 m/s wind speed the same systems as for 5 m/s can be used. For the paraffinic oil the pour point reaches 10°C above sea temperature after 1 day and mechanical recovery is judged to have *"reduced applicability"*. After 3 days the pour point increases to 15°C above sea temperature mechanical recovery is judged to be *"not applicable"*. However, if it has been possible to confine oil in a boom (e.g. current buster), a skimmer capable of pumping solidified oil should be used or a HiVisc skimmer alone operated with thrusters.

At 15 m/s wind speed *"reduced applicability"* should be expected due to the high wind speed and expected high waves. For the paraffinic oil the pour point passes 15°C above sea temperature after 2 days and mechanical recovery is judged to be *"not applicable"*. The predicted viscosity for the asphaltenic oil reaches 20000 cP after 6 hours and a skimmer capable of pumping high-viscous oil should be used.

### Dispersant use

Figure 5.5 shows the predicted time window (in hours) for mechanical recovery on the 4 different groups of crude oils and MGO at 3 selected wind speeds, before and after the drifting oil reaches a solid ice barrier. MGO is predicted at 5 and 10 m/s wind speed. At 15 m/s wind the lifetime at the sea surface is predicted to be less than 9 hours (when meeting the ice) for the MGO.

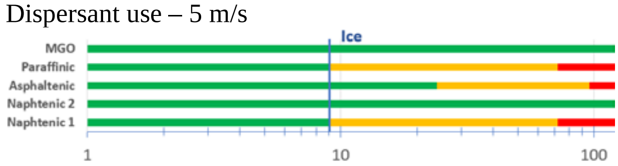
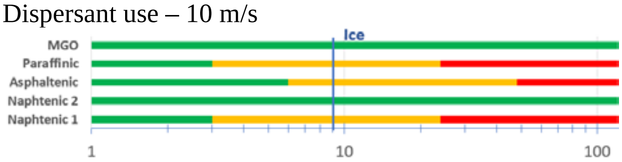
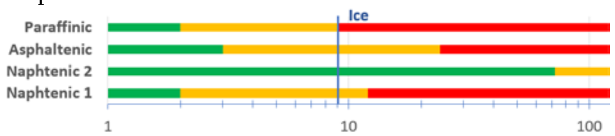
| **Applicability** | **Response at solid ice barrier** |
|---|---|
| Dispersant use – 5 m/s<br> | <br>Vessel spraying: *"applicable"*.<br>Flexible spray arm: "*applicable"*.<br>Helicopter spraying: "*applicable"*.<br>Reduced time window: viscosity limits: naphtenic 1 and asphaltenic oils and pour point: paraffinic oil. |
| Dispersant use – 10 m/s<br> | <br>Vessel spraying: *"applicable"*.<br>Flexible spray arm: "*applicable"*.<br>Helicopter spraying: "*applicable"*.<br>Reduced time window for three of the oils due to more rapid increase in viscosity and pour point. |
| Dispersant use – 15 m/s<br> | <br>Vessel spraying: *"applicable"*.<br>Flexible spray arm: "*applicable"*.<br>Helicopter spraying: "reduced *applicability"*.<br>It is only the naphtenic 2 oil that is readily dispersible when reaching the ice. |

*Figure 5.5 Predicted time window for use of dispersants at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed vessel and flexible spray arm can be used for application of dispersant along the ice barrier. Helicopter may be used if the width of the oil slick is sufficiently high for efficient application.The naphtenic 1 and asphaltenic oils reach the lower viscosity limit after 9 and 24 hours respectively, with reduced dispersibility and the upper viscosity limit after 3 and 4 days respectively, where the oil is no longer dispersible. The viscosity limits are established during dispersibility testing as part of weathering studies of the oils. For the paraffinic oil the pour point is judged to be the limiting factor, increasing to 5°C above sea water temperature after 9 hours (*"reduced applicability"*) and 15°C above sea water temperature after 3 days (*"not applicable"*).

At 10 m/s wind the oils are more weathered when reaching the ice than at 5 m/s. Due to weathering (e.g. evaporation and emulsification) the naphtenic 1 oil reaches the lower viscosity limit for dispersibility after 3 hours giving *"reduced applicability"* and the upper viscosity limit after 1 day where the oil is no longer dispersible and dispersant use judged to be *"not applicable"*. Similar numbers for lower and upper viscosity limit for the asphaltenic oil are 6 hours (reduced dispersibility) and 2 days (not dispersible). For the paraffinic oil it is the pour point of the weathered oil, giving a potential for solidification, that is the limiting factor for dispersant use, not the viscosity limits.

At 15 m/s wind speed limitations in dispersant use are the same as for 5 and 10 m/s, viscosity limits for the naphtenic and asphaltenic oils and high pour points and possible solidification for the paraffinic oil. Also, for the naphtenic 2 oil dispersant use may have *"reduced applicability"* after 3 days due to that the viscosity of the weathered oil reaches the lower viscosity limit. With the oil captured at the ice barrier, vessel and flexible spray arm can be used for application along the ice for the oil that are still dispersible.

## *In-situ* burning

Figure 5.6 shows the predicted time window (in hours) for mechanical recovery on the 4 different groups of crude oils and MGO at 3 selected wind speeds, before and after the drifting oil reaches a solid ice barrier. MGO is predicted at 5 and 10 m/s wind speed. At 15 m/s wind the lifetime at the sea surface is predicted to be less than 9 hours (when meeting the ice) for the MGO.

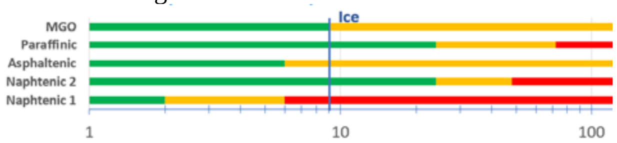
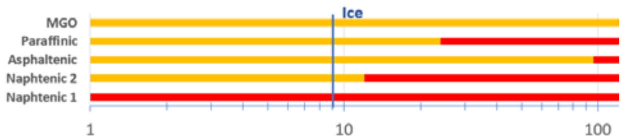
| **Applicability** | **Response at solid ice barrier** |
|---|---|
| *In-situ* burning – 5 m/s<br> | <br>Uncontained: *"applicable"*.<br>Provided sufficient emulsion thickness (tentatively > 5 mm) ISB can be used without any additional confinement and thickening of the oil. Water content in the emulsion decides the ignitability and burnability. |
| *In-situ* burning – 10 m/s<br> | <br>Uncontained: *"reduced applicability"*.<br>At wind speeds between 8-12 m/s ISB is judged to be more difficult, giving *"reduced applicability"*. It is assumed that herders cannot be used at wind speeds above 8 m/s. |
| *In-situ* burning – 15 m/s | ISB is judged to be *"not applicable"* at wind speeds above 12 m/s, because it is extremely difficult to ignite the emulsion and sustain a burn in such high wind speeds. |

*Figure 5.6 Predicted time window for in-situ burning at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed it is assumed that the weathered oil is trapped at the ice and that the thickness of the oil layer increases. Provided emulsion thickness of approximately 5 mm and above it should be possible to ignite and burn the oil without any further confinement and thickening of the oil. Fire-proof booms are judged to be difficult to use close to a solid ice barrier. Use of herders may be unnecessary if the oil has thickened otherwise but can be used on thinner parts of the oil slick. The time window for the paraffinic and naphtenic 2 oils after they have reached the ice barrier is 15 hours, before ISB is judged to have *"reduced applicability"*. The asphaltenic oil has *"reduced applicability"* when it meets the ice and the naphtenic 1 oil is no longer ignitable and burnable. For all the crude oils, the individual time window is decided by the water uptake and the water content in the emulsion. The MGO has a predicted oil thickness of 1 mm when reaching the ice. That is too thin for ignition and it is dependant on thickening at the ice barrier, either by wind/wave/current or use of herders. Due to uncertainty ISB for MGO is given *"reduced applicability"* after it meets the ice, but it can also be readily ignitable provided sufficient oil thickness.

At 10 m/s wind speed ignition, flame spreading and burning of oil can be challenging. Therefore, ISB is predicted to have *"reduced applicability"* for 4 of the oils or to be *"not applicable"* for the naphtenic 1 oil, even from the start of the predictions (in open water). The asphaltenic oil has a slower water uptake than the other oils and have a time window of more than 3 days after it hits the ice before it cannot be ignited and burned anymore. The paraffinic and naphtenic 2 oils have shorter time windows before they cannot be ignited and burned - 15 and 3 hours respectively.

At 15 m/s wind speed ISB is judged to be *"not applicable"* because according to literature it is extremely difficult to ignite and burn an emulsion at wind speeds above 12 m/s.

## 5.3 Scenario 3: Oil drifting into 20% broken ice

Scenario 3 is given the following input parameters:

| Parameter | Values |
|---|---|
| Oil types | Paraffinic oil (represented by Oseberg Blend)<br>Asphaltenic oil (represented by Grane)<br>Naphtenic 2 oil (represented by Wisting Central)<br>Naphtenic 1 oil (represented by Troll B) |
| Release rate | 4000 metric tons/day |
| Release duration | 2 days |
| Total release | 8000 metric tons |
| Sea surface temperature | 0°C |
| Wind speed | 5, 10 and 15 m/s |
| Ice conditions | The weathered oil meets broken ice with an ice coverage of 20% after 9 hours drifting time. |

### SUMMARY

In this scenario it is assumed that the oil is drifting for 9 hours in open Arctic water before it meets a broken ice field with an ice coverage of 20%. The weathered oil will stay in this ice concentration for the weathering prediction period of 5 days. Because the wave dampening in such ice coverage is expected to be low, OWM predicts that further weathering of the oil will approximately the same as if the oil was drifting in open water.

**Mechanical recovery:** In 20% broken ice coverage it is assumed that "traditional" booms cannot be used while one-vessel systems (like e.g. Current Buster and LORS) may have a potential. For the asphaltenic, naphtenic 1 and naphtenic 2 oils, the time window for use of mechanical recovery shows that it is *"applicable"* for the entire simulation period of 5 days both at 5 and 10 m/s wind speed. The paraffinic oil has a more limited time window due to increasing pour point with the potential for solidification of the oil. At 15 m/s there is judged to be *"reduced applicability"* for all oils due to high wind speed (> 10 m/s).

**Dispersant use:** In the 20% broken ice scenario it is assumed that dispersants can be applied by vessel, helicopter or fixed-wing aircraft. When the wind speed increases above 12 m/s, aerial application is judged to have *"reduced applicability"* and vessel application should be the preferred methodology. The time window varies between the four oils and with different wind speed. The naphtenic 2 oil has a wide time window at all wind speeds. The time window for the paraffinic is ruled by the pour point and potential for solidification of the oil. When the line turns yellow a pour point of 5°C above sea water temperature has been reached and when it turns red the pour point is 15°C above sea water temperature. For the two other oil types it is the lower (yellow) and upper (red) viscosity limits for dispersibility, as defined during weathering and dispersibility studies, that decides the time window.

**In-situ burning:** In 20% broken ice it is assumed that both fire-resistant booms (FRB) and herders can be used to thicken the oil. FRB is judged to have *"reduced applicability"* at ice coverages from 10 to 30%. Use of ISB is sensitive to emulsification and water content in the emulsion. For all the oil types, except the paraffinic oil, at 5 m/s wind speed the time window turns into yellow when the water content passes 30% and red when the water content exceeds 50%. For the paraffinic oil herders can be used for one day before the pour point exceeds 10°C above sea water temperature and herders cannot be used anymore. However, FRB can be used with *"reduced applicability"* (due to ice coverage) until the water content passes 50% after 4 days. At 10 m/s wind speed *"reduced applicability"* is predicted for all oil types due to strong winds making ignition, flame spreading and burning more difficult. For all oils it is the water content in the emulsion exceeding 50% that makes the timelines changing from yellow to red. At 15 m/s wind speed ISB is judged to be *"not applicable"* due to the high winds.

