

LOW SULPHUR FUELS IN THE ARCTIC

FINAL REPORT

MAY 2025



EMERGENCY PREVENTION,
PREPAREDNESS AND RESPONSE

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PREFACE

Arctic conditions possess other challenges for oil spill response compared to open and more temperate waters, such as the remoteness of the area, the low temperatures, seasonal darkness, and the presence of ice. Low Sulphur Fuel Oil (LSFO) was a relatively new type of fuel in an Arctic setting when the joint PAME and EPPR project “Low Sulphur Fuels - Fate and Behaviour in Cold Water Conditions” was started in the year 2020. The extent of the use of LSFO and the properties of such fuel in the Arctic were mostly unknown at this time. The project duration 2020–2025 was greatly influenced by COVID and the pause in the Arctic Council work due to the conflict between Russia and Ukraine.

This report summarizes the key findings from five work packages. The different reports and memos from these work packages are attached to this summary report when submitted to PAME and EPPR for approval. All these documents will be made available in the 'Publications' section on both the PAME and EPPR websites.

The project had a goal to identify the most frequently used low Sulphur bunker fuels used by ships operating in the Arctic Sea areas, and the basic fuel oil properties of these fuels. This knowledge is important for contingency planning, oil spill preparedness, and potential recovery operations. In addition, the project analyzed the properties of several selected fuels sourced from fuel oil providers supplying fuel for ships sailing in the Arctic in greater detail. The key findings, which focus on the fate, behavior, and toxicity of these fuels, have been reported. The goal of the project has been successfully achieved, and the key findings are provided in this report.

Findings identify changes in types of fuels or fuel specifications that could reduce the environmental risk in the Arctic. Important follow-up projects to fill new knowledge gaps uncovered during the project implementation are also recommended. Identifying these knowledge gaps is an important finding from the project in its own right and could be crucial for understanding LSFO and the reasons for their variation in behavior when spilled on a cold sea surface.

The project has received core financing from the Norwegian Ministry of Foreign affairs throughout the duration of the project.

The following laboratories from Canada, China, Norway, Sweden, and USA have made in-kind contributions to this project:

- Canada, ECCC, Michael Goldthorp/Robert Faragher
- China, Tongji University (TJU), Sijie Lin /Zhibo Lu
- Norway, SINTEF Ocean, Liv-Guri Faksness/Kristin R. Sørheim
- Sweden, Chalmers University, Ida-Maja Hassellöv
- USA, EPA, Mace Barron/Robyn Conmy

Experts from the Kingdom of Denmark, Iceland, Finland, Norway, Sweden, USA, Germany, Korea and Singapore have also participated in the project. Additionally, experts from the industry and NGOs have contributed, including DNV, WWF and SINTEF. A sincere thanks is given to the project participants, especially for the in-kind contributions, your contributions are highly valued.

One very important event, in this project, was meeting different commercial companies in the fuel industry. The aim of the so-called industry involvement workshop was to exchange knowledge and discuss the different challenges related to LSFOs, from different perspectives. The workshop, organized in Trondheim, Norway, February 2024, was a great success with participants representing more than 12 countries. A sincere thanks to:

- Barbara Heyberger (Marine Fuel Specialist, TotalEnergies)
- Charlotte Røjgaard (Global Marine Fuels Director, Bureau Veritas (VeriFuel))
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- Ole Gunnstein Aasbø (Senior claims Advisor, Gard)
- Richard Johnson (Technical Director, ITOPF)

for their very valuable contributions.

Arendal, 25.02.2025

Jon-Arve Røyset, Project coordinator

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1. EXECUTIVE SUMMARY

The EPPR/PAME project “Low Sulphur Fuels - Fate and Behaviour in Cold Water Conditions” was approved in 2019 and completed in 2025. The primary goal with the project was to address knowledge gaps regarding the use of low-sulphur fuels in the Arctic and assess the environmental impact of potential spills.

In 2019 the fate and behaviour of low sulphur fuel oils (LSFOs) spilled at sea was largely unknown, because this type of oil was a relatively new product, introduced to replace fuel oils banned under global sulphur fuel cap, which was implemented January 1, 2020 by the IMO. As a result of the regulatory developments, an increasing number of “new generation” LSFOs are currently being marketed for replacement of the conventional fuel types, such as heavy fuel oil (HFO) with a high content of sulphur (0.5–3.5%S).

Early analyses of the new generation LSFOs indicated that this oil type had properties that would be extremely challenging to respond to if spilled, especially if spilled into the cold Arctic environment. Therefore, this project aimed at investigating use of LSFOs in the Arctic and what properties these oils have (WP1), by using AIS data combined with bunker fuel oil data from the commercial laboratory Veritas Petroleum Services (VPS). Based on findings from these data, representative LSFOs oils used by ships sailing in the Arctic, was characterised in the laboratory (WP3/4). This work was done to get an in depth understanding about the observed variation in the physical and chemical properties, as well as getting a better understanding of fate and behaviour of LSFO spills in a cold environment, by studying toxicity, potential for natural attenuation and the effectiveness for mitigation using dispersants and *in-situ* burning (WP3/WP4 /WP5).



KEY FINDINGS FROM THIS PROJECT

1

This report provides valuable information on properties of LSFOs, including density, viscosity and pour point. Knowledge about the properties of LSFOs are key to ensure appropriate contingency planning, oil spill preparedness, and potential recovery operations if such fuel oil is accidentally discharged into the sea.

2

Using AIS data, paired with commercial bunker fuel oil data this project gained knowledge about what fuels are used, the volumes in use, and the basic fuel oil characteristics of these fuels. Findings show that there is a wide variation in properties, especially in pour point, after the implementation of the “Sulphur fuel cap”.

3

The industry involvement workshop organized as a part of this project was successful in gathering people to discuss the fate and behavior of fuel spills in cold water. Discussion topics included LSFO blending processes, emphasizing the role of additives and cutter stocks when blending LSFOs to the correct specifications; and addressing operational challenges, using fuels with high pour points, faced by shipowners in Arctic environments.

4

Findings from characterizing seven different LSFOs used in the Arctic, showed that the physical and chemical properties varied greatly among the analysed LSFOs, especially the viscosities (at low temperature) and pour point. Toxicity studies showed variable effects, with some LSFOs causing up to 100% mortality in test organisms, while others exhibited low toxicity.

5

Findings from fate and behavior testing indicates that response efforts like the use of chemical dispersants and *in-situ* burning have no or limited effect as response options.

The results from this project highlight the importance of detailed fuel characterization and expertise in determining optimal spill response strategies. The properties of these fuel oils, and their behavior on cold water surface, present significant challenges for oil spill response and cleanup operations in Arctic waters.

Analysis of used fuels in the Arctic shows that IMO's "Arctic HFO ban" outlined in MARPOL Annex 1, which came into effect on July 1, 2024, did not prohibit all residual fuels previously used by ships in the area in the Polar Code Area, as several LSFOs, which are residual fuels, will still be permitted for use having both densities and viscosities compliant with the regulations. The results from this project indicate that the many LSFOs likely will have a high degree of persistence in the Arctic environment due to the high pour points or high viscosity at low temperature. LSFOs with high pour points will solidify, or to different degrees become sticky and stiff, if accidentally discharged to a cold sea surface. As a result, an incident involving spillage of LSFO could lead to serious impacts on the Arctic marine and coastal environment, as it may be very difficult to remove the oil with conventional oil spill response equipment and methods, as well as being resistant to biodegradation.

This report identifies fuels with a high pour point as especially challenging after an acute spill in the Arctic. Fuels with a higher pour point than the water temperature will solidify to solid lumps. These lumps can drift over long distances with wind and current and in worst case freeze into the sea ice or sink. In the Arctic environment this is problematic because lumps break down slowly and may give long-term unknown negative effects, including potential release of toxins over the long term. The possibility of effective oil spill cleanup operations can also be limited in the Arctic. Therefore, fuels that remain in a liquid form when spilled and dilute and biodegrade with the help of the forces of nature are considered the better choice in remote Arctic waters.

Measuring the viscosity at only 50 °C as required by ISO 8217 is identified as incomplete for oil responders because the viscosity normally changes considerably at lower temperatures.

Prohibiting fuels with kinematic viscosity higher than 180 mm²/s measured at 5 °C and setting a requirement for an upper pour point value of 0°C (based on ISO 8217 summer requirements for DMZ and DMA), has been identified to alleviate significant challenges for spill cleanup ((i.e., the formation of solid lumps) and to reduce persistence of spilled fuel oil in the Arctic.

Distillate fuels do not present the same challenge for oil spill recovery and are generally less persistent in the marine environment. The use of distillates in the Polar Code Area would help mitigate the risks associated with a spill and could provide additional protection as sought under the Arctic HFO fuel ban.

Ensuring that critical fuel parameters, such as pour point and viscosity at low temperatures, are included in bunker delivery notes would facilitate more efficient

and targeted spill response actions. Additionally, as the marine fuel market evolves, further studies are needed to understand the environmental behaviour of alternative fuels, including biofuels and LSFO blends. The increased use of additives and cutter stocks in fuel formulations presents another area requiring investigation, as their composition and interactions in cold environments remain insufficiently understood. Expanding research in these areas will be crucial for improving spill response strategies in the future and ensuring effective protection of the Arctic marine environment.



2. INTRODUCTION

The present report summarizes the key findings and highlights from the project Low Sulphur Fuels in the Arctic. The detailed findings from the different studies in the project is published in 6 separate reports (will be made available in the 'Publications' section on both the PAME and EPPR websites). The glossary with abbreviations and technical terms can also be found in the Appendix. The conclusions and recommendations presented in this report are based on knowledge gained from the scientific work done in this project, through engaging with the industry, through work group meetings and discussions, and through compiling knowledge and experiences about low sulphur fuel oils for the last 5 years.

2.1 PROGRAM ORGANIZATION AND FUNDING

The project “Low Sulphur Fuels, Fate and Behaviour in Cold Water Conditions” consisted of the following work packages:

- WP1 Mapping of fuel used in the Arctic
 - Which low sulphur fuel oils are used on-board ships sailing in Arctic waters?
- WP2 Industry involvement workshop
 - Held in February 2024 in Trondheim, Norway
- WP3 Fuel oil characterization methodology
 - Establish a common methodology for analyzing low sulphur fuel oil in different laboratories
 - Inter-laboratory calibration study of four low sulphur fuel oils
- WP4 Characterization of LSFOs used in the Arctic
 - Characterization of low sulphur fuel oil used by ships sailing in the Arctic
 - Toxicity testing of commonly used low sulphur fuel oils
- WP5 Fate and behaviour testing
 - Fate and behaviour testing of commonly used low sulphur fuel oils.

2.2 BACKGROUND

2.2.1 ACTIVITIES IN ARCTIC WATERS

The Arctic region is experiencing extraordinary environmental and developmental transformations. As sea ice continues to retreat and thin due to climate change, access to the Arctic Ocean is expanding, enabling trans-Arctic shipping, longer shipping seasons and access to previously inaccessible areas. These changes are accompanied by growing interest in the Arctic's natural resources, driven by high commodity prices and rising global demand.

Ship traffic in the Arctic has steadily increased over the past two decades, and trends and forecasts show that this trend is going to continue to grow in the coming years. While operations in the Arctic present economic opportunities, they also present serious environmental and social concerns. Increased shipping activity can disrupt marine ecosystems, introduce pollutants, and impact Arctic communities, who may face challenges such as heightened marine disruption and potential threats to their traditional livelihoods.

Furthermore, ships operating in the Arctic environments are exposed to a number of unique risks and challenges. Poor weather conditions, low temperatures, presence of ice and the relative lack of good charts, communication systems and other navigational aids pose challenges for mariners.

The consequences of climate change, pollution and disturbance for the Arctic's fragile environment remains poorly understood, and these challenges highlight the need for international collaboration. The Arctic is a multinational region where eight Arctic states, together with Indigenous communities and other stakeholders, collaborate through the Arctic Council to ensure its stewardship. Effective cooperation between these actors is essential to address the mounting pressures and ensure the Arctic environment is protected for future generations.

2.2.2 FUELS USED IN THE ARCTIC

Fuel oil is a broad category encompassing various refined products, ranging in density from kerosene to residual fuel oil. The fundamental specifications for marine fuels are outlined in the ISO 8217:2024 standard (ISO, 2024).

HFO is a residual product of crude oil distillation. HFO is often blended with lighter fuels, such as marine gas oil or marine diesel oil, to achieve the necessary specifications. These blends, traditionally known as intermediate fuel oils (IFO), are categorized by their viscosity—such as IFO 180 and IFO 380, with viscosities of 180 mm²/s and 380 mm²/s at 50°C, respectively. Recent regulatory changes have led to the introduction of LSFOs, which substitute the traditional HFOs, and contain a maximum sulphur content of 0.5% to meet environmental standards. Marine gas oil (MGO), is composed primarily of distillates which are the lighter cuts from distillation of oil, and typically has a viscosity below 5 mm²/s at 50°C.

With growing concerns over climate change and the need to reduce global CO₂ emissions, interest in alternative energy sources, such as biofuels, has increased. Conventional biofuels (first generation) are derived from food-based crops, which are processed into fatty acid methyl esters (FAMES). Advanced biofuels (second- and third generation) do not compete directly with food and feed crops. Second-generation biofuels may be derived from waste and agricultural residues or non-food crops and are often called HVO (hydrotreated vegetable oil). Third generation, generally refer to biofuel production routes which are further away from commercialization, for instance biofuels from algae. Biodiesel is often seen as a low-

toxicity, environmentally friendly fuel, though its climate impacts vary by feedstock and production process. Studies by Faksness et al., 2024 indicate that some biofuels share similar physical properties as marine gas oils (MGOs).

