LONG TERM ICE EXPOSURE STUDIES FOR ENHANCING ARCTIC NEBA SCIENCE BASE

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The Arctic Oil Spill Response Technology - Joint Industry Programme has the goal to advance arctic oil spill response strategies and equipment as well as to increase understanding of potential impacts of oil on the Arctic marine environment. In 2013 a comprehensive review of investigations into environmental consequences of spilled oil and oil spill response technologies in the Arctic marine environment was performed by a multi-disciplinary team of experts. This review indicated that there is a significant science base for oil spill response decision-making in the Arctic already available and also listed recommendations for studies to enhance the science-base for Arctic Net Environmental Benefit Analysis (NEBA).

To follow up on the reviews' recommendations a unique long-term mesocosm experiment was executed to improve the scientific knowledge of the fate and biodegradation of oil and oil spill response residues in ice, as well as the environmental effects to ice associated ecology. Eight mesocosms were installed in the sea ice of the Van Mijenfjorden in Svea, Svalbard, Norway in February 2015 and remained in place until July 2015.

The study was designed to monitor the long term fate, behaviour, persistence and biodegradation of the oil in ice together with the impact on the microbial communities, following different response scenarios. Additionally, under-ice phyto- and zooplankton communities were sampled and monitored for effects. The same exposures were replicated in the laboratory to measure the sensitivity and resilience of the polar cod. Over the five month period that the mesocosm experiment lasted, the following parameters were studied within the water column, through the ice layer and within the water-ice interface:

- Chemical composition of the oil
- Bacterial populations and oil degrading microorganisms
- Microbial activity and biodegradation activity
- Zooplankton - survival, feeding and reproduction (under ice)
- Ice algae primary production

Results from the studies and additional modelling activities have improved our understanding of what happens to oil once frozen into ice, how microbiology is reacting to oil in ice and what the exposure potential is of the ecology associated with the ice. This information enhances the NEBA science base and helps the response community in selecting a combination of response strategies that minimises the effects to people and the environment.

KEY WORDS: Oil spill response, Arctic, Biodegradation, Ice ecology, Net Environmental Benefits Analysis (NEBA)

I. INTRODUCTION

In the event of an oil spill, there are always concerns about the severity of environmental impacts (Lloyds, 2012; DNV-GL, 2014). This concern is higher for the Arctic because of the assumption the ecosystem is more sensitive. Although available data indicates that both Arctic and temperate organisms are nearly equally sensitive to exposure to oil and oil constituents (Olsen et al., 2011; Camus et al., 2015; Gardiner et al., 2015), the habitats of Arctic organisms might be more vulnerable to the effects of petroleum hydrocarbon pollution than temperate habitats because low temperatures lead to slower losses of hydrocarbons from volatilization and biodegradation, and because oil trapped under sea ice can result in prolonged exposure. However, the reduced weathering process (evaporation, dispersion and emulsification) and behaviour of oil in ice can also actually mitigate the environmental impact. Wind and sea conditions in many Arctic areas are considerably less severe than most open ocean environments, facilitating marine operations. Furthermore, when ice concentrations prevent the effective use of traditional containment booms, the ice itself often serves as a natural barrier, preventing oil spilled offshore from entering and contaminating ecologically sensitive coastal areas (Potter et al., 2012). Assessing the environmental effects of an Arctic oil spill and deciding on the optimum response strategy is not straightforward and should be done on a case- by-case basis. Many international, national and local agencies have developed ecosystem and biodiversity assessments in order to better understand the Arctic marine ecosystem. The Net Environmental Benefit Analysis (NEBA) method provides a framework to carefully consider and select from several response options based on their effectiveness and associated environmental effects. Sound scientific knowledge about the population-level effects of an oil spill to valuable ecosystem components is also vital for the analysis (IPIECA, 2015).

The overall goal of Arctic JIP's Environmental Impacts from Arctic Oil Spills and Arctic Oil Spill Response Technologies project (IOGP, 2016), is to collect, review and improve the knowledge base for using NEBA in oil spill response decision making, and ultimately improve stakeholder acceptance of the role of environmental impact assessment in oil spill response plans and operations. This project was conducted in three phases:

1. Perform a comprehensive review on the environmental impacts of arctic oil spills and from the technologies used to respond to such spills and identify research activities to improve the knowledge base for using NEBA in the Arctic.
2. Conduct and complete the most crucial research activities identified in phase one.
3. Enhance the accessibility of the NEBA science base by dissemination of phase 2 results through publication in peer reviewed journals and at conferences and by providing online data summaries on exposure potential, sensitivity and resilience for Arctic species linked to key literature.

The phase one comprehensive review was conducted by a consortium of 14 North American and European research institutes and universities, and culminated in the online publication of a report "Environmental Effects of Spilled Oil and Response Technologies in the Arctic" (Word, 2014) which is based on over 960 literature references from investigations into spilled oil and oil spill response technologies in the Arctic marine environment. The report is the first time the significant body of research on this area has been compiled and reviewed in one place, confirming that there is a large amount of literature already available for and on oil spill response decision-making in the Arctic.