## Mechanical recovery

Figure 5.7 shows the predicted time window (in hours) for mechanical recovery on the 4 different groups of crude oils at 3 selected wind speeds, before and after the drifting oil reaches a 20% broken ice area.

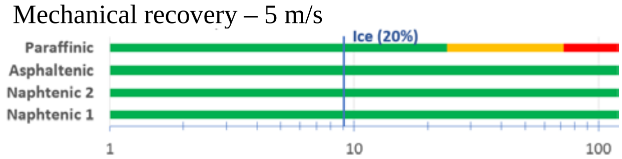
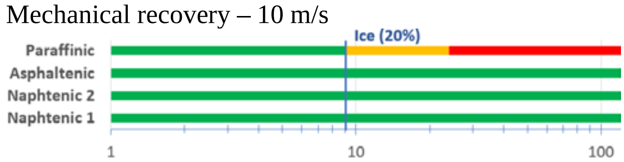
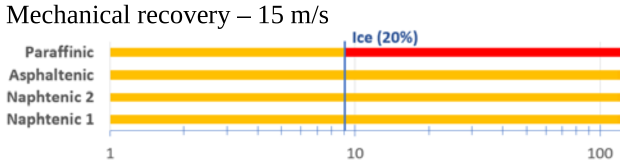
<table>
<tr><th>Applicability</th><th>Response in 20% broken ice after 9 hours</th></tr>
<tr><td>Mechanical recovery – 5 m/s

</td><td>
Flexible one-vessel system: "applicable".<br>"Usual" NOFO systems for mechanical recovery are judged to be "not applicable" in 20% broken ice. Increased pour point limits the applicability on the paraffinic oil.</td></tr>
<tr><td>Mechanical recovery – 10 m/s

</td><td>
Flexible one-vessel system: "applicable".<br>Further reduction in time window for the paraffinic oil due to more rapid weathering and pour point increase.</td></tr>
<tr><td>Mechanical recovery – 15 m/s

</td><td>
Flexible one-vessel system: "reduced applicability".<br>Flexible one-vessel system may be used but the overall effectiveness is assumed to be reduced for all oils due to high wind speed (> 10 m/s). Pour point or viscosity an issue for 3 of the oil types.</td></tr>
</table>

*Figure 5.7 Predicted time window for mechanical recovery at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed it is assumed that flexible one-vessel systems (like e.g. Current Buster and LORS) can be used in 20% broken ice conditions by moving around between scattered ice floes collecting oil. There is a time window of 5 days or more for all oils except the paraffinic oil. The paraffinic oil reaches high pour points and when the pour point is 10°C above sea temperature mechanical recovery by use of one vessel systems (without use of HiVisc skimmer) is judged to have *"reduced applicability" (*after 1 day*)* and when it reaches 15°C above sea temperature it is judged to be *"not applicable"* (3 days). "Traditional" booms in J or U configuration, towed by two vessels, are judged not to be applicable in ice conditions with 15% or more scattered ice.

At 10 m/s wind speed the flexible one-vessel systems (like e.g. Current Buster and LORS) are assumed to be the most efficient in 20% broken ice conditions. The time window for the paraffinic oil is somewhat shorter at 10 m/s wind speed compared to 5 m/s. This is due to more rapid weathering at higher wind speed. So already after 9 hours, when the weathered oil meets the ice, it has reached a pour points 10°C above sea water temperature and use of one-vessel systems without use of HiVisc skimmer is predicted to have *"reduced applicability"*. After 24 hours it has reached a pour points 15°C above sea water temperature and mechanical recovery is predicted to be *"not applicable"*.

At 15 m/s wind speed *"reduced applicability"* should be expected for all response options due to the high wind speed and expected high waves. Flexible one-vessel systems can be used, while "traditional" booms are judged to be *"not applicable"* under such ice conditions. For the naphtenic 1 and paraffinic oils increasingly high pour points may call for use of HiVisc skimmer. The same may also be relevant for the asphaltenic oil. However, this is valid only after days of weathering.

## Dispersant use

Figure 5.8 shows the predicted time window (in hours) for use of dispersant on the 4 different groups of crude oils at 3 selected wind speeds, before and after the drifting oil reaches a 20% broken ice area.

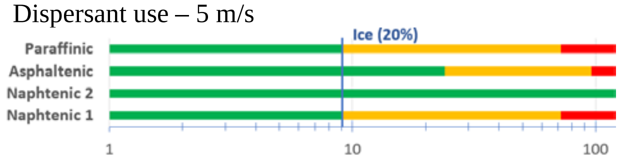
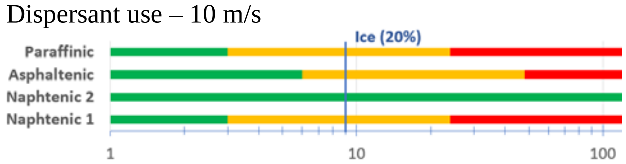
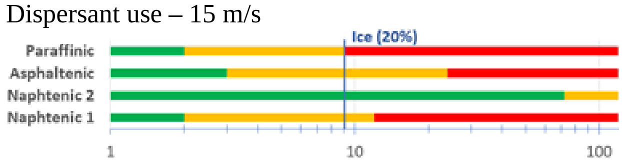
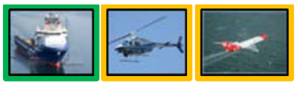
| Applicability | Response in 20% broken ice after 9 hours |
|---|---|
| Dispersant use – 5 m/s<br> | <br>Vessel spraying: *"applicable"*.<br>Helicopter spraying: "*applicable*".<br>Fixed-wing aircraft: "*applicable*".<br>There is a reduction in applicability for the naphtenic 1 and asphaltenic oils due to increased viscosity and for the paraffinic oil due to increased pour point. |
| Dispersant use – 10 m/s<br> | <br>Vessel spraying: *"applicable"*.<br>Helicopter spraying: "*applicable*".<br>Fixed-wing aircraft: "*applicable*".<br>As for 5 m/s wind speed viscosity and pour point limits the time window for three of the oils. |
| Dispersant use – 15 m/s<br> | <br>Vessel spraying: *"applicable"*.<br>Helicopter spraying: "*reduced applicability*".<br>Fixed-wing aircraft: "*reduced applicability*".<br>Vessel application is the preferred method, but aerial application can be used with expected *"reduced applicability"* at wind speeds between 12-15 m/s. |

*Figure 5.8 Predicted time window for use of dispersants at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed dispersants can be applied by vessel, helicopter and aircraft in scattered ice conditions with 20% ice coverage. After 9 hours of weathering use of dispersants is judged to have *"reduced applicability"* on the naphtenic 1 and paraffinic oils. At that time the lower viscosity limit (3000 cP) is reached for the naphtenic 1 oil. For the paraffinic oil the pour point is predicted to be the limiting factor, increasing to 5°C above sea water temperature after 9 hours. Use of dispersants on the asphaltenic oil is predicted to have *"reduced applicability"* after 24 hours when the lower viscosity limit (12000 cP) is reached. When the upper viscosity limits are reached for the naphtenic 1 and asphaltenic oils use of dispersants is judged to be *"not applicable"* as indicated by the red line. The same is relevant for the paraffinic oil reaching a pour point 15°C above sea water temperature.

At 10 m/s wind speed the same applications methods as for 5 m/s wind speed can be used. The naphtenic 1 oil has a lower viscosity limit for dispersibility of 3000 cP reached after 3 hours, where use of dispersants is predicted to have *"reduced applicability"*, and an upper viscosity limit of 7000 cP reached after 24 hours, where use of dispersants is predicted to be *"not applicable"*. The same limits for the asphaltenic oil are 12000 cP (after 6 hours) and 30000 cP (after 48 hours). For the paraffinic oil it is still the pour point that is the limiting factor.

At 15 m/s wind speed dispersant application by helicopter or fixed-wing aircraft can be performed, but *"reduced applicability"* should be expected due to the strong wind. Vessel application is assumed to be more robust in high winds than aerial application. Reduced dispersibility for all oils due to either pour point (paraffinic oil) and lower and upper viscosity limits (for the other oils) according to laboratory studies.

### *In-situ* burning

Figure 5.9 shows the predicted time window (in hours) for *in-situ* burning (ISB) on the 4 different groups of crude oils at 3 selected wind speeds, before and after the drifting oil reaches a 20% broken ice area.

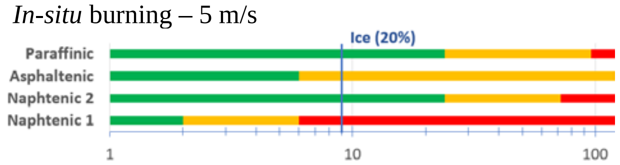
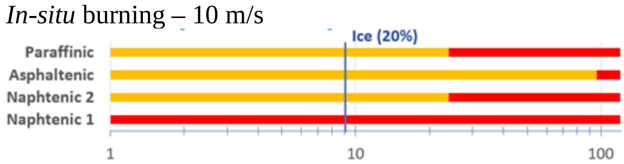
| **Applicability** | **Response in 20% broken ice after 9 hours** |
|---|---|
| *In-situ* burning – 5 m/s<br><br> |  <br>Use of herders: *"applicable"*.<br>Use of fire-resistant boom: *"reduced applicability"*.<br>The time windows for the naphtenic 1, naphtenic 2 and asphaltenic oils are dependent on the water content in the emulsion, while for the paraffinic oil pour point (use of herder) and water content is determinative. |
| *In-situ* burning – 10 m/s<br><br> | <br>Use of fire-resistant boom: *"reduced applicability"*.<br>Herders cannot be used in such strong winds (> 8 m/s).<br>Due to a rapid water uptake the naphtenic 1 oil is predicted not to be ignitable. ISB can be used for the other oils with *"reduced applicability"* due to high winds. |
| *In-situ* burning – 15 m/s | ISB is judged to be *"not applicable"* at wind speeds above 12 m/s, because it is extremely difficult to ignite the emulsion and sustain a burn in such high wind speeds. |

*Figure 5.9 Predicted time window for in-situ burning at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed both fire-resistant booms (FRB) and herders can be used to confine the oil in 20% ice coverage. It is assumed that use of FRB can collect a lot of ice together with the oil, making ignition and burning more difficult, and use of FRB is assumed to have *"reduced applicability"* when the ice coverage is between 10 and 30%. Water uptake and emulsification is reported to be a challenge for ISB and at 30% water uptake ISB is predicted to change from being *"applicable"* to have *"reduced applicability"*. For the naphtenic 1 oil that happens already after 2 hours and for the asphaltenic oil after 6 hours, before the drifting oils reach the broken ice area (after 9 hours). When the water content reaches 50% the oil is judged not to be ignitable and the timeline in figure 6.9 turn into red, for the naphtenic 1 (6 hours) and naphtenic 2 (3 days (72 hours)) oils. For the paraffinic oil the pour point increases to 10°C above sea water temperature after 1 day, and herders cannot be used anymore. However, FRB can be used to confine the oil, with *"reduced applicability"* due to the ice conditions. After 4 days (96 hours) ISB is predicted to be *"not applicable"* due to larger than 50% water content in the emulsion.

At 10 m/s wind speed ignition, flame spreading and burning of oil can be challenging. Therefore, ISB is predicted to have *"reduced applicability"* for 3 of the oils or to be *"not applicable"* for the naphtenic 1 oil. For the oils that have a potential for ISB after they have drifted into the ice, the time window is dependent on the water uptake. When the water uptake reaches 50% ISB is predicted to be *"not applicable"* and the time window turns red. The asphaltenic oil has a slower water uptake than the other oils and have a time window of more than 3 days after it hits the ice when ISB can be used. The paraffinic and naphtenic 2 oils have shorter time windows before they cannot be ignited and burned – 24 hours.