2.2.3 FUEL OIL SPILLED INTO THE MARINE ENVIRONMENT

Where there are anthropogenic activities, there is also a risk for environmental pollution. For shipping in the Arctic this can be, noise pollution, emissions gasses from burning of fossil fuels (such as CO₂, SO_x and NO_x) and particulate black carbon, and the risk of oil spills.

When oils (crude or fuel oils) are spilled into the marine environment, several natural processes take place, called weathering processes (Figure 1). Spilled oil will immediately spread on the water surface, forming an oil slick. Simultaneously, volatile components will start to evaporate, or dissolve into the water. Weather (wind and temperature) has a huge impact on the fate of the spilled oil, as does the type of oil that is spilled. If there are rough seas some oils will break into small droplets and disperse into the water column, others tend to form emulsions taking up to 80% water, thereby increases the volume of the oil on the sea surface significantly. Other weathering processes includes photooxidation, biodegradation and sedimentation (when oil is denser than water or adsorb to particles).

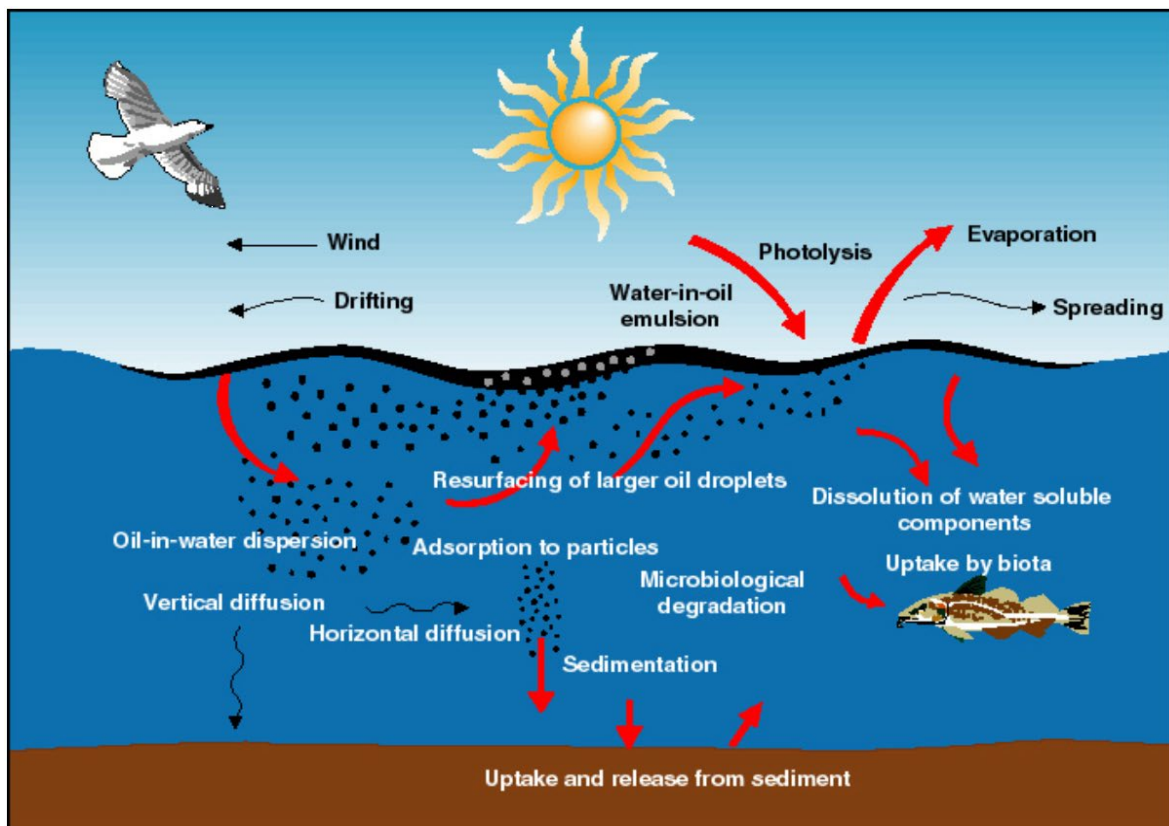


Figure 1: Weathering processes that take place when an oil is spilled on the sea surface (Daling et al., 1990)

The weathering processes will change the physical and chemical composition of the oil, as well as how the spilled oil behaves. Due to these changes the feasibility of the use of different oil spill response measures such as mechanical recovery, use of dispersants or *in-situ* burning, changes. The operational window and applicability for each response method depends on type of oil and the environmental conditions. Usually, oil response and recovery become more challenging with time. Thus, the remoteness of the Arctic makes it extra challenging (and costly) to respond to an oil spill. In addition, the harsh weather conditions, presence of ice, low temperatures, and seasonally polar darkness, can make it impossible to recover the spilled oil, leaving the oil to persist in the marine environment.



2.2.4 RELEVANT IMO REGULATIONS CONCERNING FUEL USED IN THE ARCTIC

THE IMO'S GLOBAL 2020 SULPHUR FUEL CAP

From January 1, 2020, the limit of sulphur content in ships' fuel oil was reduced to 0.5% (from 3.5%), with the aim to protect marine environment and oceans and improve air quality by reducing emissions SO_x globally. Additionally, for vessels operating in so-called Sulphur Emission Control Areas (SECA) (defined under MARPOL), the sulphur content should not exceed 0.1%.

The lower sulphur requirements were in other words introduced primarily for human health reasons, as SO_x and particulate matter cause asthma, pneumonia, lung cancer, strokes, and other diseases. There is also a clear environmental benefit from cutting emissions of sulphur from ships as it helps prevent acid rain and ocean acidification.

There are two ways of complying with the IMO 2020 regulation: (1) using exhaust gas cleaning systems ("scrubbers") reducing SO_x in the exhaust, or (2) using compliant fuel with a compliant sulphur content.

THE IMO "ARCTIC HFO BAN"

IMO's "Arctic HFO ban" can be found in MARPOL Annex 1, regulation 43A. It references regulation 43.1.2 that contains a definition of oils prohibited in the Arctic. IMO regulation (43A.1) "Special requirements for the use and carriage of oils as fuel in Arctic waters" found in Annex I of the MARPOL Convention, provides in substance the following:

- From 1 July 2024, fuel oil having a density measured at 15°C higher than 900 kg/m³ or a kinematic viscosity at 50°C higher than 180 mm²/s may no longer be used or carried as domestic fuel in bunker tanks when in Arctic waters. There are however exceptions:
 - o Ships engaged in securing the safety of ships, search and rescue operations, or dedicated to oil spill preparedness and response are exempted.
 - o Ships subject to Regulation 12A of MARPOL Annex I (oil fuel tank protection) or Regulation 1.2.1* of Part II-A of the Polar Code may use and carry for use as fuel the fuel oils defined in regulation 43.1.2 until 1 July 2029.
 - o Ships flying the flag of an Arctic member state while operating in waters subject to the sovereignty or jurisdiction of that Arctic member state, taking into account the IMO's guidelines (MEPC.1/Circ. 915), can use and carry for use as fuel the fuel oils defined in regulation 43.1.2 until 1 July 2029.

Prior to IMO's "Arctic HFO ban", larger ships operating in the Arctic, carried HFO as their primary propulsion and energy source. Spilled HFO are generally difficult to

clean up, because of high density and viscosity, and a tendency to form stable water-in-oil emulsions. HFO also degrades very slowly by microorganisms present naturally in the ocean, especially if spilled in cold Arctic water. These factors increase the environmental impact caused by an HFO spill in the Arctic. To mitigate this, was the main purpose behind the introduction of IMO's "Arctic HFO ban".

2.2.5 IMPLICATIONS OF THE RECENT REGULATIONS AND THE RESULTING ENVIRONMENTAL CONSEQUENCES

As a consequence of the "IMO sulphur cap", the refineries and other fuel blenders, started to blend fuels with a lower sulphur content, LSFOs. Different types of LSFOs are being produced to comply with the requirements; very low sulphur fuel oils (VLSFO) complying with the 0.5% sulphur limit for global use, and ultra-low sulphur fuel oils (ULSFO) complying with the 0.1% sulphur limit for use in the SECA. The new LSFOs are blended to be compatible with ship engines that used traditional high sulphur fuel oils (HSFO) prior to introduction of the "IMO sulphur cap" in 2020. However, blending of the new LSFOs to achieve the right specifications (ISO8217:2024, VLSFO and ULSFO) results in fuels that can vary widely in density, viscosity and pour point, due to the wide variation in the blending and composition.

Following the introduction of LSFOs on the market, the oil spill response community has voiced concerns about the physical and chemical properties of LSFOs and their behaviour when spilled in cold waters. Early works characterizing different LSFOs indicated that these oils did not behave like traditional residual fuels (Hellstrøm, 2017).

Concerns were primarily related to the high pour points and viscosity, which contribute to a high degree of persistence on the sea surface (Sørheim et al., 2020). High pour points will cause an oil to solidify when spilled into an environment that has a temperature below the pour point. The viscosity of an oil will increase with a decrease in temperature. Additionally, concerns were raised about challenges in responding to LSFO spills compared to traditional fuel oil spills, due to the variation of LSFO properties, narrow operational windows for various response techniques, and low compatibility with existing containment and recovery equipment.

Based on these concerns mechanical oil spill response equipment was tested through an EU-funded project, IMAROS I ("Improving response capacities and understanding the environmental impacts of new generation low sulphur marine fuel Oil Spills"). This project showed through testing of the chemical and physical properties of 13 LSFOs, that there is a high variation in the properties of the tested oils, and that they would behave and weather differently in case of a spill. As a result, the project concluded that response options would need to be adapted depending on the oil characteristics. None of the five tested conventional skimmers worked efficiently for recovery of the 13 tested LSFOs. The large variation in properties, manifested in different kinds of problems for mechanical recovery. The biggest problems were poor adhesion to skimmer material, lack of slick flow towards the

skimmer and low elasticity in the slick was low causing the oil to “brake”, (characterized as “short” properties). The LSFOs with a high pour point were a problem because the oil formed individual solid oil clumps when discharged to the test basin (IMAROS, 2022).

THE UNINTENDED CONSEQUENCES OF IMO’S “ARCTIC HFO BAN” AND 2020 SULPHUR FUEL CAP

The simultaneous but unrelated introduction of IMO’s “Arctic HFO ban” and the global sulphur fuel cap has led to unintended environmental consequences. While both regulations aimed to reduce the impact of shipping emissions and fuel spills, their combined effect incentivized the development of LSFOs as an alternative. However, many LSFOs exhibit higher pour points, increased viscosity, and greater persistence in the marine environment compared to the banned HFOs. These properties make LSFO spills more challenging to respond to, particularly in Arctic conditions. As a result, despite the regulatory intent to improve environmental protection, the transition to LSFOs has introduced new and potentially greater risks to Arctic ecosystems.



3. FUELS USED BY SHIPS SAILING IN ARCTIC WATERS

KEY FINDINGS

- It was documented that LSFOs (both ULSFO and VLSFO) used in the Arctic exhibited significant variation in properties, including pour point, viscosity, and density.
- Fuel oils used in the Arctic after the introduction of the global Sulphur cap, with a viscosity less than 180 cSt, have the largest span in pour point of the analyzed fuels, see Figure 6. A hypothesis that can explain this finding is the extensive use of additives and cutter stock to dilute fuel oil and modify its properties, see section 3.5 and Chapter 7 point 4.
- IMO’s “Arctic HFO ban” outlined in MARPOL Annex 1, which came into effect on July 1, 2024, did not prohibit all residual fuels previously used by ships in the Polar Code Area, see Figure 4 and 5.
- Viscosity and density can be relatively easily adjusted to fall just outside the definition of fuels prohibited in polar regions (Regulation 43.1.2), see Figure 7. However, such tailored fuels may still pose significant challenges for oil spill responders and the Arctic marine environment, particularly if their pour point is higher than the sea temperature, resulting in the formation of oil lumps after an acute oil spill.
- Waivers to IMO’s “Arctic HFO ban” have the consequence that HFO may still be in use in certain instances or areas of the Arctic. See paragraph 2.2.4 of this report for more details.

3.1 INTRODUCTION

According to ASTD the number of distinct ships operating in the Polar Code area grew from 1,298 in 2013 to 1,782 in 2023, marking a 37% increase over the past 10 years. Many of the “new” ships were larger ships such as bulkers, oil- and LNG tankers. These ships are used to transport energy and raw materials from the energy-and raw material rich Arctic to the market. The increase in sailed distance within the polar code area increased from 6.1 to 12.9 million nautical miles, representing a 111 % growth over the 10-year period. Such growth of the activity level naturally increases the probability of accidents such as groundings, collisions and foundering. This is especially the case in areas with new activity. Naturally the environmental risk in such areas has also increased because of the growth in the activity level. In the fragile environment of Arctic waters, it is especially important to keep environmental risks low and within acceptable limits. This project points to several measures that will help achieve this goal in its recommendations.

3.2 OBJECTIVE

The purpose of mapping fuels used in the Arctic was to close the knowledge gap on which fuels are used by ships sailing in Arctic waters after the introduction of the global sulphur cap in 2020 (<0.5%S). Furthermore, the purpose was to analyze the basic properties of these fuels. More detailed results are found in the report “Low Sulphur Fuels in the Arctic” (PAME/EPPR, 2024).

Most larger vessels use residual fuels (after the introduction of the global sulphur cap this is mainly LSFOs) for their propulsion, while smaller vessels use distillates such as diesel. Even though the majority of ships sailing in the Arctic are smaller vessels, the total volume of residual fuel used in one year is considerably larger.

In this study only the properties of residual fuels were included as the fate and behaviour of distillates are generally less challenging for responders when spilled into the Arctic marine environment. Generally, the toxicity of distillates varies greatly, which is also the case for residual fuels (Faksness et al.,2024), see also Chapter 4.

3.3 METHOD

The main steps of the bunker fuel oil analysis are as shown in Figure 2, comprising of an AIS analysis of ship traffic, collection of Veritas Petroleum Services (VPS) bunker fuel oil data, processing of results and reporting.