Recommendations from the phase one review led to focused research projects being launched to reduce remaining uncertainties on sensitivity and resiliency of sea ice communities and biodegradation of oil under Arctic conditions and to improve and advance Arctic NEBA's.

- There is an extensive, existing science base for arctic oil spill response decision-making through the NEBA (Net Environmental Benefits Analysis) process. Many baseline ecosystem and biodiversity assessments have been performed to better understand and protect the marine Arctic environment. In addition, field and laboratory studies on the fate of oil, oil spill response techniques and potential environmental effects under the different seasonal conditions in the Arctic have produced extensive data sets on oil fate and effects. Accessibility of this data should, however, be improved.
- There is also evidence that Arctic species are not more sensitive to dispersed oil than non-Arctic species and that they react to dispersed oil exposure in the same way as temperate species do. In order to fully understand the impact of oil and oil spill response techniques on species and the recovery of populations, the review recommended follow-up research into the resilience of populations.
- Furthermore, data has been reviewed that shows that approved dispersants and oils treated with dispersants are no more toxic than the oil itself. Another important finding is that biodegradation of oil in the Arctic does occur and that dispersants tested do not reduce the ability of microbes to degrade oil.
- Biological organisms tend to aggregate at interfaces like the water/ice interface, which is one of the unique features of the Arctic ecosystem. Undispersed oil might collect at this interface potentially interfering with unique Arctic resources. The review recommended that information on the potential effects of oil on these Arctic communities be developed in order to better address these in NEBA.
- The presence of ice changes the behaviour of oil and can actually mitigate the environmental impact, as the presence of ice results in reduced evaporation, dispersion and emulsification and can form a barrier so that vulnerable resources like coastlines cannot be reached. Any oil encapsulated in ice is not likely to impact marine life in the water column.

Table 1. Key findings from the phase 1 literature review (Word, 2014)

II. FIELD AND LABORATORY STUDIES; BIODEGRADATION, SENSITIVITY AND RESILIENCE

Mesocosm study set-up

As part of the phase 2 research, field experiments were set up, aimed to improve our understanding of what happens to fresh oil once frozen into ice, how microbiology is reacting to oil in ice and the potential for exposure of the ecology associated with the ice. The simulated spill scenario was; fresh oil spilled in ice free water just before freeze-up. The permitted field experiments were conducted in in-situ mesocosms, to further understand the oil weathering process and natural biodegradation of the oil under Arctic conditions, and to measure the sensitivity and resiliency of sea ice communities. A mesocosm is any outdoor experimental system that examines the natural environment under controlled conditions. Mesocosm studies provide a link between field surveys and highly controlled laboratory experiments. The use of these semi-open systems to study effects of contaminants in marine systems is well established, but this technique had never been used in Arctic ice environments. A multidisciplinary team of world class experts examined the long-term fate, behaviour, persistence and biodegradation of the oil in ice together with the impacts on the microbial and plankton communities in and under ice, following different response scenarios.

Mesocosm Construction

Cedre (France) designed eight mesocosms used in the study that were manufactured by the French engineering company G2B. The mesocosms were designed to float in open water and be resistant to icing to stay on location from the fall freeze to the spring melt. The diameter of the mesocosms, 1.6 m, was selected to minimize stresses applied on the structure over the icing period. The mesocosms consisted of a floating opaque vertical cylinder open at the top and the bottom to allow natural exchanges with the atmosphere and the water column (e.g. dilution and evaporation), but long enough (3 meters) to keep the exposure medium contained (Figure 1). Once surrounded by floating ice, the mesocosms move with the ice according to the tidal movements; this prevents movement of water through the pipe, which could lead to oil leakage out of the inner part of the mesocosm. Opaque vertical cylinders were selected (black plastic curtain). In case of real oil spills (oil slick of few hundred meters), the slick would induce a UV-light blockage at the surface of the ice (i.e. stop the penetration of light in the water column or through the ice pack).

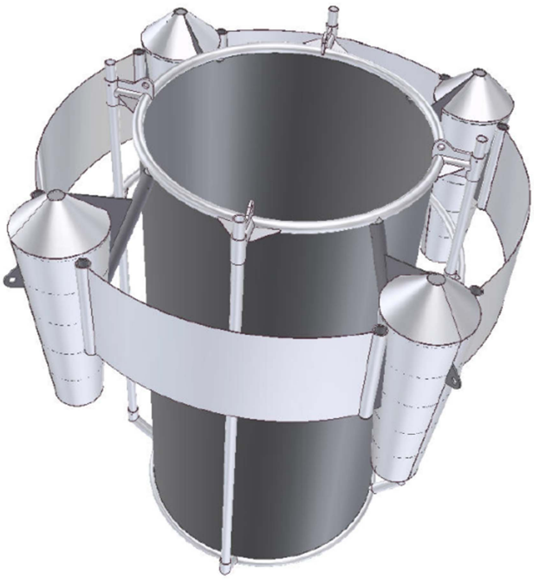

Figure 1. Construction drawing of a mesocosm showing 4 cone-shaped floaters, an outer ice barrier to withstand ice pressure and the inner cylinder where oil is dosed and samples are taken.