At 15 m/s wind speed ISB is judged to be *"not applicable"* because according to literature it is extremely difficult to ignite and burn an emulsion at wind speeds above 12 m/s.

## 5.4 Scenario 4: Oil drifting into 50% broken ice

Scenario 4 is given the following input parameters:

| Parameter | Values |
|---|---|
| Oil types | Paraffinic oil (represented by Oseberg Blend)<br>Asphaltenic oil (represented by Grane)<br>Naphtenic 2 oil (represented by Wisting Central)<br>Naphtenic 1 oil (represented by Troll B) |
| Release rate | 4000 metric tons/day |
| Release duration | 2 days |
| Total release | 8000 metric tons |
| Sea surface temperature | 0°C |
| Wind speed | 5, 10 and 15 m/s |
| Ice conditions | The weathered oil meets broken ice with an ice coverage of 50% after 9 hours drifting time. |

### SUMMARY

In this scenario it is assumed that the oil is drifting for 9 hours in open Arctic water before it meets a broken ice field with an ice coverage of 50%. The weathered oil will stay in this ice concentration for the weathering prediction period of 5 days. The wave dampening in such ice coverage is expected to be significant which will influence upon further weathering of the oil and this is reflected in the OWM predictions.

**Mechanical recovery:** In 50% broken ice coverage it is assumed that "traditional" booms cannot be used while one-vessel systems (like e.g. Current Buster and LORS) may have a potential. It is also assumed that a movable skimmer (e.g. brush drum or brush skimmers) can be used without prior confinement of the oil. This means that the oil must be confined by the ice surrounding it. It has been assumed that the oil should have a thickness of minimum 20 mm before this is an efficient method, which is not the case in these simulations. Even if both these technologies can be used, they are judged to have *"reduced applicability"*. The paraffinic oil has a reduced time window in these simulations (changing with wind speed) due to high pour points.

**Dispersant use:** In the 50% broken ice scenario it is assumed that spraying from helicopter is *"applicable"* up to 12 m/s wind speed, while spraying from vessel and fixed wing aircraft can be used with *"reduced applicability"*. There are significant differences in the time windows for the different oils. While the naphtenic 2 oil is dispersible the entire simulation period (5 days) at 5 and 10 m/s wind speed, the viscosity borders (lower and upper), established during the weathering and dispersibility studies, limit the time window for the naphtenic 2 and asphaltenic oils. The time window for the paraffinic oil is ruled by the pour point and potential for solidification of the oil. When the pour point exceeds 5°C above sea water temperature dispersant use is judged to have *"reduced applicability"* and when the pour point exceeds 15°C above sea water temperature, use of dispersants is judged to be *"not applicable"*.

**In-situ burning:** In 50% broken ice it is assumed that herders can be used to thicken the oil. Herders are sensitive to wave activity and at wind speeds above 8 m/s it is assumed that herders cannot be used. In such high ice coverage as in this scenario use of FRB is judged to be *"not applicable"*, but uncontained ISB can be used. Use of uncontained ISB is based on the assumption that the oil will be prevented from spreading and thinning by the presence of ice. It is prerequisite that the oil thickness is above 2-5 mm for this method to be used. Uncontained ISB profit by high ice coverage and it is assumed that the ice coverage needs to be at least 40% before this method can be used. At 40-60% broken ice the method is judged to have *"reduced applicability"*. For the paraffinic oil increase in pour point is the most important factor for reduction in time window by use of ISB. For the other oils, water uptake is the main limiting factor.

### Mechanical recovery

Figure 5.10 shows the predicted time window for mechanical recovery on the 4 different groups of crude oils at 3 selected wind speeds, before and after the drifting oil reaches a 50% broken ice area.

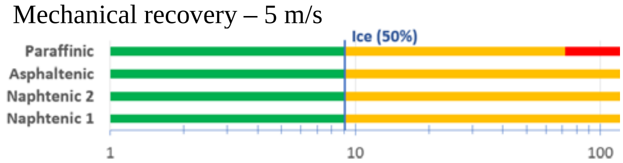
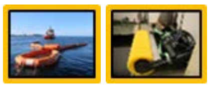
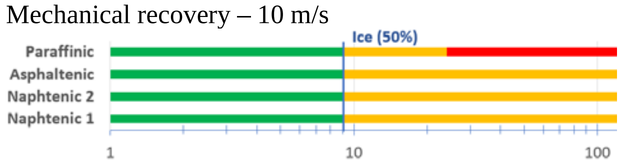
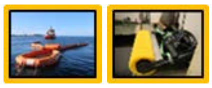
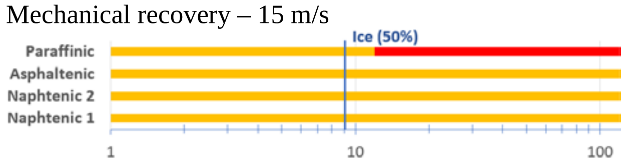
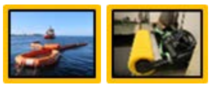
| **Applicability** | **Response in 50% broken ice after 9 hours** |
|---|---|
| Mechanical recovery – 5 m/s<br> | <br>Flexible one-vessel system: *"reduced applicability"*.<br>Uncontained: *"reduced applicability"*.<br>Increased pour point makes mechanical recovery *"not applicable"* for the paraffinic oil after 3 days. Pour point less important if a HiVisc skimmer is being used (see discussion below). |
| Mechanical recovery – 10 m/s<br> | <br>Flexible one-vessel system: *"reduced applicability"*.<br>Uncontained: *"reduced applicability"*.<br>Shorter time window for the paraffinic oil due to more rapid weathering and increase in pour point. |
| Mechanical recovery – 15 m/s<br> | <br>Flexible one-vessel system: *"reduced applicability"*.<br>Uncontained\|: *"reduced applicability"*.<br>Short time window for the paraffinic oil due to increase in pour point. |

*Figure 5.10 Predicted time window for mechanical recovery at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed it is the ice conditions that is judged to be the limiting factor for mechanical recovery in this scenario. It is assumed that flexible one-vessel systems (like e.g. Current Buster and LORS) can be used in 50% broken ice conditions by moving around between scattered ice floes collecting oil, with *"reduced applicability"*. Also, use of an active (e.g. brush drum) skimmer without prior confinement of the oil by a boom, may be feasible. However, because the oil thickness is predicted to be below 20 mm it is judged to have *"reduced applicability"*. All oils can be recovered mechanically throughout the entire simulation period except for the paraffinic oil where one-vessel or uncontained recovery is judged to be *"not applicable"* due to pour point and solidification. According to the decision criteria defined all skimmers, apart from the HiVisc skimmer, have *"reduced applicability"* for pour point below 10°C and are judged to be *"not applicable"* for pour points above 15°C. Similar values for HiVisc skimmer are 15°C and 25°C and provided that HiVisc skimmer can be used together with one vessel systems of uncontained by using the in-built thruster, it can be used for the entire prediction period of 5 days.

At 10 m/s wind speed the same methods for mechanical recovery as for 5 m/s wind speed can be used, still with *"reduced applicability"* due to ice conditions. Because the weathering takes place at a higher speed at 10 m/s wind than at 5 m/s, the time window for the paraffinic oil is shorter at 10 m/s, but a pour point of 25°C will not be reached within the prediction period of 5 days and the time window could be yellow throughout the entire prediction period..

At 15 m/s wind speed *"reduced applicability"* is predicted even before the oil hits the ice due to high winds (> 10 m/s). When the oil is drifting into the 50% broken ice after 9 hours, a combination of the ice and wind conditions makes flexible one-vessel system and skimmer only (uncontained) the only mechanical recovery methods judged to be applicable, still with *"reduced applicability"*. With the same arguments as above the time window for the paraffinic oil could be yellow up to 4 days before the pour point reaches 25°C.

## Dispersant use

Figure 5.11 shows the predicted time window for use of dispersant on the 4 different groups of crude oils at 3 selected wind speeds, before and after the drifting oil reaches a 50% broken ice area.

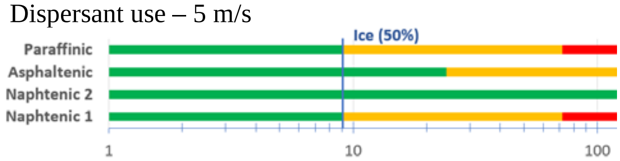
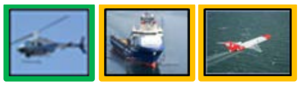
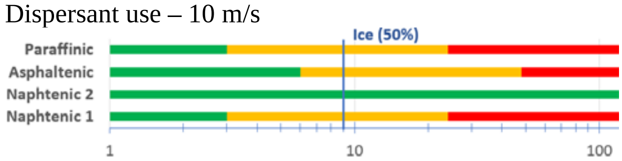
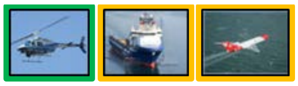
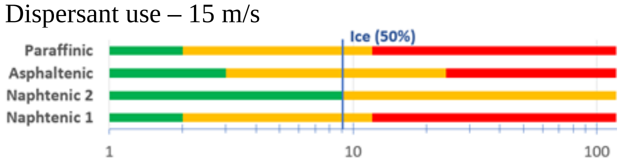
<table>
<tr><th>Applicability</th><th>Response in 50% broken ice after 9 hours</th></tr>
<tr><td>Dispersant use – 5 m/s<br>
</td><td><br>Helicopter spraying: "applicable".<br>Vessel spraying: "reduced applicability".<br>Fixed-wing aircraft spraying: "reduced applicability".<br>Viscosity (naphtenic 1 and asphaltenic oils) and pour point (paraffinic oil) limit the time window for dispersant use.</td></tr>
<tr><td>Dispersant use – 10 m/s<br>
</td><td><br>Helicopter spraying: "applicable".<br>Vessel spraying: "reduced applicability".<br>Fixed-wing aircraft spraying: "reduced applicability".<br>The weathering processes take place more rapidly at higher wind speed, which narrow the time window for dispersant use for 3 of the oil types</td></tr>
<tr><td>Dispersant use – 15 m/s<br>
</td><td><br>Helicopter spraying: " reduced applicability".<br>Vessel spraying: "reduced applicability".<br>Fixed-wing aircraft application: "reduced applicability".<br>Viscosity and pour point limit the potential for dispersant use.</td></tr>
</table>

*Figure 5.11 Predicted time window for use of dispersants at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed dispersants can be applied by helicopter, vessel and aircraft in broken ice conditions with 50% ice coverage. However, vessel and fixed-wing aircraft is judged to have *"reduced applicability"* under such high ice coverage. The naphtenic 1 and asphaltenic oils reach the lower viscosity limit after 9 hours and 1 day respectively (timeline changes from green to yellow) and the naphtenic 1 oil reach the upper viscosity limit after 3 days (from yellow to red). The paraffinic oil reaches a pour point of 5°C above sea water temperature after 9 hours (from green to yellow) and a pour point of 15°C above sea water temperature after 3 days (from yellow to red).

At 10 m/s wind speed the same dispersant applications methods as for 5 m/s wind speed can be used. Because the weathering takes place at a higher speed at 10 m/s wind than at 5 m/s, the time window for dispersant use is somewhat shorter. The same factors as for 5 m/s wind speed are relevant. The naphtenic 1 oil has a lower viscosity limit of 3000 cP which is reached after 3 hours and an upper limit of 7000 cP reached after 24 hours. The same limits for the asphaltenic oil are12000 cP (after 6 hours) and 30000 cP (after 2 days). For the paraffinic oil it is the pour point that is the limiting factor in the time window, as was also the case at 5 m/s.

At 15 m/s wind speed aerial application is judged to have *"reduced applicability"* due to the strong wind (> 12 m/s) and vessel application is judged to have *"reduced applicability"* due to high ice coverage (> 30%). The time window for the paraffinic oil is very short after it reaches the ice field before the pour point exceeds 15°C above sea water temperature. Also, the naphtenic 1 oil has a very short time window in the ice and use of dispersants is judged to be *"not applicable"* due to that the upper viscosity limit of 7000 cP has been exceeded.