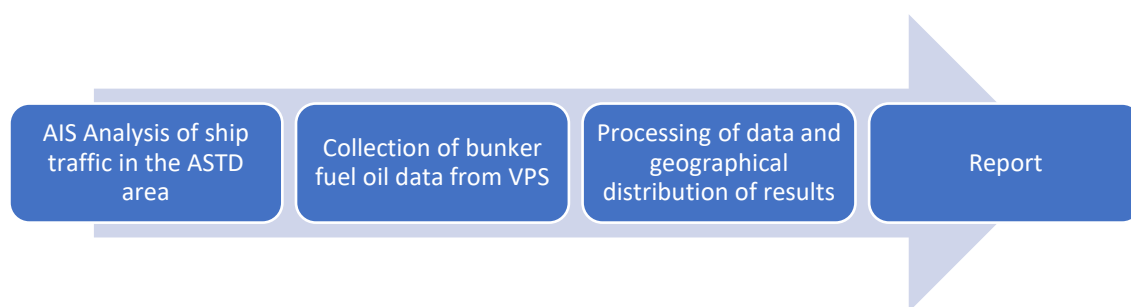


Figure 2: Bunker fuel oil analysis for ships operating in the Arctic

The fleet of ships identified through the AIS analysis was provided to VPS for merging with their bunker fuel oil data. By combining the AIS and VPS data, an overview of the fuel oil characteristics and the distribution of bunker fuel oil usage was created. In the study 2615 VLSFOs and 116 ULSFOs were mapped using the AIS and VPS data. The different graphs are prepared based on these data.

Separate analyzes for the four areas indicated in Figure 3 were also included and found in the report (PAME/EPPR, 2024). Studies for the Polar Code area have also been conducted when necessary.

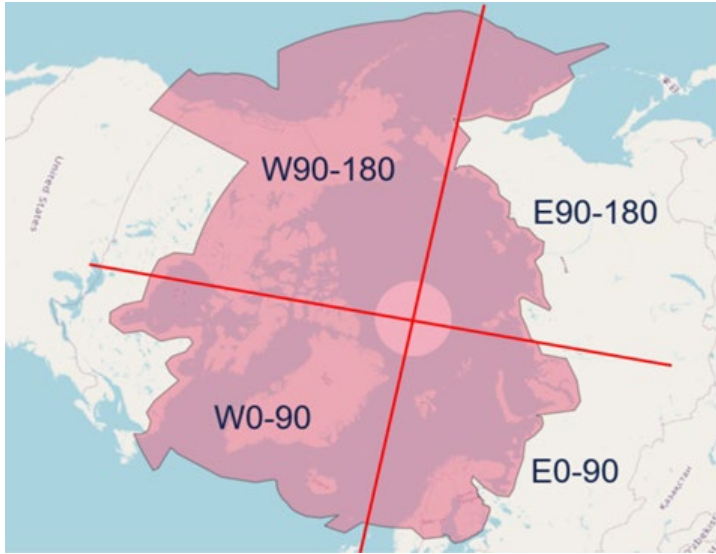
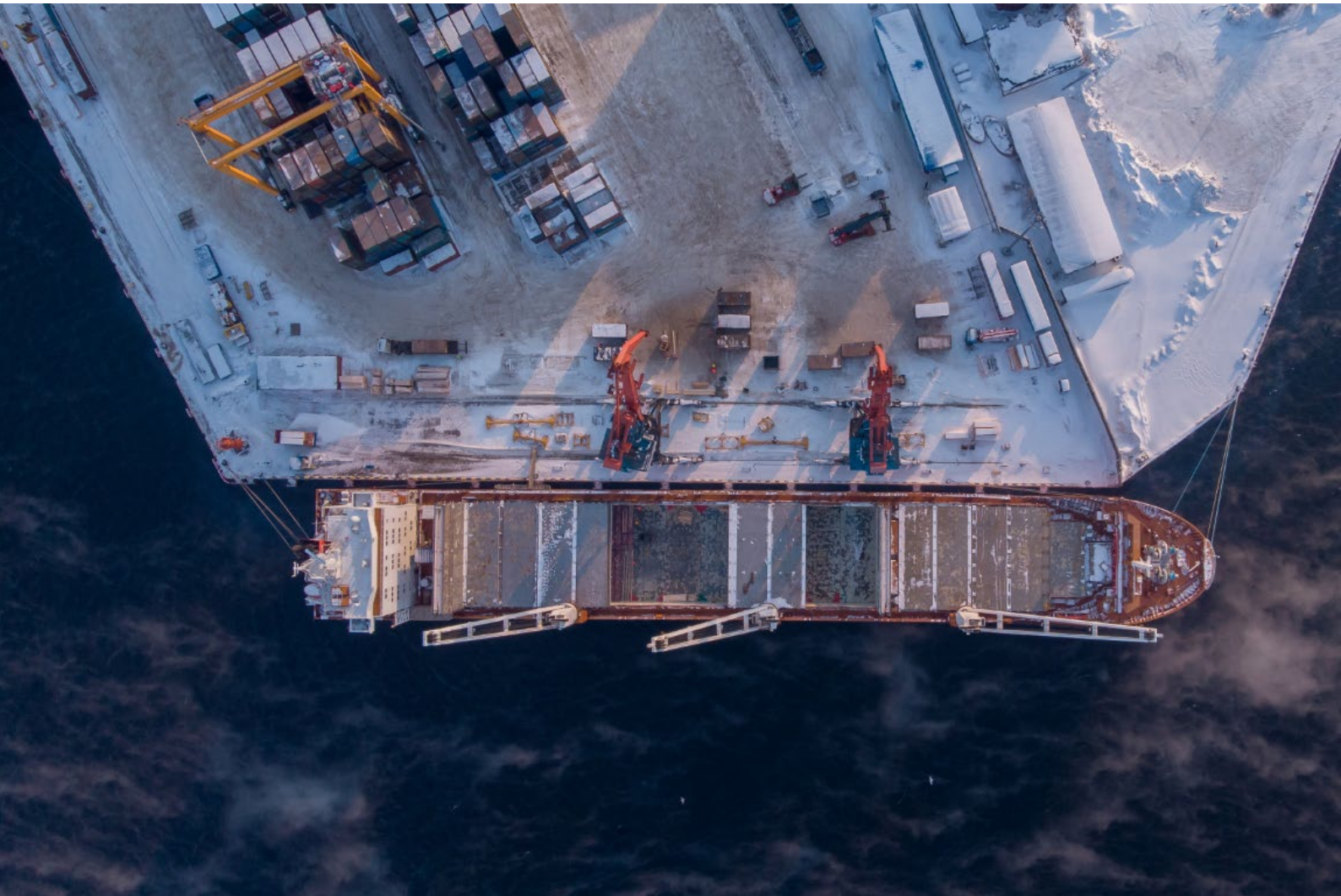


Figure 3: The ASTD area, with four geographical segments defined to compare and analyze similarities and differences in fuels used within the defined area.



3.4 CHARACTERISTICS OF FUELS USED IN THE ARCTIC

As explained in section 2.2.4 in this report IMO’s “Arctic HFO ban” outlined in MARPOL Annex 1 regulation 43A came into effect July 1, 2024. Effective from this date many of the VLSFOs previously used in Arctic waters were prohibited due to densities exceeding 900 kg/m³. However, the analyzed VLSFOs that fall outside the red box in Figure 4 are not prohibited by IMO’s “Arctic HFO ban”.

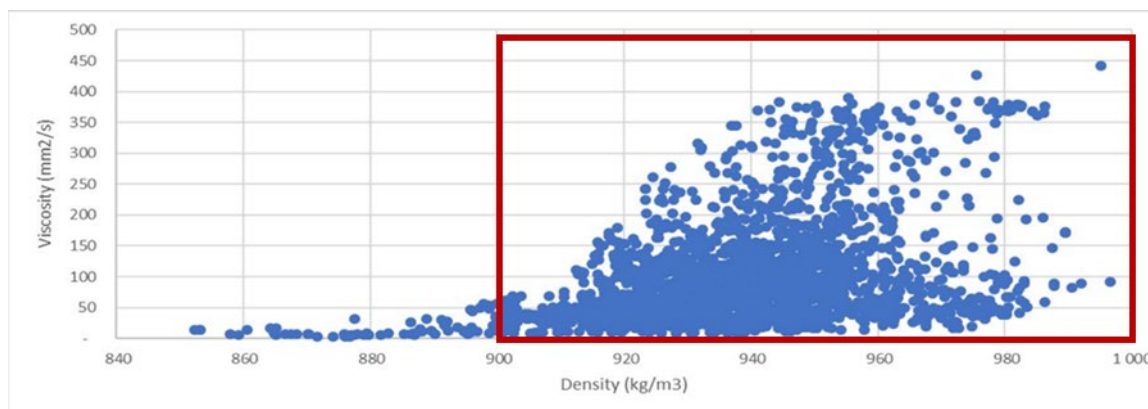


Figure 4 Relationship between density (at 15°C) and kinematic viscosity (at 50°C) for the 2615 VLSFOs mapped (0.50 % m/m sulphur limit). The VLSFOs in the marked red box are prohibited to use or carry for use as fuel in the Arctic after July 1, 2024.

ULSFO was occasionally used by a limited number of ships prior to the implementation of IMO’s “Arctic HFO ban”. As illustrated in Figure 5, the majority of the ULSFOs are still permitted after IMO’s “Arctic HFO ban”.

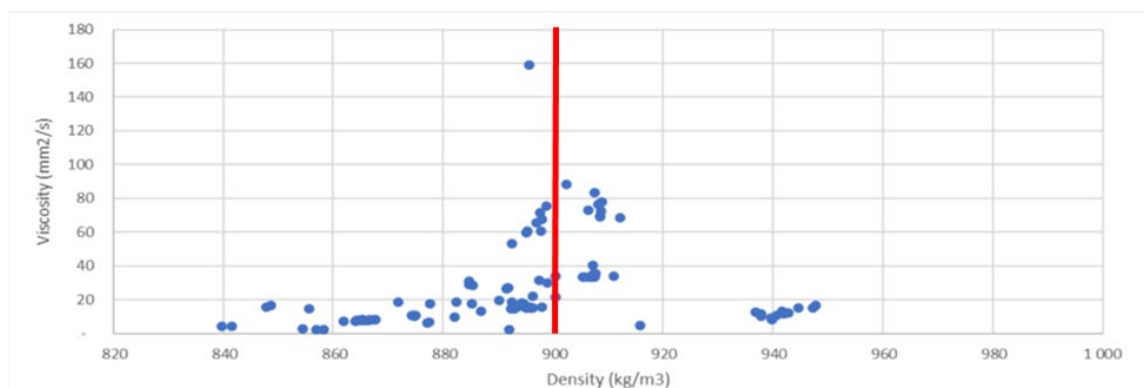


Figure 5 Relationship between density (at 15°C) and kinematic viscosity (at 50°C) for 116 ULSFOs (0.10 % m/m sulphur limit). The ULSFOs above 900 kg/m³ are prohibited to use or carry in the Arctic after July 1, 2024.

The variation in pour point is greatest for the VLSFOs with relatively low viscosities (shown in Figure 6). Fuels with viscosity above 180 mm²/s had, with only a few exceptions, what can be characterized as high pour points (> 0 °C).

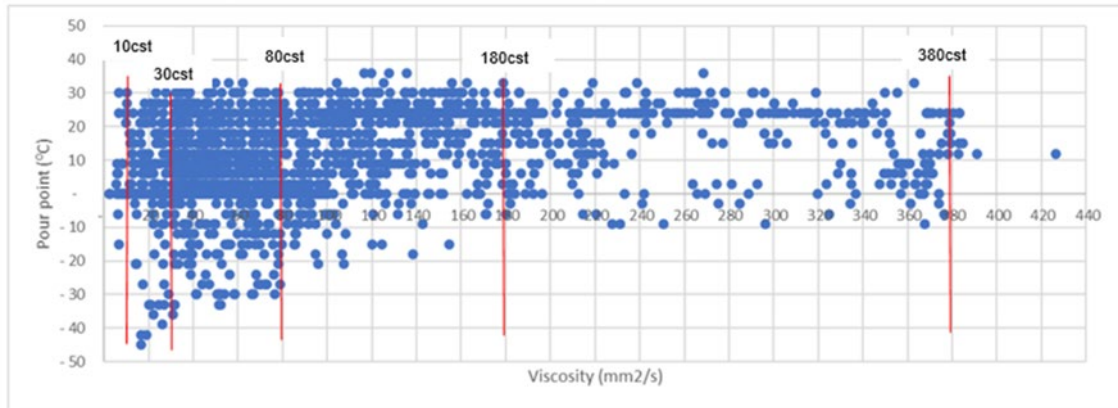


Figure 6 Relationship between kinematic viscosity (at 50°C) and pour point for 2615 VLSFOs (0.50 % m/m sulphur limit).

3.5 DISCUSSION AND CONCLUSIONS

Cutter stocks are oil and oil-related byproducts used to thin oil, i.e., to reduce viscosity and sulphur content in order to produce on-spec fuel oils. One hypothesis that can explain the observed variations in pour point, for the LSFOs with relatively low viscosity (under 180 cSt), is the extensive use of additives and cutter stock to dilute fuel oil and modify its properties. It is important to note that this is just a hypothesis that needs to be investigated further. It is believed that adding cutter stock and additives may not pose a problem, and, if carefully selected and tailored for this purpose, they can positively enhance the fuel properties when spilled on a cold sea surface.

It should also be noted that the density of VLSFOs can be reduced by for example adding paraffinic cutter stock (to make them compliant with the definition of prohibited fuels in MARPOL Annex 1 regulation 43.1.2 (see illustration Figure 7)). Such tailoring of the properties to achieve compliant densities can result in fuels that are more paraffinic (containing more wax), leading to generally higher pour points.

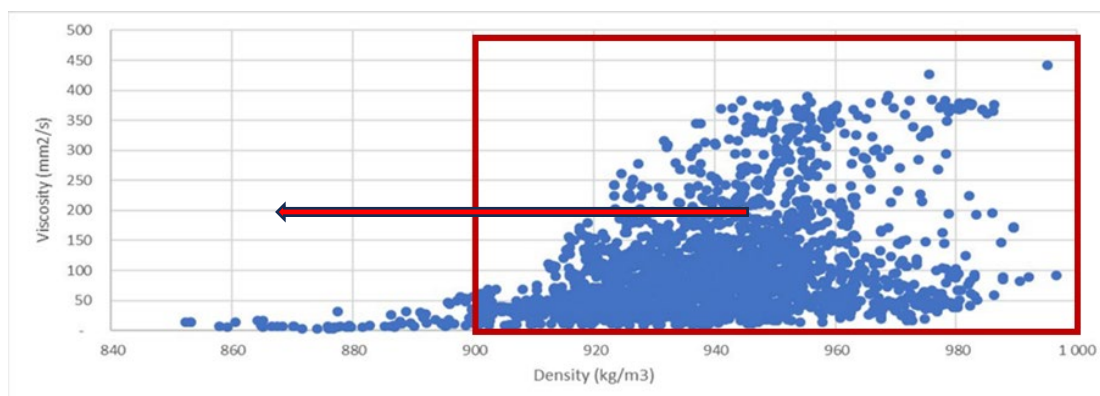


Figure 7 Additives and cutter stock can be used to tailor fuel properties in order to comply with the definition of prohibited fuels in MARPOL regulation 43.1.2 used for regulation 43A (IMO’s “Arctic HFO ban”).

This project documents that VLSFOs and ULSFO generally have lower viscosity, density and greater variation in pour point, compared to residual fuels commonly used before 2020 (including HFO). Greater variation in the pour point is highlighted as a key finding. These findings are consistent with findings done by ISO (ISO/TC28/SC4/WG6), the committee in charge of ISO 8217. ISO has analysed fuels delivered to ships globally in the first half of 2020 and compared them with HSFO data from 2018 (data source the commercial laboratory Intertek). Figure 8 illustrates clearly how the new generation fuels (VLSFO and ULSFO) differ compared to the traditional HSFOs.

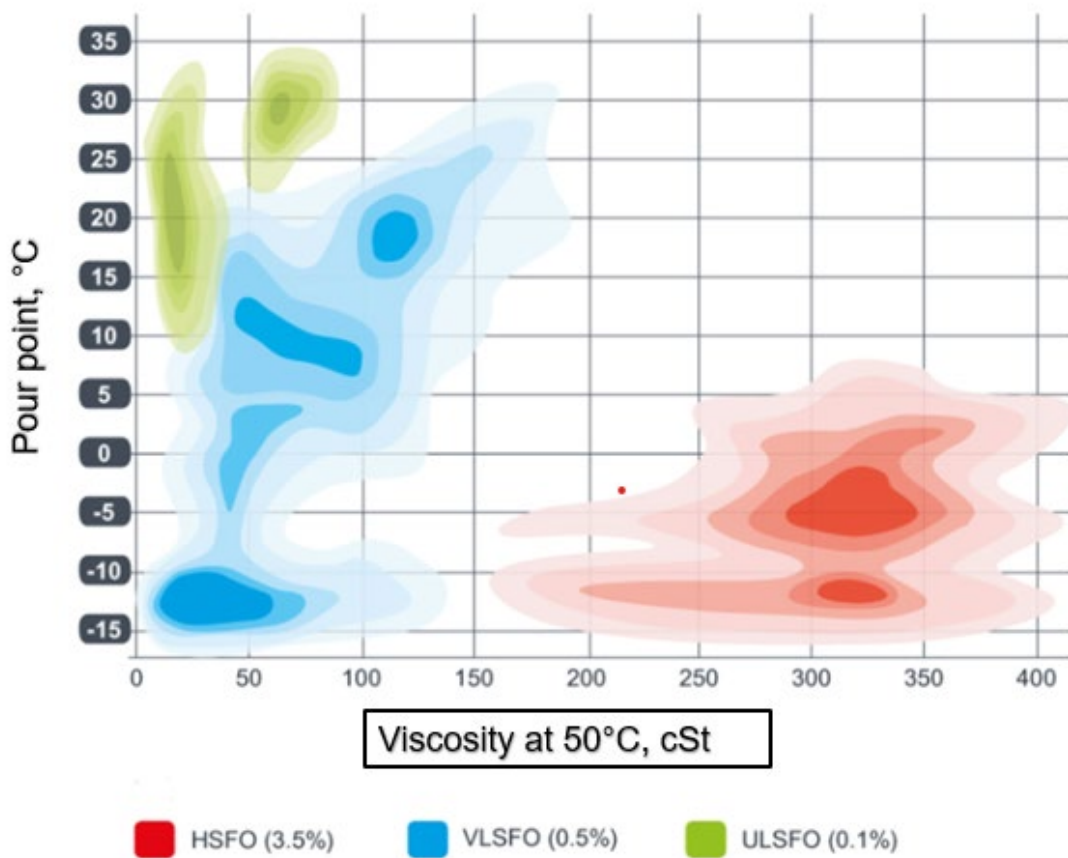


Figure 8: This figure illustrates some of the challenges with LSFOs, the large variations in pour point (°C), the temperature the fuel oil stops flowing. In this figure the traditional high sulphur heavy fuels (HSFO; 0.5-3.5%S) are showed in red, and low sulphur fuel oils VLSFO (0.1-0.5 %S) and ULSFO (< 0.1%S) are shown in blue and green respectively. Data source Intertek 2020

4. CHARACTERIZATION OF NEW LOW SULPHUR MARINE FUELS

KEY FINDINGS

- The results from the interlaboratory calibration of the selected LSFOs showed that measurement of wax, pour point and viscosity was very sensitive to the method used for measuring. Highlighting that Standardized methods are needed to obtain reliable and comparable data of LSFOs properties.
- Characterization of the seven selected LSFOs showed that the chemical and physical properties of the LSFOs varied greatly.
- Measuring the viscosity of many of the LSFOs was challenging, and it is recommended to conduct viscosity measurements as temperature sweeps down to 0°C to get more reliable viscosity values.
- A significant increase in viscosity was observed in several LSFOs at lower temperatures.
- Calculation of toxic units of the WAFs could be an alternative to predict toxicity, as it was challenging to compare toxic effects of the same oils tested in different laboratories, even when the same methods are used.
- It is essential to expand the knowledge of the properties and weathering behaviors of the most commonly used LSFOs, as this will enable informed decision-making and enhance the effectiveness of oil spill mitigation efforts.

The goal when characterizing fuel oils is to get a fundamental understanding of the properties that are relevant for the environmental consequences of a fuel oil spill or for the response operations. Fuel oils are a complex mixture of hydrocarbons and other organic components, hence the physical and chemical properties of each oil will vary greatly. Physical and chemical properties of oils determine how that specific oil behaves when spilled at sea and what techniques can be effective for oil spill cleanup.

The most relevant physical properties in the context of this project are density, viscosity (at different temperatures), and pour point. Pour point is the lowest temperature where the oil still flows, and under this temperature the oil stops flowing and solidifies. These properties are important for oil spill response.

The most relevant chemical properties in the context of this project are sulphur content, wax content and PAH content. The sulphur content determines if it is a low sulphur fuel oil or not, while wax content tells something about how the fuel oil will behave at low temperatures, how the fuel oil needs to be handled and what the fuel

can be used for. High wax content is usually related to a high pour point. PAH content can give indications about toxicity, where a high concentration of PAHs makes the fuel oil more toxic.

4.1 INTERLABORATORY CALIBRATION

It is important to correctly measure the properties of the fuel oils, not only for the fuel users that need to know if the fuel is compatible with their engines, but also for oil spill response efforts.

In the context of oil spill response, understanding oil fate and behaviour at sea (drifting, spreading, evaporation, dissolution, dispersion, emulsification, biodegradation and sedimentation) is crucial. Oil spill behaviour can be predicted using oil spill models, where oil properties are important input parameters. The accuracy of these models is directly tied to the quality of input data, and more precise property measurements lead to more reliable predictions. Having detailed information on the spilled oil's properties enables responders to make informed decisions about the most effective cleanup methods and equipment, as not all recovery techniques or response equipment are suitable for every type of oil. Thus, having quality data about physical and chemical properties improves the efficiency of response operations and minimizes environmental impact.

The intention of performing an interlaboratory calibration is to verify the reliability and consistency of methods and measurements across different laboratories. These studies assess the accuracy of each laboratory's performance, evaluate measurement uncertainty, and confirm the effectiveness of recommended methods. By doing so, they help maintain standardization and reliability in testing across multiple laboratories.

To gain knowledge about fuel oil properties, oils are characterized in the laboratory, based on best practice methodology. Five countries (Canada, China, Norway, Sweden and USA) accepted to participate in this interlaboratory comparison study, and to follow the suggested methodology guidelines for screening of fuel oils (Daling et al., 2021). The guidelines include characterization of oil properties relevant for fate, behaviour, fingerprinting characterization, and relative toxicity, when spilled in cold or Arctic seawater.

4.1.1 OBJECTIVES

The main objective of performing an interlaboratory calibration was (1) to establish the best practice methodology for characterizing properties of different LSFOs, related to fate and behaviour, and the relative toxicity when spilled in Arctic seawaters, and (2) to evaluate if the methodologies gave comparable and consistent results between the participating laboratories.

Good laboratory practice and quality assurance as well as experienced personnel in oil characterization are a prerequisite to achieve these goals.

4.1.2 INTERCALIBRATION BETWEEN FIVE LABORATORIES ON HOW TO CHARACTERIZE LOW SULPHUR FUEL OILS

Three low sulphur fuel oils were characterized through the interlaboratory comparison study by the participating laboratories from Canada, China, Norway, Sweden, and USA.

The oils analyzed are described in Table 1 and were a wide range gas oil (WRG), a marine gas oil (MGO) and a VLSFO. The physical-chemical properties of the oils and other characteristics are given in and in Figure 9 to Figure 14.

4.1.3 METHODS AND TECHNIQUES USED TO CHARACTERIZE FUEL OIL PROPERTIES

A common guideline for the methodology for measuring relevant properties, by Daling et al. (2021) was agreed on to be used by all laboratories as long as instrumentation was available.

4.1.4 CHALLENGES WITH CHARACTERIZATION OF LSFO, RECOMMENDATIONS AND LESSONS LEARNED

It was more challenging than expected to get a complete set of data from all participants of the interlaboratory calibration, as it turned out that not all laboratories were able to perform all measurements.

Comparable results, with relatively low variation, were reported for measurements of the physical properties of the oils, such as water content, density, flash point, boiling point distribution. The same was observed for sulphur-, CHN-, and metal-content. This indicates that these parameters could be measured reliably using existing methods and instrumentation. However, the study also revealed that the two different methods applied for measuring pour points resulted in large variation in the results for all three oils.

Another challenge was the preparation of Low-Energy Water Accommodated Fractions (WAF) of the LSFOs. The laboratories generated WAFs with different chemical composition using the same fuel. It is assumed that this difference was caused by variations in temperatures of the water and the fuel oils during preparation of the WAF. The concentration of WAF also depends on the absence of oil droplets after preparation. Oil droplets can alter both the total concentration and composition significantly, as well as physically effecting the test animals. Thus, presence of oil droplets can also explain the variations observed in our data.

Initially, it was agreed that all laboratories should expose the marine copepod *Acartia tonsa* to the WAFs, however only two laboratories were able to use *A. tonsa* as a test species. Therefore, eight different species were tested (Faksness and Daling, 2023). Although some trends can be observed in toxic effects on the exposed organisms, the variation in the WAF chemistry makes it challenging to give any recommendations regarding suitable test organisms to test toxicity of LSFOs.

A summary of the tested fuel oil parameters and recommendations for what methods to be used when analyzing LSFOs are given in Table 1 (physical chemical analysis) and Table 2 (chemical analysis and toxicity testing of WAFs). Further details about the test results can be found in Faksness and Daling, 2023.