### *In-situ* burning

Figure 5.12 shows the predicted time window for *in-situ* burning (ISB) on the 4 different groups of crude oils at 3 selected wind speeds, before and after the drifting oil reaches a 50% broken ice area.

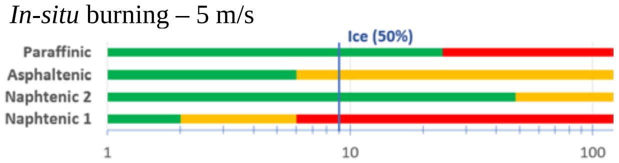
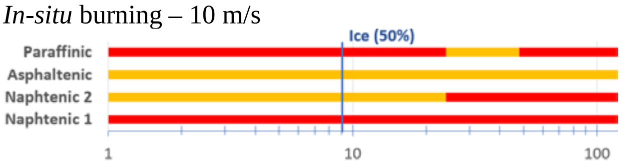
| Applicability | Response in 50% broken ice after 9 hours |
|---|---|
| *In-situ* burning – 5 m/s<br><br> |  <br>Use of herders: *"applicable"*.<br>Uncontained: *"reduced applicability"*.<br>The time window for the naphtenic 1, naphtenic 2 and asphaltenic oils is dependent on the water content in the emulsion, while for the paraffinic oil pour point is determinative. |
| *In-situ* burning – 10 m/s<br><br> | <br>Uncontained: *"reduced applicability"*.<br>Due to a rapid water uptake the naphtenic 1 oil is predicted not to be ignitable. The paraffinic oil is not ignitable the first 15 hours in the ice due to low oil thickness (< 2mm). |
| *In-situ* burning – 15 m/s | ISB is judged to be *"not applicable"* at wind speeds above 12 m/s, because it is extremely difficult to ignite the emulsion and sustain a burn in such high wind speeds. |

*Figure 5.12 Predicted time window for in-situ burning at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed herders can be used to confine the oil in 50% ice coverage, assuming that the oil thickness is between 0.5 and 2 mm. Also uncontained ISB can be used, but with *"reduced applicability"*. Fire-resistant booms (FRB) can be used before the oil hits the ice but are judged to be *"not applicable"* in ice concentrations above 30% as it can collect a lot of ice together with the oil, making ignition and burning difficult. For three of the oils (naphtenic 1 and 2 and asphaltenic oils), water uptake gave a reduction in time window as 30% water is judged to give *"reduced applicability"* while 50% water is judged to make ISB *"not applicable"*. For the paraffinic oil it is an increase in pour point that that makes ISB *"not applicable"* (after 24 hours), when the pour point increased to 10°C above sea water temperature, and herders cannot be used anymore.

At 10 m/s wind speed ignition, flame spreading and burning of oil can be challenging. For the two oils that are judged to be ignitable and burnable, FRB can be used before the oil meets the ice and uncontained ISB can be used in the ice, both with *"reduced applicability"*. The naphtenic 1 oil has a very rapid water uptake and reach a water content of 50% already after 1 hour and is judged not to be ignitable and burnable. The naphtenic 2 oil has a time window of 24 hours before ISB is judged to be *"not applicable"* due to a water content above 50%. Uncontained ISB can be used for the asphaltenic oil after it has met the ice field. For the paraffinic oil the oil thickness is predicted to be too low (< 2mm) for ISB the first 15 hours in the ice field before it increases to above 2 mm. ISB can then be used but is judged to have *"reduced applicability"*. After 48 hours a water content of 50% has been reached and ISB is judged to be *"not applicable"*.

At 15 m/s wind speed ISB is judged to be *"not applicable"* because according to literature it is extremely difficult to ignite and burn an emulsion at wind speeds above 12 m/s.

## 5.5 Scenario 5: Oil drifting into 70% broken ice

Scenario 5 is given the following input parameters:

| Parameter | Values |
|---|---|
| Oil types | Paraffinic oil (represented by Oseberg Blend)<br>Asphaltenic oil (represented by Grane)<br>Naphtenic 2 oil (represented by Wisting Central)<br>Naphtenic 1 oil (represented by Troll B) |
| Release rate | 4000 metric tons/day |
| Release duration | 2 days |
| Total release | 8000 metric tons |
| Sea surface temperature | 0°C |
| Wind speed | 5, 10 and 15 m/s |
| Ice conditions | The weathered oil meets broken ice with an ice coverage of 70% after 9 hours drifting time. |

### SUMMARY

In this scenario it is assumed that the oil is drifting for 9 hours in open Arctic water before it meets a broken ice field with an ice coverage of 70%. The weathered oil will stay in this ice concentration for the weathering prediction period of 5 days. The wave dampening in such ice coverage is expected to be significant which will influence upon further weathering of the oil as the OWM predicts reduced weathering.

**Mechanical recovery:** In 70% broken ice coverage it is assumed that "traditional" booms or one-vessel systems (like e.g. Current Buster and LORS) cannot be used. It is assumed that an active and movable skimmer (e.g. brush drum or brush skimmers) can be used without prior mechanical confinement. It is assumed that the ice can reduce spreading and thinning of the oil and be a kind of a natural confinement. In this study it is assumed that the oil thickness should be 20 mm or more before uncontained mechanical recovery is judged to be applicable. In these simulations the emulsion thickness in the ice varies between 2-7 mm depending on oil type and time after discharge. Therefore, use of a skimmer only is judged to have *"reduced applicability"* under all wind conditions simulated.

**Dispersant use:** In the 70% broken ice scenario it is assumed that a flexible spray arm can be used as an application method. Artificial agitation of the surface oil layer treated with dispersant may be needed to initiate the dispersion process. Helicopter application followed by artificial agitation may also be used but is judged to have *"reduced applicability"* under such high ice coverage (> 50% ice). There is a large difference in time window between the different oils using dispersants. The naphtenic 2 oil can be dispersed using a flexible spray arm for the entire simulation period in ice under all wind conditions simulated. For the naphtenic 1 and asphaltenic oils the lower and upper viscosity limits, as established in laboratory weathering and dispersibility testing, will be determinative for the time windows. The paraffinic oil has high pour point which can promote solidification of the oil. This is not advantageous for use of dispersants and increase in pour point by weathering time and increasing wind speed will influence the time window.

**In-situ burning:** In 70% broken ice the main ISB strategy should be to try to ignite the oil uncontained. Herders can be used at 5 m/s wind speed, but herders are judged to have *"reduced applicability"* at ice coverages between 60-80%. This is because the oil thickness is expected to be so high that there will be no further thickening of the oil layer by use of herders. When the wind speed increases to above 8 m/s ISB by use of herders is judged to be *"not applicable"*. Uncontained ISB will have *"reduced applicability"* at 5 m/s wind speed mainly due to an oil thickness predicted to be under 5 mm, which is used as a minimum ignitable thickness for weathered and emulsified crude oils. ISB and especially ignition and flame spreading are sensitive to wind. For that reason, at 10 m/s wind speed, all methods for ISB is judged to have *"reduced applicability"* (except for herder use where the boarder is 5-8 m/s), while at 15 m/s it is assumed that the oils are not ignitable and ISB is judged to be *"not applicable"*.

### Mechanical recovery

Figure 5.13 shows the predicted time window for mechanical recovery on the 4 different groups of crude oils at 3 selected wind speeds, before and after the drifting oil reaches a 70% broken ice area.

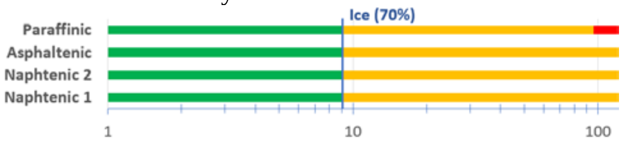
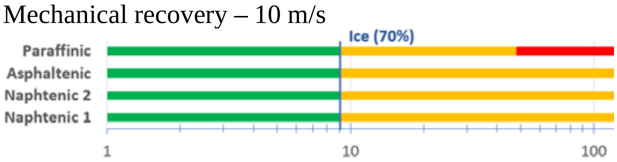
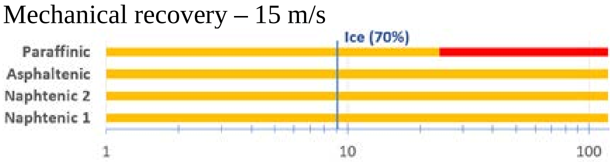
| **Applicability** | **Response in 70% broken ice after 9 hours** |
|---|---|
| Mechanical recovery – 5 m/s<br><br> | <br>Uncontained: *"reduced applicability"*.<br>Oil layer thickness may be a limiting factor for uncontained mechanical recovery. Increased pour point makes mechanical recovery *"not applicable"* for the paraffinic oil after 4 days. |
| Mechanical recovery – 10 m/s<br><br> | <br>Uncontained: *"reduced applicability"*.<br>Predicted oil layer thickness below 20 mm gives the reduction in applicability. Pour point limits the time window for the paraffinic oil. |
| Mechanical recovery – 15 m/s<br><br> | <br>Uncontained: *"reduced applicability"*.<br>Short time window for the paraffinic oil due to increase in pour point. |

*Figure 5.13 Predicted time window for mechanical recovery at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed use of an active and moveable (e.g. brush drum) skimmer without prior confinement of the oil by a boom, may be feasible. It is assumed that the ice can reduce spreading and thinning of the oil and be a kind of a natural confinement. In this study it is assumed that the oil thickness should be 20 mm or more before uncontained mechanical recovery is judged to be applicable. In these simulations the emulsion thickness in the ice varies between 2-6 mm depending on oil type and time after discharge. Therefore, use of a skimmer only is judged to have *"reduced applicability"*. Use of one-vessel systems (e.g. Current Buster, LORS) and "traditional" use of booms and skimmers are judged to be *"not applicable"*, given the prevailing ice conditions. As discussed in the 50% broken ice scenario above all skimmers, apart from the HiVisc skimmer, are judged to have *"reduced applicability"* for pour point below 10°C and judged to be *"not applicable"* for pour points above 15°C. However, if a HiVisc skimmer can be used the upper pour point limit is 25°C, which makes the time window for the paraffinic oil yellow throughout the entire prediction period of 5 days for all wind speeds.

At 10 m/s wind speed the same method for mechanical recovery (active movable skimmer without confinement) as for 5 m/s wind speed can be used, still with *"reduced applicability"* due to ice conditions. Because the weathering takes place at a higher speed at 10 m/s wind than at 5 m/s, the time window for the paraffinic oil is shorter at 10 m/s due to high pour point using the limits for other skimmers than the HiVisc skimmer (see above).

At 15 m/s wind speed *"reduced applicability"* is predicted even before the oil hits the ice due to high winds (> 10 m/s). When the oil is drifting into the 70% broken ice after 9 hours, skimmer only (uncontained) is the only mechanical recovery methods judged to be applicable. Beside wind speed, oil thickness is the main limiting factors as it varies from 2-7 mm in these predictions.

## Dispersant use

Figure 5.14 shows the predicted time window for use of dispersant on the 4 different groups of crude oils at 3 selected wind speeds, before and after the drifting oil reaches a 70% broken ice area.