Table 1: A summary of the reported parameters for the physical-chemical oil analyzes and an evaluation of the results, including a recommendation of further analysis of the specific test parameters

Test parameters	Methods applied by the laboratories in inter-cal.	Indication of variation	Comments	Recommended method
In oil				
Water content	ASTM E203, ASTM D6304	Low, but varied	Diff. methods used	ASTM E203
Density	ASTM D5002, ASTM D4052, ISO 12185	Minor variation	Robust parameter	ASTM D5002 (measured at 15 °C)
Pour point	ASTM D5949, ASTM D97	Too large variation	Different principles for the two methods	ASTM D97
Flash point	ASTM D7094, ASTM D93, ISO2719	Low	Robust	ASTM D7094
Viscosity – temp sweep	Dynamic, from 50 to 0 °C (1°C/min, shear 10 s ⁻¹)	Low	Only two labs	Recommended for oils with high pour points
Viscosity	ASTM 7042 (dynamic) ASTM D445 (kinematic) Measurement at 2 °C recommended	OK for dynamic measured at same temp.	Two labs reported kinematic viscosity	ASTM D7042, combined with temp sweep.
Interfacial tension	Spinning drop or Pendant drop	Large variation	Oils with high PP challenging for all labs	Exclude parameter
True boiling point	ASTM D7169, ASTM D2887	Relative comparable, but minor diff	Larger variation bp>350 °C	ASTM D7169
GC/FID (oil dissolved in DCM)	EPA 8015D	Varied	Only reported by two labs. Diff GC conditions.	GC chromatograms must be included
Asphaltenes	ASTM D6560, IP 143. Hard or soft asphaltenes “Hard” in n-heptane “Soft” in n-pentane	Some, but diff methods (hard or soft).	High detection limit for some laboratories	Indicate if soft or hard asphaltenes are reported.
Wax	Bridiè et al., 1980, or in-house. Wax precipitation at -30 or -10 °C	Varied, depending on precipitation temperature	Lower wax content on all oils at -10 °C	Bridiè et al., 1980. with wax precipitation at -30 °C (overnight)
Sulphur	ASTM D4294, ISO 8754	Low	One lab lower than other labs	ASTM D4294
CHN	ASTM D5291, ASTM D5762	Low	Specific request from Germany	Exclude parameter, gives limited info
Metals	ASTM D5185, ASTM D5762, IP501	Rel. low conc, but OK	Most metals below detection limits	ASTM 5185. Exclude, or analyze only Ni, V and Fe
SVOC/PAH	US EPA 8070D, 8270E (GC/MS)	Rel low variation two labs	RRF applied different in the labs	Exclude decalins and phenols. Agree on use of RRF
VOC	US EPA 524.3 (GC/MS headspace) USEPA 8260D (P&T GC/MS)	Large variation, also for BTEX	Only reported by two laboratories.	Difference between labs too large to give any recommendation, but should be included, especially for oils with comp with bp lower than C10 present.
Diagnostic ratios (DR)	CEN (2012)	Rel good	Only one lab used COSI-web (automatic integration)	Not to be included in oil characterization

Table 2: A summary of the reported parameters for chemical analysis and toxicity testing of the WAFs and an evaluation of the results, including a recommendation of further analysis of the specific test parameters.

Test parameters	Methods applied by the laboratories in inter-cal.	Indication of variation	Comments	Recommended method
Preparation of low-energy WAF (WAF)	CROSERF LE-WAF (Aurand and Coelho (2005))	Large variation on all WAFs for all labs	Not all labs provided GC chromatograms, but assumed that there was oil droplets in some of the WAFs (high conc 4-6 rings PAH)	Aurand and Coelho (2005), and instructions given in Faksness and Sørheim (2024).
GC/FID (TPH)	EPA 8015D	Varied	Only reported by two labs. Diff GC conditions.	To quantify total petroleum hydrocarbon in the WAF. GC chromatograms must be provided to confirm that low-energy WAF is prepared (no n-alkanes detected in GC/FID)
SVOC/PAH	US EPA 8070D, 8270E (GC/MS)	Rel low variation two labs	RRF applied different in the labs	Exclude decalins and phenols. Agree on use of RRF
VOC	US EPA 524.3 (GC/MS headspace) USEPA 8260D (P&T GC/MS)	Large variation, also for BTEX	Only reported by two laboratories.	Difference between labs too large to give any recommendation, but at least BTEX should be included, especially for oils with comp with bp lower than C10 present.
Toxicity of WAF	ISO 14669:1999 <i>A. tonsa</i> recommended, but tested only by two labs	Rel good correlations WAFs of VLSFO and MGO, but diff for WRG.	Toxicity depends on WAF conc.	ISO 14669:1999, <i>A. tonsa</i> . Pos and neg controls must be within limits given in the ISO standard.
Toxicity of WAF	Other species tested <i>Americamysis bahia</i> , <i>Menidia beryllina</i> , <i>Moina mongolica</i> , <i>Nitokra spinipes</i> , <i>Calanus finmarchicus</i> , <i>Danio rerio</i>	Rel good correlations WAFs of VLSFO and MGO, but diff for WRG.	8 different species tested, some trends can be observed, but as the tests have been performed in different labs the value of the trends are uncertain.	Alternative species may be tested
Toxic unit	Predict toxicity of WAF based on chemical composition of WAF Di Toro et al. (2007) and instructions in Faksness and Sørheim, 2024.	As chemistry of WAFs varied, TU varied	High contribution of 4-6 ring PAHs to TU indicated that there was oil droplets present in some WAFs.	Continue with Di Toro et al. (2007)/Faksness and Sørheim, 2024, or use revised method described in e.g. McGrath et al., (2018).

4.2 CHARACTERIZATION OF LOW SULPHUR MARINE FUELS USING RECOMMENDED METHODS

As highlighted earlier in this report, LSFOs shows significant variation in their properties compared to traditional HFOs. And as LSFOs have been replacing traditional HFOs of varying grades (such as IFO 180 and IFO 380) in Arctic waters, knowledge about physical and chemical properties of this new types of oils in cold environments is crucial.

The large variation in LSFO properties influences their fate and behaviour following an acute spill, particularly under cold-water conditions. Many LSFOs will solidify if discharged on a cold sea surface, which can negatively impact the performance of oil spill response equipment. The best way to respond to such spills becomes much more specific, as properties and thus the behaviour of individual LSFOs varies more than traditional heavy fuel oils.

Operative experience from past HFO spills, combined with laboratory studies of their physical and chemical properties and weathering behaviour, gained over several decades, has been instrumental in guiding environmental risk assessments and knowledge-based response strategies under various environmental conditions, including Arctic environments. To achieve similar preparedness and response capabilities for LSFOs, it is essential to expand the knowledge of the properties and weathering behaviour of the most commonly used LSFOs. This will enable informed decision-making and enhance the effectiveness of oil spill mitigation efforts.

4.2.1 OBJECTIVES

The main objective of this part of the project was to generate knowledge about the properties related to the fate, behaviour and acute toxicity of additional four new LSFOs. The selected fuel oils were among the most commonly used LSFOs in the Arctic (as outlined in Figure 3).

4.2.2 CHARACTERIZATION OF LOW SULPHUR FUEL OILS

The methodology for testing fuel oil properties was updated and revised after the interlaboratory calibration (Faksness and Sørheim, 2024) and used to test the four new LSFOs. All the seven fuel oils tested in this project are listed in Table 1. The participating countries and their accompanying laboratories were the same as in the interlaboratory calibration.

Table 3: Description of the oils used in the interlaboratory calibration and for characterization of LSFs for fate and behaviour testing. Sample ID used in tables and figures are shown.

Oil type	Sample ID	% S	Refinery country	Comment
Wide Range Gas oil (WRG)	WRG	<0.05%	Sweden	Interlab. calibration
Marine Gas Oil (MGO)	MGO	<0.1%	Norway	Interlab. calibration
VLSFO	VLSFO Belgium 1	< 0.5%	Belgium	Interlab. calibration
VLSFO	VLSFO Canada	<0.5%	Canada	Characterisation
ULSFO	ULSFO	<0.1%	Latvia	Characterisation
VLSFO	VLSFO Belgium 2	<0.5%	Belgium	Characterisation
VLSFO	VLSFO Latvia	<0.5%	Latvia	Characterisation



4.2.3 PHYSICAL AND CHEMICAL PROPERTIES

The most important physical-chemical properties of the seven fuel oils characterized in this project are given in Table 4 (includes the three oils from the interlaboratory comparison). There was a wide variation in the physical-chemical properties of these tested LSFOs. For example, the pour points of the fuel oils varied from lower than -36 °C in 'VLSFO Canada' to +39 °C in 'VLSFO Latvia', and their wax contents from 0.6 wt% in MGO to more than 10 wt% in ULSFO. Even after revising the methodology, the properties of some of the LSFOs made them challenging to measure. This was especially the case when measuring viscosity at low temperatures for the LSFOs with high pour points (ULSFO and 'VLSFO Latvia'). This tendency has also been observed previously (when measuring other LSFOs). Based on this it is suggested to measure temperature sweeps of viscosity on such fuel oils, instead of measuring viscosity at a specific temperature (static). As seen in Figure 9, the viscosity increases when the temperature decreases, which may result in challenges regarding oil spill response for accidental oil spills with several of these fuels in low temperature water.

Table 4: Physical-chemical properties of the oils, including the three oils from the interlaboratory comparison. The results presented are from Norway (black font) and Canada (blue fonts).

		WRG	MGO	VLSFO Belgium1	VLSFO Canada	VLSFO Belgium2	ULSFO	VLSFO Latvia
Water content	vol%	0.23 (0.10)	0.20 (0.03)	0.37 (0.14)	0.05 (0.04)	0.16 (0.12)	0.04 (0.02)	6.5 (7.2)
Density (15°C)	g/mL	0.873 (0.876)	0.865 (0.865)	0.969 (0.971)	0.885 (0.885)	0.965 (0.965)	0.869 (0.877)	0.914 (0.918)
Pour point	°C	-6 (27*)	-18 (-15*)	15 (24*)	<-36 (<-51)	15 (6)	30 (24)	39 (42)
Flash point	°C	113 (118)	68 (69)	109 (115)	73 (74)	108	153 (156)	149
Viscosity (2°C, 10s⁻¹, temperature sweep)	cSt	218	6.6	19755	28	17816	9353	100917
Asphaltenes (hard)	wt%	0.010	0.013	2.64	1.4		0.03	
Asphaltenes (soft)	wt%	0.07	0.02	5.0	3.2 (3.4)	4.6	0.1 (0.4)	3.2
Wax (-10 °C)	wt%	6.5	0.6	6.0	1.4		10.3	
Wax (-30 °C)	wt%	12	2.3	7.6	3.6 (4.1)	11	21 (18)	19
Sulphur	wt%	0.04 (0.05)	0.08 (0.08)	0.54 (0.51)	0.46 (0.47)	0.50 (0.50)	0.13 (0.12)	0.39 (0.42)

*) ASTM D5949 (not D97)

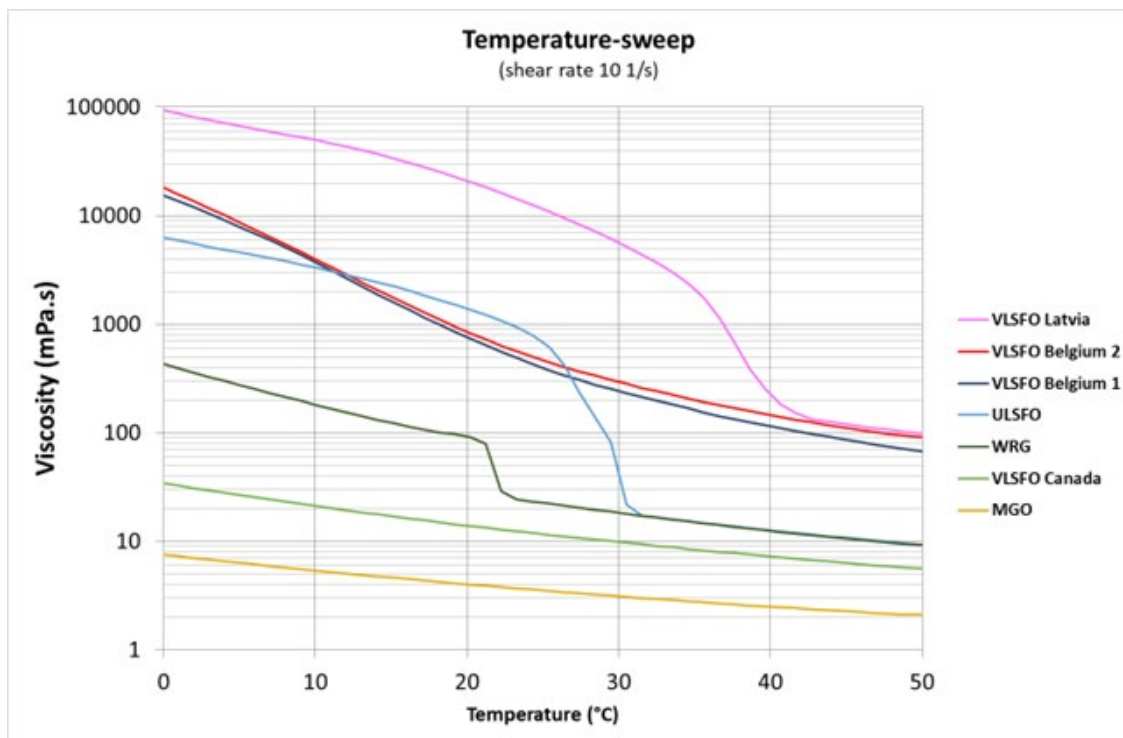


Figure 9: Temperature sweep of the viscosity from 50 °C down to 0°C (shear rate 10 s⁻¹). All oils have viscosity < 180 mPa.s at 50 °C (1 mPa.s = 1 cSt)

4.2.4 CHEMICAL CHARACTERISTICS AND TOXICITY OF LSFO

Chemical analysis, by gas chromatography (GC) can give valuable insight about an oil's chemical composition. The GC chromatogram can indicate the oil type, and these chromatograms illustrate that there were seven very different fuel oils that were analyzed and thereby confirmed the finding from the physical analyzes. The GC chromatograms of the fuel oils are given in Figure 10 (interlaboratory comparison) and Figure 11 (characterization of LSFOs for fate and behaviour testing).

WAFs were prepared of all fuel oils, and examples are shown in the GC chromatograms of 'VLSFO Canada' and 'VLSFO Belgium 1' in Figure 12. The "chemical profile" of a WAF is different from its parent oil due to the different water solubilities of the various components (Figure 13). There should be only water-soluble oil components, such as naphthalene and C1-naphthalenes present in the WAFs, and those can often be identified in the GC chromatograms.

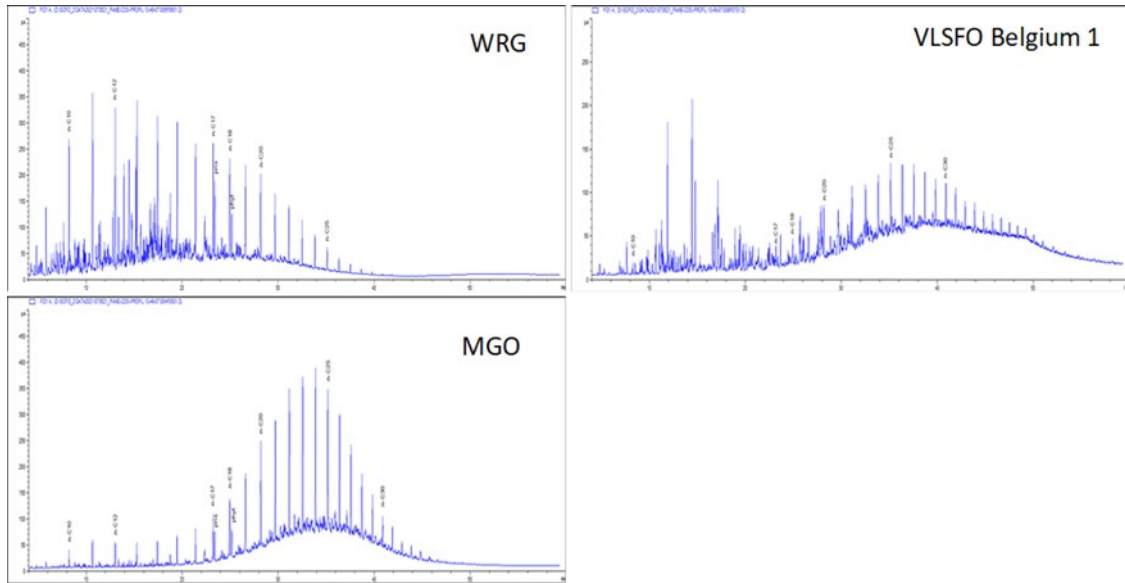


Figure 10: GC chromatograms of the oils analyzed in the interlaboratory comparison.

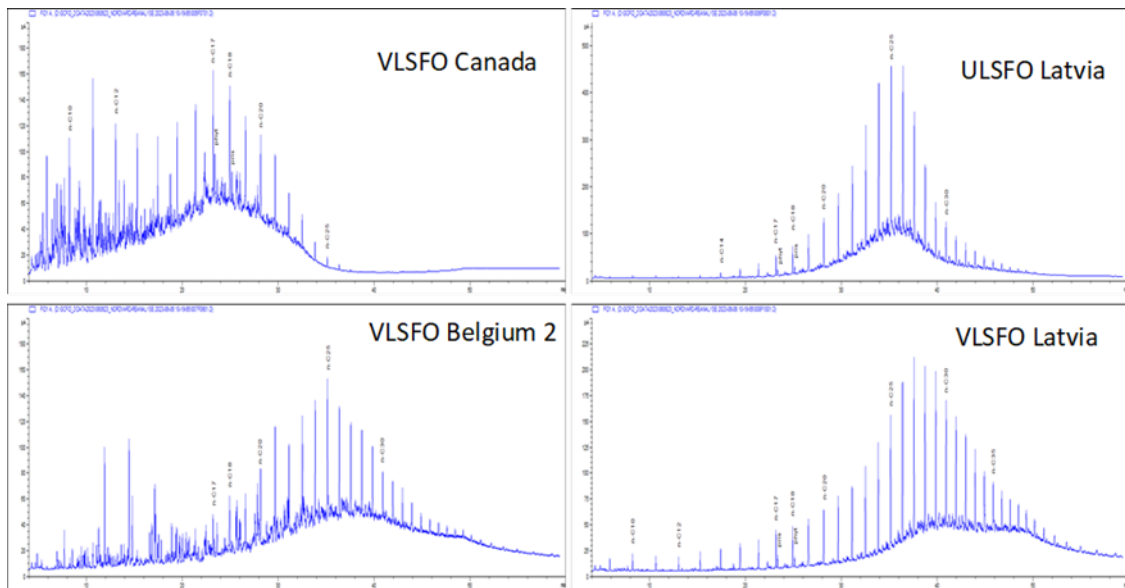


Figure 11: GC chromatograms of the oils analyzed for characterization of LSFOs for fate and behaviour testing.

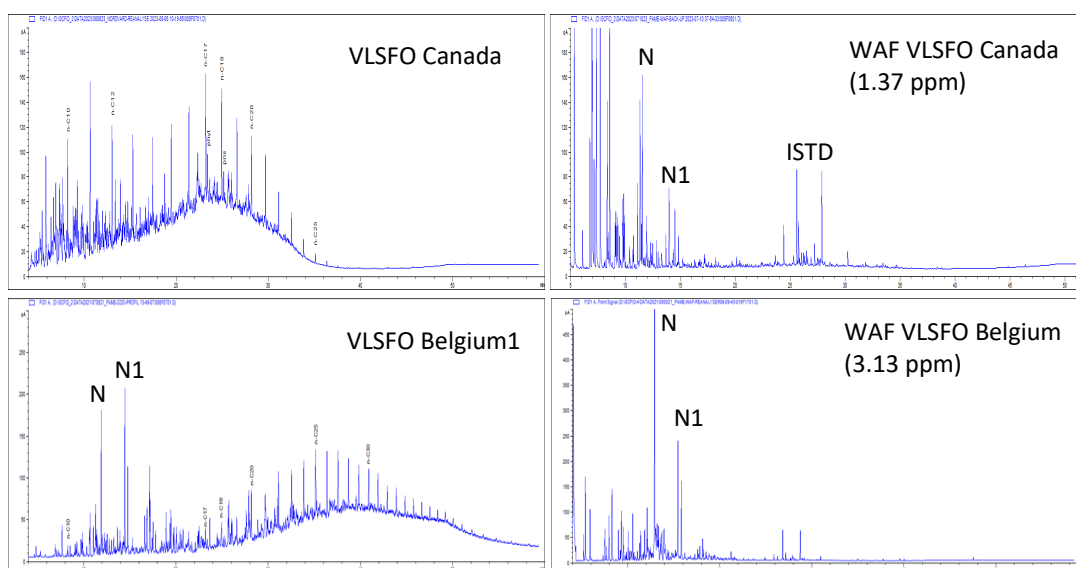


Figure 12: GC chromatograms of oils (left chromatograms) and their corresponding WAFs (right chromatograms). The peaks labelled N and N1 are naphthalene and C1-naphthalenes, and the two peaks labelled ISTD are added internal standards.

Figure 13 (A) summarizes the composition of the main groups of the aromatics in the fuel oils. The chemical compositions of the analyzed oils were quite different, as also shown in the GC chromatograms. WRG and the two fuel oils from Latvia have lower concentrations of aromatics than the other fuel oils. Naphthalenes, 2-3 ring PAHs and 4-6 ring PAHs are dominating in the two VLSFOs from Belgium. In the VLSFO from Canada, approximately 40% of the quantified components were volatiles, and in the MGO nearly 50% of the quantified components were volatile organic components (VOCs).

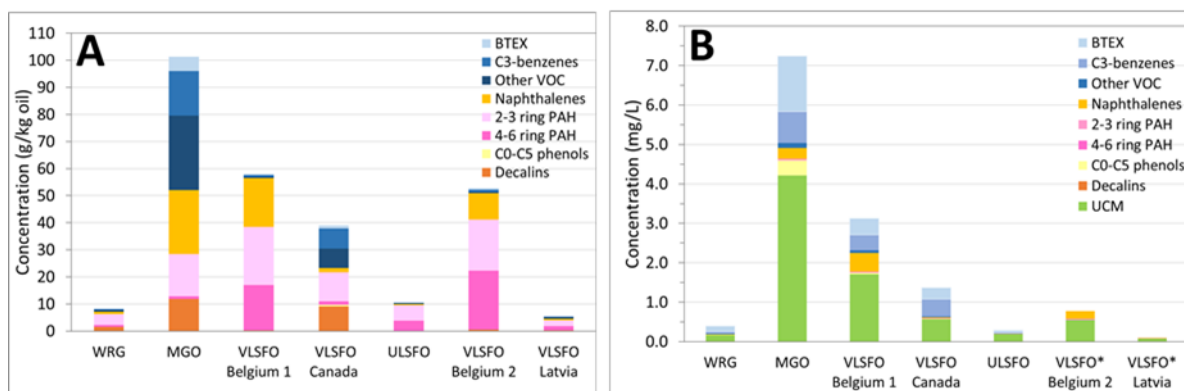


Figure 13: Chemical composition in the oils (A, left figure) and their WAFs (B, right figure). The WAFs of VLSFO Belgium 2 and VLSFO Latvia are results from Canada (did not analyze volatiles), and the remaining WAFs are from Norway

Figure 13 (B) gives the concentrations of the water-soluble components of the WAFs. The VOCs (especially BTEX and C3-benzenes) usually constitute a major part of WAFs prepared from fresh oils, as found with MGO and ‘VLSFO Canada’ analyzed in this

project. The naphthalenes are generally the dominating semi volatile organic components (SVOC), as they have a relatively high solubility in water. The remaining total WAF consists mainly of a large group of unresolved polar components (UCM).

Highest WAF concentration was measured in WAF of MGO (7.24 mg/L) and the lowest in ULSFO (0.28 mg/L) and 'VLSFO Latvia' (0.10 mg/L). Previously, the chemical composition of more than 50 fuel oils were compared, approximately 50% of them LSFOs (Faksness and Daling, 2022). The comparison revealed that the chemical composition of the LSFOs varied, and that no specific trends could be observed. The PAH contents varied from 0.5% to 7.5% in the LSFOs. In addition, the chemical composition of WAFs of 18 of these LSFOs were compared, and the WAF concentrations varied from 0.25 mg/L (in a VLSFO) to 8.7 mg/L (MGO/DMA). The oils and the WAFs studied here are in the same range.

The acute toxicity, expressed as LC50-values can be reported in percent dilution of a 100% WAF (relative toxicity, LC50 given in percent (%)), or as normalized to the total WAF concentration (specific toxicity, LC50 given in mg/L). Specific toxicity is the traditional approach for expressing toxicity. LC50 or 50% lethal concentration, can be defined as the exposure concentration mortal to 50% of the test organisms. Low LC50 indicates a higher toxicity, while a high LC50 corresponds to lower toxicity.

The specific toxicity to marine copepods *A. tonsa* and *Calanus finmarchicus* is shown in Figure 14 (A). The lethal immobilization in WAFs of WRG, ULSFO, and 'VLSFO Latvia' were too low for calculation of LC50 (less than 50% mortality of the test organisms). These WAFs also had the lowest WAF concentrations.

The acute toxicity, expressed as toxic units (TU) is given in Figure 14 (B), and is predicted based on the chemical composition of the WAFs and the octanol-water partition coefficient (K_{ow}) for the individual components in the WAFs. A $TU > 1$ for the total WAF implies more than 50% mortality in the test organisms. TU was higher than 1 in the WAF of MGO (1.36). The lowest TUs were calculated in WAFs of WRG (0.23) and ULSFO (0.35).

These results indicate that the toxicity to most of the studied LSFOs are predicted to be relatively low under Arctic conditions. The observed mortality was less than 50% in two of the WAFs, and calculated TUs were less than 1 in all systems, except MGO. This could be due to that the content of water soluble, bio-available oil components in the fuels were rather low.

This is in accordance with the results presented in Figure 13 (B) and reflects that the chemical composition of a WAF is an important factor when the corresponding observed toxicity should be evaluated. In Faksness and Daling (2022), TUs of 18 WAFs of LSFOs were compared, and there were only two of these WAFs that had $TU > 1$, both MGOs, which also had the highest WAF concentrations.

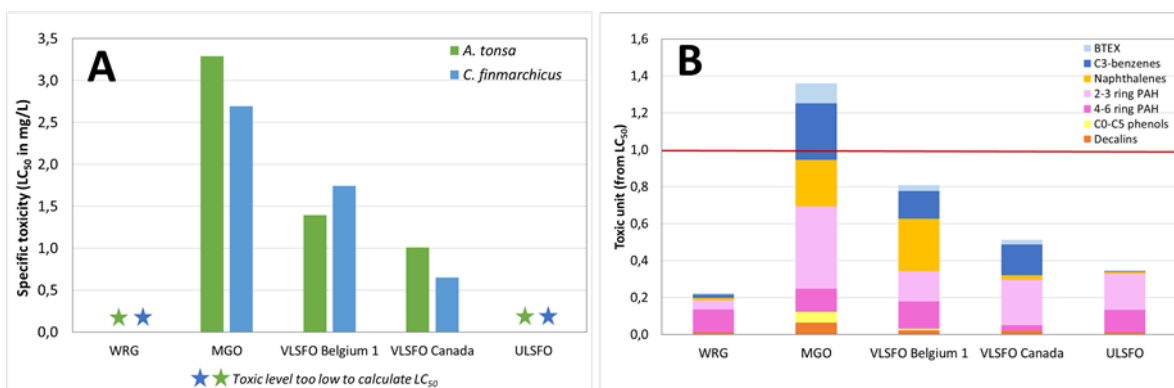


Figure 14: Acute toxicity LC₅₀ expressed as specific toxicity to *A. tonsa* (green bars) and *C. finmarchicus* (blue bars) (A) and predicted toxic units (B). The blue and green stars indicate that the toxicity was too low to calculate LC₅₀s.

4.3 DISCUSSIONS AND CONCLUSIONS

Physical-chemical properties and chemical composition were characterized in seven LSFOs. Four oils were classified as VLSFO with <0.5% S, and three ULSFO with < 0.1% S (WRG, MGO and ULSFO). There was a wide variation in the physical-chemical properties of these LSFOs as the pour point of the oils varied from -36 to +39 °C, and their wax contents from 0.6 wt% to 10.3 wt%. Their varying properties will result in very different behaviour if these oils are spilled on sea, especially under cold water conditions. Many of the fuels will solidify if discharged on a cold sea surface, because of high pour points, and this will cause challenges for oil spill response and will negatively impact effectiveness of oil spill response equipment.