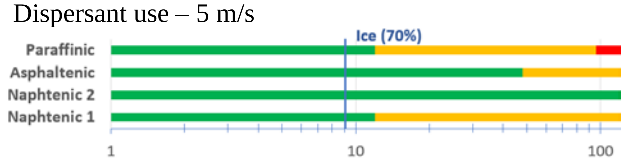
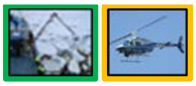
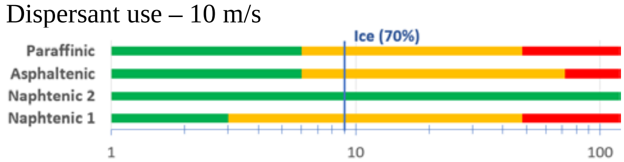
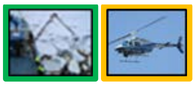
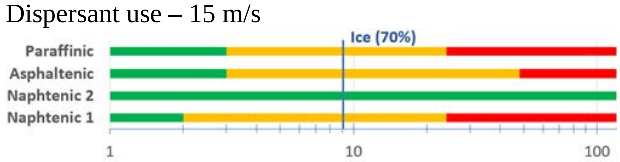
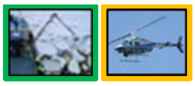
| **Applicability** | **Response in 70% broken ice after 9 hours** |
|---|---|
| Dispersant use – 5 m/s   |  Flexible spray arm: "*applicable*".<br>Helicopter spraying: *"reduced applicability"*.<br>Ice conditions prevent use of vessel and aircraft application. Viscosity (naphtenic 1 and asphaltenic oils) and pour point (paraffinic oil) limit the time window for dispersant use. |
| Dispersant use – 10 m/s   |  Flexible spray arm: "*applicable*".<br>Helicopter spraying: *"reduced applicability"*.<br>Viscosity (naphtenic 1 and asphaltenic oils) and pour point (paraffinic oil) limit the time window for dispersant use. |
| Dispersant use – 15 m/s   |  Flexible spray arm: "*applicable*".<br>Helicopter spraying: *"reduced applicability"*.<br>Viscosity (naphtenic 1 and asphaltenic oils) and pour point (paraffinic oil) limit the time window for dispersant use. |

*Figure 5.14 Predicted time window for use of dispersants at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed dispersants a flexible spray arm can be used as an application method. Artificial agitation of the surface oil layer treated with dispersant may be needed to initiate the dispersion process. Helicopter may also be used but is judged to have *"reduced applicability"* under such high ice coverage. Artificial energy (agitation) will be necessary. While the naphtenic 2 oil is readily dispersible throughout the entire prediction period of 5 days, the naphtenic 1 and asphaltenic oils have time windows indicating *"reduced applicability"*. This is due to that the lower viscosity limit for dispersant efficiency has been reached. For the paraffinic oil the pour point is the limiting factor, 5°C (yellow) and 15°C (red) above sea water temperature.

At 10 m/s wind speed the same dispersant applications methods as for 5 m/s wind speed can be used. Because the weathering takes place at a higher speed at 10 m/s wind than at 5 m/s, the time window for dispersant use is somewhat shorter. The same factors as for 5 m/s wind speed are relevant. The naphtenic 1 oil has a lower viscosity limit of 3000 cP which is reached after 3 hours and an upper limit of 7000 cP reached after 48 hours. The same limits for the asphaltenic oil are12000 cP (after 6 hours) and 30000 cP (after 3 days). For the paraffinic oil it is the pour point that is the limiting factor in the time window, as was also the case at 5 m/s. For the naphtenic 2 oil use of a flexible spray arm is judged to be "*applicable"* throughout the entire simulation period in ice, while use of helicopter to apply dispersant, followed by artificial energy, is judged to have *"reduced applicability"* due to the high ice concentration.

At 15 m/s wind speed the same dispersant applications methods as for 5 and 10 m/s wind speed can be used. It is also the same factors restricting the time window for three of the oils (viscosity and pour point), but due to increased wind speed the weathering processes take place more rapidly and the time windows are shorter that at 10 m/s wind.

### *In-situ* burning

Figure 5.15 shows the predicted time window for *in-situ* burning (ISB) on the 4 different groups of crude oils at 3 selected wind speeds, before and after the drifting oil reaches a 70% broken ice area.

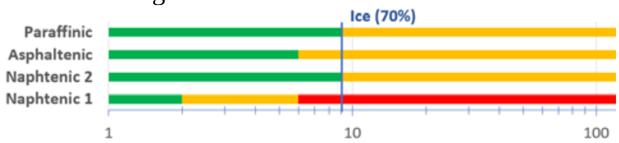
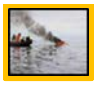
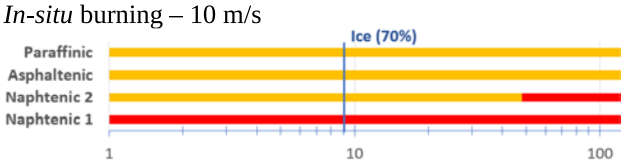
| Applicability | Response in 70% broken ice after 9 hours |
|---|---|
| *In-situ* burning – 5 m/s<br><br> |  <br>Use of herders: *"reduced applicability"*.<br>Uncontained: *"reduced applicability"*.<br>The predicted oil thickness reduces the applicability of uncontained ISB. Use of herders is restricted by the high ice concentration. |
| *In-situ* burning – 10 m/s<br><br> | <br>Uncontained: *"reduced applicability"*.<br>Due to a rapid water uptake the naphtenic 1 oil is predicted not to be ignitable. For the other oils wind speed, oil thickness and water uptake are factors that reduce the applicability of ISB. |
| *In-situ* burning – 15 m/s | ISB is judged to be *"not applicable"* at wind speeds above 12 m/s, because it is extremely difficult to ignite the emulsion and sustain a burn in such high wind speeds. |

*Figure 5.15 Predicted time window for in-situ burning at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed herders can be used to confine the oil but with *"reduced applicability"* due to the high ice coverage. Also uncontained ISB can be used with *"reduced applicability"* due to low oil thickness (< 5mm). Fire-resistant booms (FRB) cannot be used in such high ice concentration. The naphtenic 1 oil is not ignitable when reaching the ice field due to that the water content has reached 50%.

At 10 m/s wind speed ignition, flame spreading and burning of oil can be challenging. For the oils that are judged to be ignitable and burnable, uncontained ISB can be used in the ice with *"reduced applicability"*. The other methods for ISB, FRB and herders, cannot be used due to ice coverage (FRB) and strong winds (herders). The naphtenic 1 oil has a very rapid water uptake and reach a water content of 50% already after 1 hour and is judged not to be ignitable and burnable. ISB as a response option is judged to have *"reduced applicability"* for all the other oils in this scenario due to wind speed higher than 8 m/s, predicted oil thickness < 5mm and water content in the emulsion > 30%. The naphtenic 2 oil reach a water uptake of 50% after 2 days where ISB is judged to be *"not applicable"*.

At 15 m/s wind speed ISB is judged to be *"not applicable"* because according to literature it is extremely difficult to ignite and burn an emulsion at wind speeds above 12 m/s.

## 5.6 Scenario 6: Oil drifting into frazil ice

Scenario 5 is given the following input parameters:

| Parameter | Values |
|---|---|
| Oil types | Paraffinic oil (represented by Oseberg Blend)<br>Asphaltenic oil (represented by Grane)<br>Naphtenic 2 oil (represented by Wisting Central)<br>Naphtenic 1 oil (represented by Troll B)<br>Marine Gas Oil (MGO) |
| Release rate | Crude oils: 4000 metric tons/day; MGO: 167 $m^3$/hour |
| Release duration | Crude oils: 2 days; MGO: 6 hrs |
| Total release | Crude oils: 8000 metric tons; MGO: 1000 $m^3$ |
| Sea surface temperature | 0°C |
| Wind speed | 5, 10 and 15 m/s |
| Ice conditions | The weathered oil meets frazil ice after 9 hours drifting time. |

### SUMMARY

In this scenario it is assumed that the oil is drifting for 9 hours in open Arctic water before it meets an area with frazil ice. The weathered oil will stay in this ice scenario for the prediction period of 5 days. Waves are expected to be able to propagate into frazil/grease ice by Stokes drift. Low frequency waves can penetrate deeper into the ice field. The waves will be dampened in the ice and decay after some time. When the oil is "trapped" in the frazil ice it will influence and slow down further weathering of the oil.

**Mechanical recovery:** This is probably the most challenging ice scenario (frazil ice) for mechanical recovery. Booms cannot be used under these ice conditions and uncontained recovery seems to be the only known mechanical response option available that might have a potential. According to the decision criteria defined as basis for this work the oil thickness should be at least 20 mm for uncontained recovery to be *"applicable"*. For thicknesses 0.2-20 mm the method is judged to have *"reduced applicability"*. The crude oils in this scenario are predicted to have oil thicknesses between 4 to 13 mm when the oil drifts into the ice, with a similar thickness for the MGO predicted to 1 mm. Combined with low recovery rates for brush skimmers in slush ice, as demonstrated in basin experiments (https://www.sintef.no/projectweb/jip-oil-in-ice/publications/), mechanical recovery of the crude oil types studied in this project is judged to have *"reduced applicability"*, on the border to being *"not applicable"*. For the MGO mechanical recovery is judged to be *"not applicable"* due to the low oil thickness. Rotating brush drum skimmers operated from an excavator crane onboard a vessel, floating brush skimmers connected to a vessel by an umbilical or vessel stern mounted brush drums are examples of techniques that can be used in this scenario.

**Dispersant use:** Laboratory experiments performed as part of WP1 in the FateIce project showed that some of the MGO and naphtenic 2 oils migrated rapidly through the frazil ice layer to the surface. The same for the naphtenic 1 oil, but somewhat slower. It's a prerequisite when using dispersants that the oil is on the surface and can contact the dispersant applied. These three oils are assumed to be on the frazil ice surface where they can be treated with dispersants by helicopter application of spray arm. The other oils included in this study floated deeply on top of the ice or were partly pushed down in the ice by the oscillating movement caused by wave action and are probably not so exposed to dispersant application. Powerful artificial energy (for instance water flushing) will be necessary to initiate the dispersion process and push the dispersed oil through the ice layer and into the underlaying sea water. Further laboratory/basin experiments are necessary to evaluate use of dispersants in such an ice scenario and it should also be included in future field experiments.

**In-situ burning:** The minimum ignitable thickness for fresh crude in frazil ice is up to double that on open water, up to 2 mm (Buist et. al., 2013). For weathered oils it is even higher, and the decision rules defined in this project suggest 2-5 mm as *"reduced applicability"* and > 5 mm for *"applicable"*. Flame spreading velocities are significantly reduced in brash ice. The thicknesses for the crude oils in this study are above 2 mm (4-13 mm) when the oil hits the ice, and as such ISB could be a viable response option. MGO has a predicted thickness of 1 mm when hitting the ice, meaning that it is not ignitable. For the crude oils uncontained ISB can be used, provided that the wind speed is not too high (> 12 m/s), but the naphtenic oils may have reduced time windows due to rapid water uptake and too high water contents (> 50%) for ignition.

### Mechanical recovery

Figure 5.16 shows the predicted time window for mechanical recovery on the 4 different groups of crude oils and a Marine Gas Oil (MGO) at 3 selected wind speeds, before and after the drifting oil reaches a frazil ice area.