According to MARPOL Annex 1, regulation 43A and 43.1.2, fuels with kinematic viscosity higher than 180 mm²/s at 50 °C are prohibited in the Arctic, see also chapter 2.2.4 in this report. In the Certificate of Analysis (CoA) for fuels, usually only viscosity measurement at 50 °C is reported. According to the MARPOL regulation, all fuel oil analyzed in the laboratory through this project, and presented in Figure 9, are allowed in the Arctic, even though an accidental oil spill with several of these fuels will be challenging regarding oil spill response and environmental consequences due to the high viscosity (over 180 mm²/s, < 10 °C) at low temperatures.

Under Arctic conditions, the results from this project indicate that acute toxicity of LSFOs most likely will be relatively low, as the content of water soluble, bio-available oil components that dissolve into the water column is limited. However, LSFOs with low pour points and products such as MGOs/DMA, may cause harmful effects to organisms if spilled in the marine environment. It is important to emphasize that the long-term toxic effects were not assessed in this study.

5. LOW SULPHUR FUELS AND IDENTIFICATION OF ENVIRONMENTAL IMPACT IN A COLD MARINE ENVIRONMENT

KEY FINDINGS

- Chemical dispersion is not an effective method to combat LSFO spills on cold sea surfaces.
- The LSFOs tested were found to be ignitable but could be difficult to ignite if weathered at sea.
- Biodegradation of LSFOs, fresh as well as chemically dispersed, is not expected to play a major role in the short-term fate of an oil spill.
- Overall LSFOs are likely to remain persistent in the environment, posing long-term risks to particular surface and shoreline organisms. The acute toxicity of LSFOs to zooplankton is on the other hand relatively low.

Fritt-Rasmussen et al. (2023) have summarized the current knowledge of environmental fate and behaviour of LSFO spilled in cold seawater through a project funded by the Nordic Council of Ministers. The project included laboratory experiments to study the effectiveness of responding to LSFO spills in cold seawater using *in-situ* burning (ISB) and chemical dispersion, as well as the potential for biodegradation of LSFOs and chemically dispersed LSFOs. Three LSFOs were included in the study: Wide range diesel (WRD), ULSFO, and HDME50. The overall objective was to evaluate which key organisms are at the most risk in the marine environment from an untreated as well as treated (burned, chemically dispersed) LSFO spill.

Fritt-Rasmussen et al. (2023) found that the main challenge for many of the new generation of LSFOs is that many (but not all) have a high pour point and viscosity. Their results indicated that the LSFOs tested likely had a high degree of persistence on the sea surface and shoreline even when chemical dispersion or ISB was attempted, and that chemical dispersion is not an effective method to respond to the tested LSFO. The small-scale ISB tests were all successful. The potential environmental impact of a successful ISB of the tested LSFOs (WRD and ULSFO) were concluded to be associated with the smoke plume and the remaining residue. The biodegradation rates observed after 28 days in the tested oils (WRD and ULSFO) were comparable or slightly slower than degradation rates earlier reported for heavy fuel oil at low temperature, and the addition of dispersant inhibited biodegradation even further. For oil at the sea surface, the most vulnerable organisms are seabirds. Oil and burn residue beaching result in possible smothering of the shoreline community. Stranding of oil can also cause toxic effects to fish species spawning near shoreline in coastal areas.

6. INDUSTRY INVOLVEMENT WORKSHOP

6.1 BACKGROUND

The workshop was designed to promote collaboration and knowledge exchange among key stakeholders, including project participants, government representatives from Arctic states, and industry experts. The participants will contribute diverse perspectives on the challenges and advancements associated with LSFOs in Arctic conditions.

The primary objective of the workshop focused to bridge the gap between research, industry, and emergency responders by facilitating dialogue and cooperation on critical issues related to LSFOs. Key discussions will focus on understanding the fate and behaviour of fuel spills in cold water, informed by the presentation of project findings. The workshop also explored LSFO blending processes, emphasizing the role of additives and cutter stocks, and addressed operational challenges faced by shipowners in Arctic environments.



Workshop participants.

6.2 STRUCTURE OF THE MEETING

The workshop was organized in Trondheim, Norway, February 2024, and chaired by the project coordinator Jon Arve Røyset as project coordinator, from the Norwegian Coastal Administration.

Workshop participants were welcomed by Ole Kristian Bjerkemo as Chair of EPPR. Day one of the workshop was divided into four sessions, with presentations from the workshop participants.

On day two of the workshop participants were split into three groups to work on questions on how to better characterize low sulphur fuel oils and how to blend a low sulphur fuel oil for Arctic conditions. The group work was summarized in a plenary session followed by a discussion about recommendations.



Figure: Jon Arve presents at the workshop.

6.3 PRESENTATIONS

Session 1 - Fate and behaviour of low sulphur fuels on cold sea

- Low sulphur fuels, fate and behaviour in cold water conditions. Presented by Jon-Arve Røyset, Senior advisor at the Norwegian Coastal Administration, Department of Oil Spill Protection and Environmental Preparedness
- Environment and Climate Change Canada's experience on Low Sulphur Fuels. Presented by Robert Faragher, Oil Research Scientist at Environment Climate Change Canada
- SINTEFs experience with low Sulphur fuels from different projects. Presented by Liv-Guri Faksness, Senior Research Scientist at SINTEF Ocean AS
- Experiences from the IMAROS-project. Presented by Silje Berger, Project manager and Bjørn Ronny Frost, Senior Engineer, at the Norwegian Coastal Administration, Department of Oil Spill Protection and Environmental Preparedness.

Session 2 – How is low sulphur fuel produced and blended? Cutter stock used in blending low sulphur fuel. Reasons for the high wax content? Role of additives

- Marine fuel blending. Presented by Barbara Heyberger, Marine Fuel Specialist at TotalEnergies
- Low sulphur fuels in cold water conditions. Presented by Charlotte Røjgaard, Global Marine Fuels Director at Bureau Veritas (VeriFuel)
- Additives for low sulphur fuel oils. Presented by Jérôme Maheu, Technical Officer at Aderco
- Marine fuel additives. Presented by Dewi Ballard, Chief chemical engineer at Infineum UK Ltd



Session 3 – Categorizing low sulphur fuels

- Marine fuel specifications. Presented by Monique B. Vermeire, Fuels Technologist at Chevron, and representative for the International Organization of Standardization (ISO)

Session 4 – Laboratory testing and measurement procedures for low sulphur fuel. Methodology - Analyzing low Sulphur fuels (Pour point, density, aromatic content, and toxicity), Procedures, methodology and experience.

- Cold flow properties VLSFO. Presented by Mats Christensen, Fuel Specialist at Veritas Petroleum services.
- Laboratory testing and measurement procedures for LSFOs. Presented by Kristin R. Sørheim, Senior project leader at SINTEF Ocean.
- A fate and behaviour evaluation of emerging low sulphur fuels. Presented by Robert Faragher, Oil Research Scientist at Environment Climate Change Canada
- Low sulphur fuel analysis: differences compared to traditional heavy fuel oil. Presented by Robert Faragher, Oil Research Scientist at Environment Climate Change Canada

6.4 GROUP WORK

At day 2 participants were divided into three groups to discuss the following topics:

1. Harmonizing best practice methodologies for laboratories
2. Setting criteria for best practice VLSFO blending for cold water conditions

The group's notes are summarized in the sections below and are based on the original notes compiled by the groups. The workshop notes have been edited to ensure clarity and consistency.

HARMONIZING BEST PRACTICE METHODOLOGIES FOR LABORATORIES

The overall goal discussing this topic was to recommend best practice methodology for characterizing LSFOs, suggest improvements to these methodologies, and to suggest concrete follow-up projects for improving laboratory testing procedures.



Physical properties

- Pour point
 - The use of different methods and instruments make direct pour point comparison between labs unreliable.
 - Capabilities:
 - Norway (SINTEF) use ASTM-D97 (ISO 3016 equivalent) for testing.
 - VPS used in-house high throughput tests. Use ISO 3016 to test of-spec oils.
 - USA (EPA) relies on commercial labs for oil analysis, with limited governmental capability.
 - Canada (ECCC) uses an in-house, automated, high-throughput system. Has challenges measuring dark oils, which is potentially affecting the results.
 - Recommendation: Adopt ISO 3016/ASTM-D97 as the preferred method for measuring pour point.
- Cloud point/wax appearance temperature
 - Recommendation: Testing of wax appearance temperature can used to test whether or not pour point reducing additives have been added (also on dark fuels). VPS has an inhouse method than can be considered.
- Viscosity
 - Recommendation: Measure kinematic viscosity over a temperature sweep, starting from minimum 50 °C and measure down to 0 °C. Fuels that behave like a solid/semi-solid (at room temperature) should be preheated
- Density
 - Recommendation: Use ASTM-D5002 measured at 15°C, or ASTM-D1250 if measured at 50°C.
- Interfacial tension
 - Recommendation: Not an essential parameter. If measured, the report should specify the type of water used for the measurement.

Chemical properties

- Wax content:
 - Recommendation: Wax precipitation should be measured with a precipitation temperature down to -30 °C. Consider doing a controlled verification study to compare precipitation temperatures (e.g. -10, -20 and -30 °C).
- Asphaltenes

- Recommendation: Measure both soft and hard asphaltenes with the same refluxing times, using ASTM D6560. Important to report what type is measured (soft (in n-pentane) or hard (in n-heptane)).

SETTING CRITERIA FOR BEST PRACTICE LSFO BLENDING FOR COLD WATER CONDITIONS

The overall goal was to discuss and agree on criteria for blending an optimal LSFO for use in the Arctic that are compatible with existing oil spill recovery equipment, in Arctic waters.

Requirements for fuels used in the Arctic from July 2024.

- The blended fuels will need to comply with existing criteria:
 - Sulphur content <0.5% S
 - Density < 900 kg/m³
 - Viscosity < 180 mm²/s

Suggestions for blending Arctic LSFO

- Blending with biofuel.
 - Blending in a biofuel component can be positive for the environment. Biofuels blends are considered to be cleaner by the public. Elevated NO_x emissions may be a drawback.
 - Biofuel/LSFO blends may need special fuel standards. Could consider increasing the density criteria to 910 kg/m³.
 - Concerns related to the amount of biofuel on the market if the demand increases.
- Consider how to use additives to lower pour point.
- Blending with the aim of approaching the properties of the HDME 50 (pour point: 6-12°C; density: 900-915 kg/m³; viscosity: 30-45 cSt), as this is an oil that is easy to recover.

Use of additives

- It would be beneficial with lower pour point, and additives could be part of the solution, as they have the potential to lower pour point with 10-15 °C.
- Better knowledge about the fuel blending protocols would be a benefit. Information about addition of additives, in the blending process, is not available when purchasing the fuel, thus it's not possible to know if adding additives to with the aim of lowering pour point (in tank) will have an effect.
- It would be beneficial for consumers, and first responders, to be able to trace information about additives by including this information in the fuel information sheet. However, this can be challenging, as fuel providers will be hesitant to share blending secrets.

Other thoughts and comments

- Use of distillates might be the best solution for the Arctic, but cost can be an issue.
- Just a small percentage of fuels meets both the criteria in IMO’s “Arctic HFO ban” and the Global Sulphur cap. Can enough of this fuel be produced to meet the demand?
- It would be useful to know the wax content of the spilled fuel oil, from an oil spill response perspective.
- It is very challenging to be prepared to respond to spills of LSFO when the variation in pour point is so large (-36 to +40 °C). A consideration would be to develop criteria to reduce the span in pour point.
- Can pour point be included in the list of criteria for Arctic use (alongside viscosity, density, and sulphur content)?
 - This is challenging, as blenders only have values for “apparent pour point” at the first stage of blending, and actual pour point cannot be tested before the blend is mixed.

Recommendations about new research and knowledge gaps

- The effect of additives when a biofuel/LSFO blend is spilled in cold water conditions and how current oil spill response equipment handles biofuel/LSFO blends is a knowledge gap.
- The effect and fate of additives when the fuel is spilled at sea in cold water is a knowledge gap.
 - Additives can lower the pour point when mixed inside a tank, but will it still be able to keep the pour point low if this mixture is released to sea? Temperature change, emulsification processes and other factors might the the efficacy of the additives.
 - Recommendation: initiate new research projects to close knowledge gaps regarding LSFOs (with additives) spilled in cold water (start with meso-scale lab. tests, and move on to basin tests if the results are promising).

6.5 CONCLUSION

The industry involvement workshop was a success, providing valuable insights and discussions. It was unfortunate that it the workshop was postponed to the later part of the project (due to the COVID-19 pandemic and the situation in Ukraine), regardless the benefits of these workshops remain clear. This approach should also be incorporated into our next project to strengthen collaboration and knowledge sharing, even considering organizing two workshops, one at the beginning and another at the end, to maximize learning and engagement from the industry.

7. DISCUSSION AND CONCLUDING REMARKS

Spills of residual fuel oils in the Arctic can cause long-term environmental damage due to the oils' persistence in the environment and challenges with cleaning up spills because of the oil properties, harsh weather conditions, and remoteness from oil spill preparedness resources. Fuel lumps also have the potential to drift long distances and in the worst-case freeze into the sea ice.

One of the purposes of this project was to close the knowledge gap on which fuels are used by ships sailing in the Arctic (Chapter 3 - fuels used by ships sailing in Arctic waters). Furthermore, to analyze the basic properties of these fuels (Chapter 4 – characterization of new low sulphur marine fuels). This report provides information on the properties of LSFOs, including density, viscosity and pour point. These are important parameters to ensure appropriate contingency planning, oil spill preparedness, and potential recovery operations if such fuel oil is accidentally discharged to sea. The results presented in this report provide important findings while also revealing key knowledge gaps and the need for further research, which will be discussed in the following section.



1. The properties of residual fuel oils, and their behaviour on cold water surfaces, present significant challenges for oil spill response and cleanup operations in Arctic waters

Findings from this project showed that many of the LSFOs required by IMO in the global 2020 sulphur fuel cap have high pour points and high viscosity at low temperature (see Chapter 3 and 4), which can cause long-term environmental damage due to the oils' persistence in the environment and will cause various challenges for oil spill recovery.