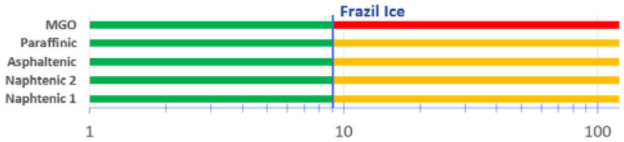
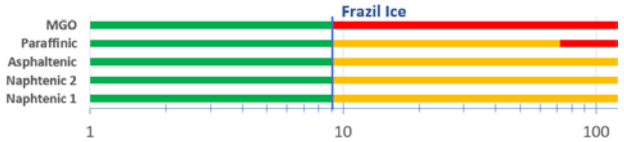
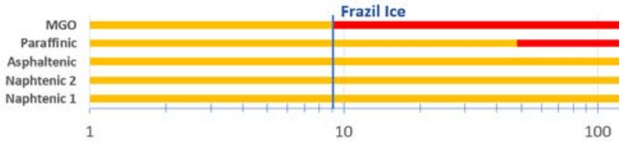
| **Applicability** | **Response in frazil ice after 9 hours** |
|---|---|
| Mechanical recovery – 5 m/s<br><br> | <br>Uncontained recovery: *"reduced applicability"*.<br>Oil layer thickness is predicted to be a limiting factor for uncontained mechanical recovery. MGO has very low thickness when meeting the ice (predicted to be tentatively 1 mm). |
| Mechanical recovery – 10 m/s<br><br> | <br>Uncontained recovery: *"reduced applicability"*.<br>Predicted oil layer thickness below 20 mm gives the reduction in applicability. The paraffinic oil has a shorter time window due to pour point. |
| Mechanical recovery – 15 m/s<br><br> | <br>Uncontained recovery: *"reduced applicability"*.<br>Oil layer thickness, pour point for the paraffinic oil and strong winds reduces the applicability of mechanical recovery in this scenario. |

*Figure 5.16 Predicted time window for mechanical recovery at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed the thickness of the oil layer is predicted to be the main factor making mechanical recovery in this ice condition having *"reduced applicability"*. It is assumed that the oil thickness should be at least 20 mm for making uncontained mechanical recovery applicable in such ice conditions, and the crude oils are predicted to have thicknesses varying from 4 to 13 mm when the oil meets the ice. Basin experiments have shown that although a rotating brush skimmer can recover oil in slush ice, the recovery rate will be very low compared to open water. This is probably the most challenging ice scenario for mechanical recovery and is judged to be on the border between *"reduced applicability"* and *"not applicable"*. For MGO the thickness is predicted to be 1 mm when drifting into the ice and combined with expected low recovery rate due to ice conditions, mechanical recovery is judged to be *"not applicable"*. Rotating brush drum skimmers operated from an excavator crane onboard a vessel, floating brush skimmers connected to a vessel by an umbilical or vessel stern mounted brush drums are examples of techniques that can be used in this scenario.

At 10 m/s wind speed the same methods for uncontained mechanical recovery, as suggested for 5 m/s wind speed, can be used with *"reduced applicability"* due to oil thickness considerations. Because the weathering takes place at a higher speed at 10 m/s wind than at 5 m/s, with a faster increase in pour point, the time window for the paraffinic oil is shorter at 10 m/s.

At 15 m/s wind speed *"reduced applicability"* is predicted even before the oil hits the ice due to high winds (> 10 m/s). When the oil is drifting into the frazil ice after 9 hours, uncontained oil recovery is the only mechanical recovery methods judged to be applicable, but low effectiveness should be expected.

### Dispersant use

Figure 5.17 shows the predicted time window (in hours) for use of dispersant on the 4 different groups of crude oils and a Marine Gas Oil (MGO) at 3 selected wind speeds, before and after the drifting oil reaches a frazil ice area.

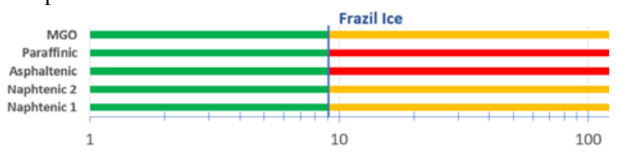
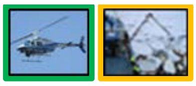
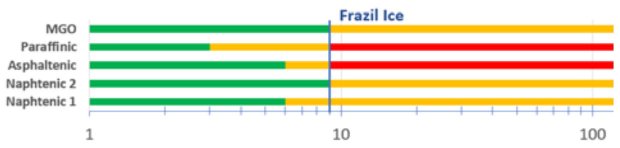
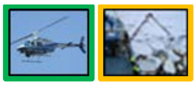
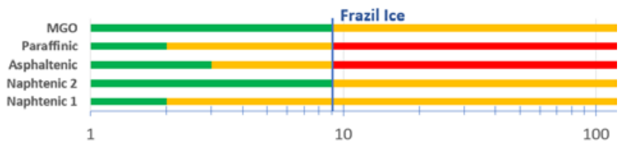
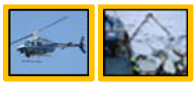
| **Applicability** | **Response in frazil ice after 9 hours** |
|---|---|
| Dispersant use – 5 m/s   |  Helicopter spraying: "*applicable*".<br>Flexible spray arm: *"reduced applicability"*.<br>Artificial energy (agitation) will be necessary to start the dispersion process after dispersant has been applied. |
| Dispersant use – 10 m/s   |  Helicopter spraying: "*applicable*".<br>Flexible spray arm: *"reduced applicability"*.<br>Artificial energy (agitation) will be necessary to start the dispersion process after dispersant has been applied. |
| Dispersant use – 15 m/s   |  Helicopter spraying: *"reduced applicability"*.<br>Flexible spray arm: *"reduced applicability"*.<br>High winds will reduce the applicability using helicopter spraying. |

*Figure 5.17 Predicted time window for use of dispersants at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed use of dispersants is judged to be feasible in this ice scenario for some of the oils. Laboratory experiments performed in the FateIce WP1 indicated considerable differences between different weathered oils for vertical migration in frazil ice. The weathered oil must be on the ice surface to make contact with the dispersant. Especially the MGO and Naphtenic 2 oils migrated rapidly to the ice surface. The naphtenic 1 oil somewhat slower but came to the surface and stayed as a surface film throughout the laboratory experiments. The paraffinic and asphaltenic oils had a much slower rising time, were partly pushed down in the ice layer by wave action or floated deeply on top of the ice. Based on these experiments MGO and the naphtenic 1 and 2 oils are judged to be accessible to dispersant treatment in such an ice scenario. However, powerful artificial energy (for instance water flushing) will be necessary to initiate the dispersion process and push the dispersed oil through the ice layer and into the underlaying sea water. Helicopter application is judged to be *"applicable"* while flexible spray arm is judged to have *"reduced applicability"* due to reduced manoeuvrability in such dense ice conditions.

At 10 m/s wind speed is much the same overall picture as at 5 m/s. The naphtenic 1 oil reach its lower viscosity limit after 6 hours.

At 15 m/s wind speed helicopter application is judged to have *"reduced applicability"* due to high winds. Spray arm can still be used with *"reduced applicability"*.

### *In-situ* burning

Figure 5.18 shows the predicted time window (in hours) for *in-situ* burning (ISB) on the 4 different groups of crude oils and a Marine Gas Oil (MGO) at 3 selected wind speeds, before and after the drifting oil reaches a frazil ice area.

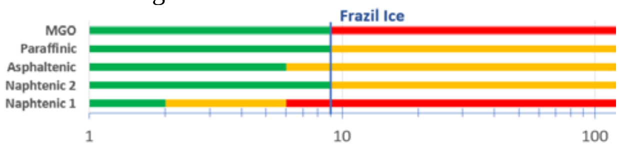
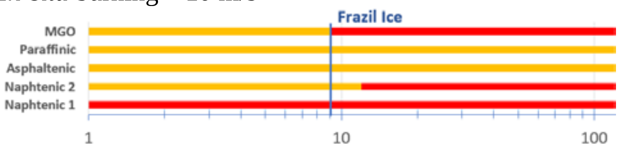
| **Applicability** | **Response in frazil ice after 9 hours** |
|---|---|
| *In-situ* burning – 5 m/s   |  Uncontained: *"reduced applicability"*. Ignitability may be reduced by low oil thickness (below 5 mm) and burnability (e.g. flame spreading) due to ice conditions. FRB and herders cannot be used in the ice. |
| *In-situ* burning – 10 m/s   |  Uncontained: *"reduced applicability"*. Wind speed and ignitability/burnability are limiting factors for all oils. For the two naphtenic oils water uptake above 50% makes the timeline red and for MGO low oil thickness makes it not ignitable when it meets the ice. |
| *In-situ* burning – 15 m/s | ISB is judged to be *"not applicable"* at wind speeds above 12 m/s, because it is extremely difficult to ignite the emulsion and sustain a burn in such high wind speeds. |

*Figure 5.18 Predicted time window for in-situ burning at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed uncontained ISB can be used provided that the oil has sufficient thickness. The minimum ignitable thickness in frazil ice is estimated to be 2 mm. Flame spreading velocities are significantly reduced in frazil ice. Therefore, uncontained ISB in frazil ice is judged to have *"reduced applicability"*. MGO is predicted to have a thickness of 1 mm when the oil reaches the frazil ice area and uncontained ISB is judged to be *"not applicable"*. The naphtenic 1 oil has a water content above 50% when the oil reaches the ice field and ISB is judged to be *"not applicable"*.

At 10 m/s wind speed uncontained ISB can be used for the paraffinic and asphaltenic oils after the oil has been mixed into the ice, with *"reduced applicability"* due to the mixing of weathered oil with frazil ice making ignition and burning more challenging. MGO may still be burnable after it has hit the ice field, but due to spreading in open water the oil thickness is very low (tentatively 1 mm) and it is judged not to be ignitable. For the two naphtenic oils rapid water uptake is the main reason for making ISB *"not applicable"* but the naphtenic 2 oil is still ignitable a few hours after it has migrated into the ice.

At 15 m/s wind speed ISB is judged to be *"not applicable"* because according to literature it is extremely difficult to ignite and burn an emulsion at wind speeds above 12 m/s.

## 5.7 Scenario 7: Oil released in 50% broken ice

Scenario 7 is given the following input parameters:

| Parameter | Values |
|---|---|
| Oil types | Paraffinic oil (represented by Oseberg Blend)<br>Asphaltenic oil (represented by Grane)<br>Naphtenic 2 oil (represented by Wisting Central)<br>Naphtenic 1 oil (represented by Troll B)<br>Marine Gas Oil (MGO) |
| Release rate | Crude oils: 4000 metric tons/day; MGO: 167 $m^3$/hour |
| Release duration | Crude oils: 2 days; MGO: 6 hrs |
| Total release | Crude oils: 8000 metric tons; MGO: 1000 $m^3$ |
| Sea surface temperature | 0°C |
| Wind speed | 5, 10 and 15 m/s |
| Ice conditions | Fresh oil is released in 50% broken ice. |

### SUMMARY

In this scenario it is assumed that the oil is released within a broken ice field with 50% ice coverage. The oil will stay in this ice scenario for the simulation period of 5 days. Waves are expected to be dampened in the ice which will have an influence on weathering of the oil and the potential for different response options.

**Mechanical recovery:** A broken ice scenario with an ice coverage of 50% can be viewed as being among the most challenging conditions for mechanical recovery. "Traditional" booms cannot be used in such high ice coverage. One-vessel systems like e.g. current buster can be used, but in ice coverages above 30% they are judged to have *"reduced applicability"* due to reduced manoeuvrability and collection of ice together with the oil. Use of uncontained oil recovery (e.g. using a skimmer without use of booms) requires an ice coverage above 50% to be fully applicable, as the oil may spread to a thickness below what is possible to recover mechanically. Therefore, all mechanical response options defined to have a potential in this scenario are judged to have *"reduced applicability"* under all wind conditions predicted.

**Dispersant use:** Helicopter spraying is judged to be *"applicable"* at wind speeds 5 and 10 m/s in this scenario, with *"reduced applicability"* at higher wind speed. Both fixed-wing aircraft application and vessel application is hampered by the ice conditions and is assumed to have *"reduced applicability"*. Due to the weathering taking place the viscosity of the oils increases and the naphtenic 1 and asphaltenic oils reach viscosity limits as established in dispersibility testing as part of laboratory weathering studies. For the paraffinic oil it is the pour point and the potential for solidification that restrict the time window.