These challenges are related to escape from booms and various difficulties when using skimmers, to poor dispersibility and varying degrees of ignitability and burn efficiency for in situ burning (see Chapter 5, IMAROS (2022) and Sørheim et al (2020)). Cleanup efforts in Arctic conditions are further complicated by the harshness of the environment, remoteness and the lack of infrastructure, which are significant limitations on pollution response in the event of an oil spill. LSFOs with high viscosity and tendency to solidify at low temperature will also be persistent against natural degradation, similarly as the fuel oils prohibited under regulation 43A and 43.1.2 of MARPOL Annex I ("the Arctic HFO-ban"). Furthermore, the fuel analysis, completed as a part of this project (see Chapter 3), shows that several fuels currently used in the Arctic would not be prohibited under the existing regulation (Figure 4 and Figure 5).

Recalling Resolution MEPC.342(77) *Protecting the Arctic from Shipping Black Carbon Emissions* adopted in 2021 that encourages the voluntary use of distillates or other cleaner alternative fuels in the Arctic to reduce Black Carbon emissions, it is noted that distillate fuels do not present the same challenge for oil spill recovery and are generally less persistent in the marine environment. The use of distillates in the Polar Code Area would help mitigate the risks associated with a spill and could provide additional protection as sought under the Arctic HFO fuel ban.

Additionally, this report identifies several fuel characteristics that create specific challenges for spill response. Addressing these characteristics through prohibiting fuels with kinematic viscosity higher than 180 mm²/s measured at 5 °C and setting a requirement for an upper pour point value of 0°C (based on ISO 8127 summer requirements for DMZ and DMA), would both alleviate significant challenges for spill cleanup and the persistence of fuel oil in the Arctic. Fuels in a liquid form that dilute and biodegrade with the help of the forces of nature are considered the better choice in remote Arctic waters.

2. In order to respond to acute spills in a targeted, adequate and efficient way, the most important data should be easily and readily available to the responders/authorities as part of the bunker delivery note.

The Bunker Delivery Note (BDN) is a mandatory document to be carried by ships of 400 gross tonnage and above (MARPOL Annex VI/18.5). The BDN contains

information about the fuels on board the vessel including fuel characteristic information such as density (at 15 °C), sulphur content, and flash point.

In light of the findings of this report that identify specific characteristics important to the clean up and response for fuels spills in the Arctic, there is an opportunity to provide additional information that could be of assistance to response efforts. Including such information on the BDN would ensure critical information is readily available in case of an incident. The following additional parameters were identified in the analysis as most important for oil response:

- Pour point - ASTM D97
- Viscosity measured at 5 and 50 °C – ASTM 445 or D7042

It is noted that the 5 °C recommendation differs from the current temperature standard for viscosity measurements. This additional information would allow responders to better anticipate the behaviour of the spilled oil (than currently required 50°C), and is based on an evaluation of cost and benefit: measuring 5 °C as an addition to 50 °C has a neglectable cost for the fuel provider/buyer, but has a very high benefit for responders to acute pollution.

Additionally, it may be beneficial to include information on the BDN indicating whether additives to change the cold flow properties have been added to the fuel by the producer. This would provide valuable insights for both oil spill responders and fuel purchasers and users.



3. As the fuels market undergoes further changes with the increased adoption of alternative fuels, additional studies on the consequences of accidental spills of such fuels on the environment will be needed.

The environmental consequences of LSFO spills in the Arctic environment is, to a large extent, a knowledge gap. Fuels that solidify in cold water to solid lumps can drift over long distances and freeze into the ice or sink. In the Arctic environment this long-term effect of LSFO is problematic because they break down slowly in the environment.

Many discharge-consequence models in use today typically are based on the chemistry and characteristics of older HFO blends. This will cause inaccurate predictions because the models are not designed to work on the fuels that they are being applied to.

As such, a follow up study of environmental consequences of different fuel qualities and quantities of LSFO in the Arctic environment is needed. The result of such a study would help craft an updated system of new consequence classes according to spill volume, fuel type and its characteristics. As well as how this will impact the Arctic environment including different beach types.

Toxicity studies would yield additional information on toxicity profiles of new fuels that will be important for predicting impacts to the marine environment, flora, and fauna in the event of a spill.

However, the interlaboratory calibration study (Chapter 4.1) revealed that it was very challenging to compare toxic effects of the same oils tested in different laboratories, even though the same methodology guidelines were followed. Firstly, it was not possible to perform the testing of acute toxicity on a common test species between the laboratories, and secondly, there was a large variation in the chemical composition (and concentration) in the prepared exposure mediums (WAFs) from the same oil between laboratories.

This makes it difficult to give any recommendations regarding suitable test organisms to test toxicity of LSFOs, and further work is needed for obtaining consistent results. As an alternative, calculation of toxic units of the WAFs could be an option. Toxic units are based on the chemical composition of the WAFs and should in theory reflect the toxicity of the bioavailable water-soluble oil components of that specific oil, which can be released into the water under an oil slick spilled in the environment. However, this method is limited to the suite of analytes given by the method and may not take adverse effects by components not quantified into account. Of special concern may be additives used to tailor the characteristics of the fuel oil to specific uses.

4. Use of additives and cutter stock has become more frequent when blending LSFOs however, their properties are not well understood and represent a knowledge gap that should be addressed.

LSFOs are blended fuels that use processes similar to traditional high sulphur fuel grades. However, the use of additives and so-called cutter stock has become more frequent, when blending LSFOs.

Cutter stocks are oil and oil-related byproducts used to thin oil, i.e., to reduce viscosity and sulphur content in order to produce on-spec fuel oils. Blending of marine fuel oils has become more complex over the years, as the blends can contain heavier oil fractions. The requirement for a maximum sulphur limit in fuel oils introduced often require paraffinic product to be used as cutter stock. To blend a spec low sulphur fuel often requires a combination of different cutter stocks, and often in combination with additives. Additives are generally used to improve the flow properties and operability of LSFOs and have become an important component to stabilise such fuels.

The chemical properties of these additives and cutter stocks are largely under-researched and not well understood. A project studying commonly used cutter stocks for producing low sulphur fuels is needed, including research on the effect of adding different types and volumes of cutter stocks to residual blends. The impact of additives when LSFOs are spilled at a cold sea surface also represents a knowledge gap. Better knowledge about the impact and effect of additives can be important to produce more suitable fuels for Arctic conditions. A project aiming to improve the knowledge on additives, their variation and complexity and their effects on residual fuel is therefore identified as a follow up project.

5. Since the blending of biofuels into marine fuels has become common, further research is needed to understand their behaviour in the event of an Arctic spill.

As part of the European Commission's Fit for 55 legislative package, the FuelEU Maritime Regulation (Regulation (EU) 2023/1805) promotes the use of renewable, low-carbon fuels and clean energy technologies for ships essential to support decarbonisation in the sector. The Regulation is fully applied from 1 January 2025 for ships sailing between EU ports and EEA ports. Blending in biofuels to ordinary marine fossil fuel are the easiest way to comply with the FuelEU Maritime regulation today. Ships affected by the FuelEU regulation occasionally sail into the Arctic, where they either use such fuel for their primary propulsion, or carry it in one or several fuel tanks.

In July 2023, IMO Member States adopted the 2023 IMO Strategy on Reduction of GHG Emissions from Ships, with enhanced targets to tackle harmful emissions. It is envisaged that a review of the 2023 IMO GHG Strategy will be finalized when the Marine Environment Committee meets in autumn 2028, with a view to adoption of the 2028 IMO Strategy on reduction of GHG emissions from ships.

The increased demand for alternative energy sources and fuels has triggered primary interest in development of biofuel to reduce global CO₂ emissions. As new green fuels become available to shipping fleets that rely on renewable feedstocks to create them, several risk factors have been identified where significant knowledge gaps exist regarding their use. These factors include, emissions pertaining to soot formation and NO_x as well as their fate/behaviour in the event of an Arctic spill.

If an accidental spill with biofuels happens, the results from Faksness et al. (2024) showed that use of chemical dispersant can be an effective response option, especially under conditions with breaking waves. However, the viscosity and water uptake in the tested biofuels were low, so the potential for boom leakage will be present. Data also suggests that certain biofuels are temperature-sensitive and can gel at lower temperatures. Consequently, fuels containing biofuels, including distillates, and may behave unexpectedly if accidentally released into cold seawater.

Changes in the properties, toxicity, and behaviour of LSFOs when blended with biofuels require further research and analysis along with the development of practical operational guidance before they can be considered suitable for use in the Arctic environment. Additionally, more research is needed to understand how biofuel properties may impact oil spill response strategies.

6. Industry involvement workshop

The industry involvement workshop provided valuable insights, fostering a shared understanding of the challenges and facilitating the proposal of effective measures. It is recommended that this workshop be incorporated into all follow-up projects outlined in this report.



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APPENDIX: GLOSSARY OF TECHNICAL TERMS USED IN THIS REPORT

Term	Explanation
Additives	Additives are chemical compounds that prevent crystal growth and modify crystallization behavior of the fuel to improve Cold flow properties of the fuel.
Asphaltenes	Complex nonpolar components in the oil that can play a significant role in the stabilization of water-in-oil emulsions. "Hard" asphaltenes can be precipitated from n-heptane and "soft" asphaltenes from n-pentane.
ASTD	Arctic Ship Traffic System owned by Arctic council and administered by the PAME working group.
ASTM	American Society for Testing and Materials (develop international voluntary consensus standards)
BDN	Bunker delivery note (Standard document required by Annex VI of MARPOL which contains information on fuel delivery)
Biofuel	Is a renewable energy source. Can be derived from biomass and converted into FAMES (conventional biofuel) or derived from waste or agricultural residues and are called HVO (advanced biofuels)
CHN	Carbon, hydrogen and nitrogen
CoA	Certificate of analysis (A certified document issued by a commercial laboratory after testing the oil product after specific criteria).
CROSERF	The chemical response to oil spills: Ecological effects and Research Forum (Developed a protocol that described a standard method for reproducible preparation of exposure media as well as recommended specific analytical methods for comparative toxicity testing (in 2005))
Cutter stock	Cutter stocks are oil and oil-related byproducts used to thin oil, i.e., to reduce viscosity and Sulphur content to produce on-spec fuel oils.
Density	Expressed as specific gravity, which is density in fresh water. Most oils float on seawater (density of approx 1.025 at 20 °C). Measured in g/cm ³ or kg/l.
EPPR	Emergency Prevention, Preparedness and Response (Arctic Council working group)
FAME	Fatty Acid Methyl Esters
Flash point	The lowest temperature at which an ignitable vapor is generated (will ignite with an ignition source)
Foundering	"'Foundering' refers to the sinking, collapsing, or failing of a vessel, typically due to structural issues with its hull. This often occurs when heavy weather conditions combine with structural failures, which can be attributed to factors such as the hull's age or design."
Grounding	Includes both powered grounding and drift grounding. Power grounding is grounding under engine power. Drift grounding is grounding due to engine failure and that the ship drifts aground.
HFO	Heavy fuel oil
HSFO	High sulphur fuel oil (>0.5 % S)
HVO	Hydrotreated vegetable oil
IFT	Interfacial tension (when an interface forms between two dissimilar phases (oil and water))
IMO	The International Maritime Organization

ISO	International Organization for Standardization (develop and publish international standards)
LC50	The exposure concentration lethal to 50% of the tested organisms (low LC50-values indicate high toxicity (high values indicate lower toxicity)
LSFO	Low sulphur fuel oil
Marine distillate fuels	Distillate Marine Fuel is a grade specification for marine fuels. The most recognized classification of distillates is specified by the International Organization for Standardization's ISO 8217 standard, which classifies marine fuels based on their properties and intended uses. ISO 8217:2024 is setting the requirements for both distillate and residual marine fuels.
MARPOL	The International Convention for the Prevention of Pollution from Ships
MEPC	Marine Environment Protection Committee (addresses environmental issues under IMO's remit)
MGO	Marine gas oil
PAME	Protection of the Arctic Marine Environment (Arctic Council working group)
Pour point	The lowest temperature an oil will flow
Polar code area	IMO's International Code for Ships Operating in Polar Waters (Polar Code area) is mandatory under both the International Convention for the Safety of Life at Sea (SOLAS) and the International Convention for the Prevention of Pollution from Ships (MARPOL). The Polar Code covers the full range of design, construction, equipment, operational, training, search and rescue and environmental protection.
PPR	Pollution Prevention and Response (IMO Sub-committee)
Residual fuel oil	Residual fuels, as their name implies, are predominantly comprised of the less valuable residues from the various fractionation and conversion processes at a refinery.
SECA	Sulphur Emission Control Area
SVOC	Semi volatile component (eg. Naphthalenes and PAHs)
True boiling point	Is the boiling point range distribution of petroleum fractions (by high temperature gas chromatography)
TU	Toxic unit (A predicted expression of toxicity, TU >1 implies that the exposure solution is expected to cause more than 50 % mortality in the test organisms. Higher value indicate higher toxicity)
ULSFO	Ultra-low sulphur fuel oil (<0.1 % S)
US EPA	United States Environmental Protection Agency (EPA's mission is to protect human health and the environment)
Viscosity	The oil's resistance to flow (viscosity increase with decreasing temperature). Viscosity is measured in mm ² /s or cSt. 1 mm ² /s = 1 cSt.
VLSFO	Very low sulphur fuel oil (<0.5 % S)
VOC	Volatile components (e.g. BTEX (benzene, toluene, ethylbenzene, xylenes))
WAF	Water Accommodated Fraction (generation of systems with water soluble oil components)
Wax	Straight chain saturated hydrocarbons with carbon atoms ranging from C18 to C36.
WRG	Wide range gas oil

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