**In-situ burning:** At 5 m/s wind there is a fairly long time-window where ISB is *"applicable"* for most of the oils, stretching from 9 hours to 4 days. Confinement and thickening of the oil are judged to be necessary and fire-resistant booms cannot be used in such high ice coverage. Then use of herders is the only option in such a scenario. Herders are sensitive to wind and at a wind speed above 8 m/s they cannot be use anymore. Then uncontained ISB is judged to be the only option at 10 m/s wind, but according to the decision rules with *"reduced applicability"* due to low ice coverage (< 60%) and high wind speed that may influence on ignition (> 8 m/s). Thickness of the oil layer may be a challenge for several of the oils, but because this is fresh oils released inside the ice it is anticipated that they can be ignited and burned at somewhat lower thickness than weathered oils drifting into the ice. For the oils where the time window turns into red that is due to that the oil has reached a water uptake of 50% and is judged to be not ignitable.

## Mechanical recovery

Figure 5.19 shows the predicted time window for mechanical recovery on the 4 different groups of crude oils and a Marine Gas Oil (MGO) at 3 selected wind speeds, as the oils weather in the ice field.

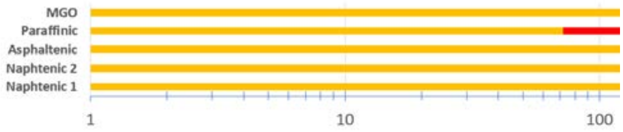
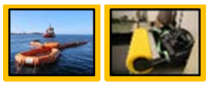
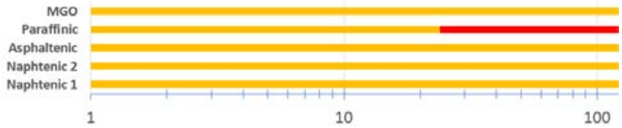
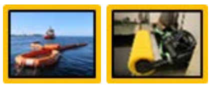
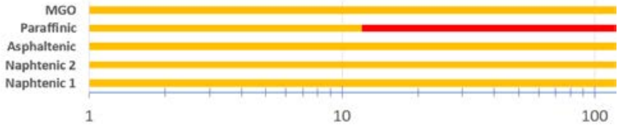
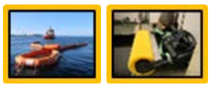
| **Applicability** | **Response in 50% broken ice** |
|---|---|
| Mechanical recovery – 5 m/s   |  Flexible one-vessel system: *"reduced applicability"*. Uncontained recovery: *"reduced applicability"*. Ice coverage (> 30%) is a limiting factor for one-vessel systems and oil layer thickness (< 20mm) is a limiting factor for uncontained recovery. |
| Mechanical recovery – 10 m/s   |  Flexible one-vessel system: *"reduced applicability"*. Uncontained recovery: *"reduced applicability"*. The overall picture is like 5 m/s wind. Due to more rapid weathering and pour point increase at 10 m/s wind, the time window for the paraffinic oil is shorter. |
| Mechanical recovery – 15 m/s   |  Flexible one-vessel system: *"reduced applicability"*. Uncontained recovery: *"reduced applicability"*. Restrictions in use of mechanical recovery are the same as for 5 and 10 m/s wind speed. In addition a wind speed of 15 m/s is judged to reduce the applicability for all mechanical response options. |

*Figure 5.19 Predicted time window for mechanical recovery at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed use of flexible one-vessel systems or uncontained recovery (skimmer only) can be used, but with *"reduced applicability"*. One-vessel systems utilize small and flexible booms and according to decision rules implemented in this project, the ice coverage should have been below 30% for these systems to work optimally. Uncontained recovery, for instance by use of a skimmer only, requires that the oil is confined and up concentrated by the ice. An oil thickness higher than 20 mm and ice coverage higher than 50% is assumed to be necessary for optimal use of uncontained recovery. The paraffinic oil faces some problems with high pour point and risk for solidification after 3 days of weathering. Use of "traditional" booms is judged not to be applicable in this scenario, because there is too much ice.

At 10 m/s wind speed the same strategies and response methods as for 5 m/s wind speed can be used. One-vessel systems like current buster and LORS can be used in this scenario with the restrictions regarding ice coverage as mentioned above. Rotating brush drum skimmers operated from an excavator crane onboard a vessel, floating brush skimmers connected to a vessel by an umbilical or vessel stern-mounted brush drums are examples of uncontained recovery techniques that can be used in this scenario. Use of skimmers without prior confinement of the oil by a boom requires that the ice can act to confine the oil, so it can reach a thickness the skimmer can operate effectively in.

At 15 m/s wind speed flexible one-vessel systems or uncontained recovery (skimmer only) can still be used with *"reduced applicability"*. In addition to the restrictions mentioned above, a wind speed of 15 m/s is judged to reduce the applicability for all mechanical recover options. The paraffinic oil reaches a pour point 15°C above the sea water temperature and a risk for solidification after 12 hours.

## Dispersant use

Figure 5.20 shows the predicted time window for use of dispersant on the 4 different groups of crude oils and a Marine Gas Oil (MGO) at 3 selected wind speeds, as the oils weather in the ice field.

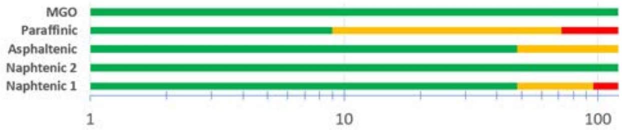
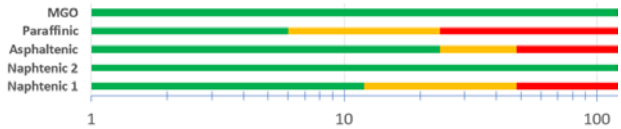
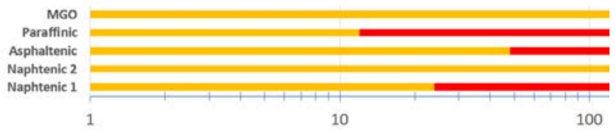
| **Applicability** | **Response in 50% broken ice** |
|---|---|
| Dispersant use – 5 m/s   |  Helicopter spraying: *"applicable"*.<br>Vessel spraying: *"reduced applicability"*.<br>Fixed-wing aircraft spraying: *"reduced applicability"*.<br>For the naphtenic 1 and asphaltenic oils the viscosity reduces the time window, while for the paraffinic oil it is the pour point. |
| Dispersant use – 10 m/s   |  Helicopter spraying: *"applicable"*.<br>Vessel spraying: *"reduced applicability"*.<br>Fixed-wing aircraft spraying: *"reduced applicability"*.<br>The same response options as for 5 m/s wind with shorter time-windows for 3 of the crude oils. |
| Dispersant use – 15 m/s   |  Helicopter spraying: *"reduced applicability"*.<br>Vessel spraying: *"reduced applicability"*.<br>Fixed-wing aircraft spraying: *"reduced applicability"*.<br>All application methods are judged to have *"reduced applicability"* when the wind speed has increased to 15 m/s, but the three methods defined above can still be used. |

*Figure 5.20 Predicted time window for use of dispersants at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed helicopter spraying is judged to be *"applicable"* in this scenario. Application by fix-wing aircraft is assumed to have *"reduced applicability"* in 30-50% ice coverage and vessel application the same in 30-60% ice. Both MGO and the naphtenic 2 oil have a long time-window stretching over the entire prediction period of 5 days. The naphtenic 1 oil meets the lower (2 days) and the upper (4 days) viscosity limits established during dispersibility testing of the oil as part of a weathering laboratory study. The asphaltenic oil meets the lower viscosity limit after 2 days of weathering. For the paraffinic oil it is the pour point and the potential for solidification that restrict the time window.

At 10 m/s wind speed the same response options as for 5 m/s wind is recommended. However, at increased wind speed the weathering processes take place more rapidly and it takes shorter time for the naphtenic 1 and asphaltenic oils to meet their viscosity limits and for the paraffinic oil to meet its pour point limits.

At 15 m/s wind speed helicopter spraying is changed from *"applicable"* to having *"reduced applicability"* due to increased wind speed. The applicability of dispersant application by aircraft and vessel is still reduced due to the ice conditions. The upper viscosity limit reduces the time window for the naphtenic 1 and asphaltenic oils while pour point and the potential for solidification does the same for the paraffinic oil.

### *In-situ* burning

Figure 5.21 shows the predicted time window for *in-situ* burning (ISB) on the 4 different groups of crude oils and a Marine Gas Oil (MGO) at 3 selected wind speeds, as the oils weather in the ice field.

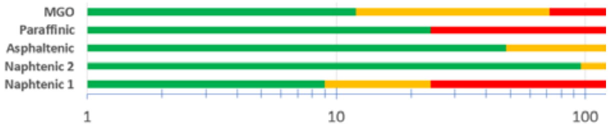
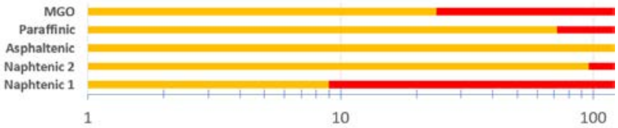
| **Applicability** | **Response in 50% broken ice** |
|---|---|
| *In-situ* burning – 5 m/s   |  Use of herders: *"applicable"*.<br>In 50% broken ice, oil can be ignited and burned. Methods for confinement and thickening are necessary. Fire-resistant booms cannot be operated in 50% ice but use of herders is an option. |
| *In-situ* burning – 10 m/s   |  Uncontained: *"reduced applicability"*.<br>Wind and ice conditions make use of herders and fire-resistant booms inapplicable. Use of uncontained ISB is hampered by ice, wind and oil thickness. |
| *In-situ* burning – 15 m/s | ISB is judged to be *"not applicable"* at wind speeds above 12 m/s, because it is extremely difficult to ignite the emulsion and sustain a burn in such high wind speeds. |

*Figure 5.21 Predicted time window for in-situ burning at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed herders can be used to confine and thicken the oil before ignition. The time windows are somewhat restricted, due to water uptake for the crude oils, except for the paraffinic oil. It is assumed that when a water content of 30% have been reached there will be *"reduced applicability"* for ISB and above 50% the methodology is judged to be *"not applicable"*. For the paraffinic oil increasing pour point reduces the applicability. MGO is ignitable and burnable under these conditions, but after 12 hours the oil thickness is predicted to be below 1 mm when ISB is judged to have *"reduced applicability"* and it is judged to be *"not applicable"* after 3 days when the oil thickness falls below 0.5 mm.

At 10 m/s wind speed herders cannot be used due to the wind conditions (wind speed > 8 m/s). Use of fire-resistant booms is judged to be inapplicable due to ice coverage above 30%. Uncontained ISB can be used, but according to the decision rules with *"reduced applicability"* due to low ice coverage (< 60%) and high wind speed that may influence on ignition (> 8 m/s). Thickness of the oil layer may be a challenge for several of the oils, but because this is fresh oils released inside the ice it is anticipated that they can be ignited and burned at somewhat lower thickness than weathered oils drifting into the ice. For the oils where the time window turns into red that is due to that the oil has reached a water uptake of 50% and is judged to be not ignitable.

At 15 m/s wind speed ISB is judged to be *"not applicable"* because according to literature it is extremely difficult to ignite and burn an emulsion at wind speeds above 12 m/s.

## 5.8 Scenario 8: Oil released in 70% broken ice

Scenario 8 is given the following input parameters:

| Parameter | Values |
|---|---|
| Oil types | Paraffinic oil (represented by Oseberg Blend)<br>Asphaltenic oil (represented by Grane)<br>Naphtenic 2 oil (represented by Wisting Central)<br>Naphtenic 1 oil (represented by Troll B)<br>Marine Gas Oil (MGO) |
| Release rate | Crude oils: 4000 metric tons/day; MGO: 167 $m^3$/hour |
| Release duration | Crude oils: 2 days; MGO: 6 hrs |
| Total release | Crude oils: 8000 metric tons; MGO: 1000 $m^3$ |
| Sea surface temperature | 0°C |
| Wind speed | 5, 10 and 15 m/s |
| Ice conditions | Fresh oil is released in 70% broken ice. |

### SUMMARY

In this scenario it is assumed that the oil is released within a broken ice field with 70% ice coverage. The oil will stay in this ice scenario for the simulation period of 5 days. Waves are expected to be dampened in the ice which will have an influence on weathering of the oil and the potential for different response options.

**Mechanical recovery:** In 70% broken ice uncontained recovery is judged to be the only mechanical response method available. That can be a rotating brush drum skimmer operated from an excavator crane onboard a vessel, a floating brush skimmer operated by thrusters and connected to a vessel by an umbilical or vessel stern mounted brush drum skimmers. Use of "traditional" booms and one-vessel systems is judged to be *"not applicable"* due to the high ice coverage. High pour point is judged to limit the time window for the paraffinic oil but a HiVisc skimmer can handle solidified oil with higher pour point than the other skimmers evaluated and the time window for the paraffinic oil would be longer.

**Dispersant use:** Use of dispersants in such a scenario is judged to be a relevant response option. A flexible spray arm operated from a vessel can be recommended application method, but it may take some time to cover larger areas. Artificial energy will be needed and can be supplied by prop-wash or water flushing. Helicopter application can cover larger areas more rapidly, but in dense ice, as in this scenario, it will be less accurate in hitting the oil and not the ice. Therefore, it is evaluated to have *"reduced applicability"*. Artificial energy will be necessary to initiate the dispersion process which requires additional vessel support. Because the weathering processes take place more slowly in high ice coverage, the time windows for use of dispersants is generally long, especially for MGO and the naphtenic 2 oil.

**In-situ burning:** An emulsion should have a thickness of around 5 mm while a fresh un-weathered oil can be ignited and burned at lower thicknesses (tentatively 2-5 mm). In 70% ice coverage it is assumed that the ice can act to confine the oil to thicknesses high enough for ignition and burning. Uncontained ISB is judged to be *"applicable"* in this scenario, while herders can be used in areas where the oil thickness is below 2 mm. The MGO is judged to have a somewhat reduced time window due to spreading/thinning of the oil slick, but this can be overcome if herders can be used to confine the oil slick. The naphtenic 1 oil has a reduced time window due to a water uptake which is more rapid than for the other oils. However, ISB can be used in this scenario, but with the overall judgement of *"reduced applicability"* when the wind increases to above 8 m/s and ignition is judged to be more challenging.

### Mechanical recovery

Figure 5.22 shows the predicted time window for mechanical recovery on the 4 different groups of crude oils and a Marine Gas Oil (MGO) at 3 selected wind speeds, as the oils weather in the ice field.

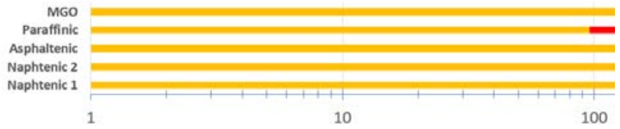
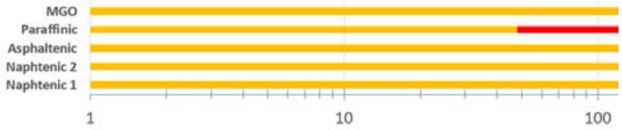
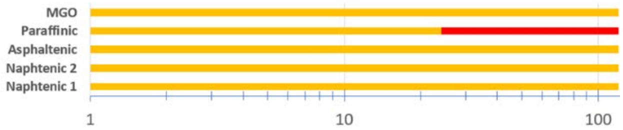
| Applicability | Response in 70% broken ice |
|---|---|
| Mechanical recovery – 5 m/s   |  Uncontained recovery: *"reduced applicability"*. Mean oil layer thickness is predicted to be below 20 mm, which is a limiting factor for uncontained recovery. However, it is assumed that pockets of oil between ice floes can have thickness above 20 mm. |
| Mechanical recovery – 10 m/s   |  Uncontained recovery: *"reduced applicability"*. The same response option as at 5 m/s wind. High pour point limits the time window for the paraffinic oil. |
| Mechanical recovery – 15 m/s   |  Uncontained recovery: *"reduced applicability"*. Restrictions in use of mechanical recovery are the same as for 5 and 10 m/s wind speed. In addition a wind speed of 15 m/s is judged to reduce the applicability for all mechanical response options. |

*Figure 5.22 Predicted time window for mechanical recovery at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind in the ice conditions defined uncontained recovery is assumed to be the only relevant option, but with *"reduced applicability"* due to oil layer thickness. Use of "traditional" booms and one-vessel systems is judged to be *"not applicable"* due to the high ice coverage. The decision rules used say that the oil thickness should be above 20 mm before uncontained recovery is judged to be applicable. There can be areas within the ice field with higher thickness that that, but the mean oil thickness is predicted to be below 20 mm. Rotating brush drum skimmers operated from an excavator crane onboard a vessel, floating brush skimmers connected to a vessel by an umbilical or vessel stern mounted brush drums are examples of techniques that can be used in this scenario.

At 10 m/s wind speed the time window for the paraffinic oil is shorter that at 5 m/s wind due to more rapid weathering. In general, mechanical recovery still is judged to have *"reduced applicability"* and it is the oil layer thickness that is the limiting factor. However, increased wind speed can cause the oil to be further confined between ice floes and give increased oil thickness which is an advantage for uncontained mechanical recovery.

At 15 m/s wind speed uncontained mechanical recovery can still be used. The possibilities to find pockets of oil with higher oil thickness may be even higher in this strong wind scenario, but the skimmer operation can be more challenging at increased wind speed.

### Dispersant use

Figure 5.23 shows the predicted time window for use of dispersant on the 4 different groups of crude oils and a Marine Gas Oil (MGO) at 3 selected wind speeds, as the oils weather in the ice field.

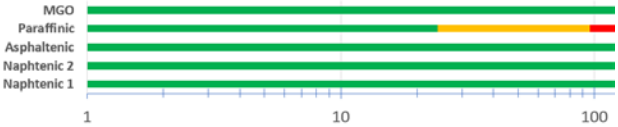
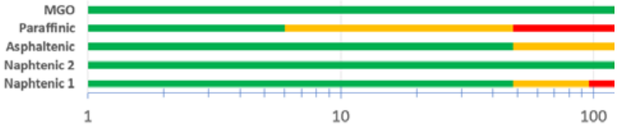
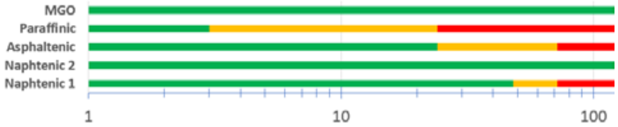
| **Applicability** | **Response in 70% broken ice** |
|---|---|
| Dispersant use – 5 m/s<br> |  <br>Flexible spray arm: "*applicable*".<br>Helicopter spraying: *"reduced applicability"*.<br>Flexible spray arm can be used in combination with artificial turbulence (prop-wash). Helicopter application is less efficient in ice coverages above 50%. |
| Dispersant use – 10 m/s<br> |  <br>Flexible spray arm: "*applicable*".<br>Helicopter spraying: *"reduced applicability"*.<br>The same response options as for 5 m/s wind with shorter time-windows for 3 of the crude oils. |
| Dispersant use – 15 m/s<br> |  <br>Flexible spray arm: "*applicable*".<br>Helicopter spraying: *"reduced applicability"*.<br>Viscosity limits for two of the oils and pour point for one, limits the time windows. |

*Figure 5.23 Predicted time window for use of dispersants at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed flexible spray arm can be used but needs to be combined with addition of extra turbulence because the energy conditions in such high ice coverage is expected to be insufficient to start the dispersion of the treated oil slick. All oils are dispersible for the 5 days prediction period, except the paraffinic oil that face challenges with pour point and solidification. Use of helicopter application is hampered by the high ice coverage but can be used with *"reduced applicability"*.

At 10 m/s wind speed the same application methods as for 5 m/s wind can be used. Both MGO and the naphtenic 2 oil are dispersible throughout the entire prediction period of 5 days. The asphaltenic and naphtenic 1 oils have shorter time windows due to the viscosity limits for dispersibility, established through laboratory testing. The paraffinic oil faces some challenges with high pour points.

At 15 m/s wind speed a flexible spray arm can still be used with un-reduced applicability. The time window is shorter for three of the oils caused by the same factors as above and faster weathering of the oils due to increased wind speed. However, MGO and the naphtenic 2 oil are still dispersible over the entire prediction period.

### *In-situ* burning

Figure 5.24 shows the predicted time window for *in-situ* burning (ISB) on the 4 different groups of crude oils and a Marine Gas Oil (MGO) at 3 selected wind speeds, as the oils weather in the ice field.

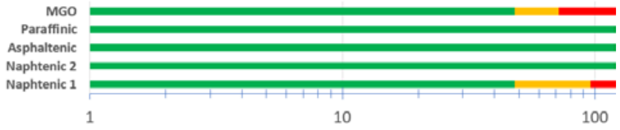
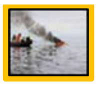
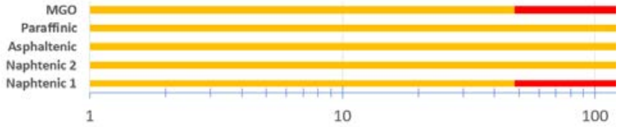
| **Applicability** | **Response in 70% broken ice** |
|---|---|
| *In-situ* burning – 5 m/s<br> |  <br>Uncontained: *"applicable"*.<br>Use of herders: *"reduced applicability"*.<br>In such high ice coverage, it is expected that the ice will confine the oil to a thickness high enough for ignition and burning. Herders can be used but are judged not to have any effect on oils that already has a certain thickness (> 0.5-2 mm) |
| *In-situ* burning – 10 m/s<br> | <br>Uncontained: *"applicable"*.<br>Wind and ice conditions make use of herders and fire-resistant booms inapplicable. Use of uncontained ISB is still judged to be *"applicable"*, but ignition is challenging at this high wind speed. |
| *In-situ* burning – 15 m/s | ISB is judged to be *"not applicable"* at wind speeds above 12 m/s, because it is extremely difficult to ignite the emulsion and sustain a burn in such high wind speeds. |

*Figure 5.24 Predicted time window for in-situ burning at 3 different wind speeds. The x-axis gives drifting time in hours (logarithmic scale).*

At 5 m/s wind speed the relatively fresh oil can be ignited and burned without prior confinement and thickening of the oil. An emulsion should have a thickness of around 5 mm while a fresh un-weathered oil can be ignited and burned at lower thicknesses (tentatively 2-5 mm). The naphtenic 1 oil reach a water content of 30% after 2 days when ISB is judged to have *"reduced applicability"* and a water content of 50% after 4 days when it is not ignitable and burnable anymore. The MGO has a somewhat reduced time window due to spreading/thinning of the oil slick making ignition difficult.

At 10 m/s wind speed herders cannot be used due to the wind conditions (wind speed > 8 m/s). Use of fire-resistant booms is judged to be inapplicable due to ice coverage above 30%. Uncontained ISB can be used, but according to the decision criteria ISB will have *"reduced applicability"* due to wind speed. Thickness of the oil layer may be a challenge for several of the oils, but because this is fresh oils released inside the ice it is anticipated that they can be ignited and burned at somewhat lower thickness than weathered oils drifting into the ice. Also, due to the high ice coverage thicker oil can be found in pockets between ice floes and can be further thickened by the increasing wind. For the naphtenic 1 oil a water content of 50% limit the time window, while for the MGO predicted low oil thickness limits the time window.

At 15 m/s wind speed ISB is judged to be *"not applicable"* because according to literature it is extremely difficult to ignite and burn an emulsion at wind speeds above 12 m/s.

## 6 References

Data on ignitability are found in literature combined with data from field trials in 2008, 2009 and 2016. Literature referenced is: Brandvik et al., 2010; Buist et al., 2013A; Buist et al., 2013B; Buist et al., 2016; Dickins 2017.

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