Mesocosm Installation and Treatment

The eight mesocosms were installed in the Van MijenFjorden in Svea, Svalbard, Norway in February 2015 once the fjord ice was sufficiently thick, stable, and safe for personnel to transit and work. Large holes (3m x 3m) were cut in the 80cm thick ice with a chainsaw, and the ice blocks pulled out by means of man power and transported away from the site by snow scooter. The mesocosms were transported to the experimental site individually on a modified sledge pulled by a snow scooter and once on site the mesocosm, lowered into the water (Figure 2).

Immediately after installation, the exposure medium was introduced onto the water inside the mesocosms. Two mesocosms served as control with no oil. Two other contained only oil to follow natural attenuation. In two other an unsuccessful dispersant application was simulated. These contained dispersant (Finasol OSR52) mixed with oil (1:20) without any additional mixing energy. Instead of the oil getting dispersed in the water column, oil mixed with dispersant froze into the ice. The final two mesocosms contained residues from an in-situ burn response. In all exposure mesocosms the amount of oil was kept constant (20 litres oil or burn residue resulting from burning 20 litres of KOBBE crude oil). In the mesocosm simulating natural attenuation this resulted in a slick of 1 cm thickness. KOBBE crude oil, produced by the GOLIAT oil field in the Barents Sea, was used in all of the experiments.

Figure 2. Mesocosm directly after installation.

Crude Oil and Dispersant Used for Treatments

Physical and chemical analyses of the fresh oil were performed at Cedre. The KOBBE crude oil (produced by the GOLIAT oil field in the Barents Sea) is a relatively light crude oil centred on n-C14, with a density of 0.816 g/mL (at 2 °C) and a viscosity of 6 mPa.s (at 2 °C and a shear rate of 10 s-1). The distillation curve obtained during the sample preparation of the 250 °C residue is representative of the maximum evolution at sea, and results of this distillation provides a reliable prediction of the maximum evaporation rate expected when spilled at sea. The evaporation rate is 50 %. The content of asphaltenes is low (0.3 % w/w, i.e. by mass) and the content of wax is moderate (11 %). The crude oil pour point is -39 °C. The fresh oil is thus not in the solid form at the temperatures encountered during the field work. The pour point is related to the wax content, and it increases over time due to the evaporation process. The surface and interfacial tensions (measured between the oil and the air and the oil and the water) are of 24.73 and 13.44 mN/m, respectively. The maximum water content is of 77.9 %.

The production of burned residue was done in collaboration with the French institute INERIS (Verneuil-en-Halatte, France): 20 L of the KOBBE oil was burned for 3 min. This was the time needed for the fire to go out, leading to approximately 2 L of burned residue (i.e., approximately 85 – 90 % of the fresh oil volume was burned).

The dispersant FINASOL OSR52 is approved for use in many countries and presents an efficiency of 79 ± 3 %, measured using the IFP test (NF T 90-345) on viscosity oil of 1,300 cSt. In response of an acute toxicity test, the dispersant toxicity of brown shrimps (*Crangon crangon*) exposed during 6 hours to 960 mg.L-1 causes a mortality of 3.3 % (NF T90-349 method). Finally, the biodegradability of the dispersant is at least 50 % according to a test performed by INERIS (NF T 90-346).

Sampling Schedule

Field work started end of January 2015 and lasted until the ice melting period (July 2015) to cover different winter temperatures and environmental conditions, as well as the spring peak of biological activity. The first sampling (water) was performed right after the mesocosm installation (T0). At four additional occasions samples were taken:

- Second sampling (T1) March.
- Third sampling (T2) April.
- Fourth sampling (T3) May.
- Fifth sampling (T4) and decommissioning of the mesocosms July

For sampling periods T1 – T3, 3 or 4 ice cores were collected from each mesocosm (random distribution of sampling points in each mesocosm) using a 9 cm diameter corer which was cleaned after drilling in each mesocosm. All samples and measurements were taken using the same cores to be able to correlate the data between the different analyses and experiments. A separate corer was used in the polluted mesocosm to avoid any transfer of petroleum to the clean and control sites. At each of the four sampling times (T1, T2, T3 and T4), water was collected at three different depths in mesocosms, using a manual pump: for T1, T2 and T3, just below the ice, at 1 m below ice, and at 2 m below the ice. For the T4, at 0.7 m, 1 m and 2 m below the sea surface. Deeper seawater samples were collected using Niskin bottles. Clean sites, located in the same fjord but approx. 120 m away from the mesocosms were also sampled.

Figure 3. Overview of the eight mesocosms installed in Van Meijenfjorden, Svea, Norway.

III. METHODS AND RESULTS

Hydrocarbon Chemistry and Microbial Response

At three sampling points (T1-T3) ice cores were collected from each mesocosm using a 9 cm diameter corer. Ice cores were sampled from the mesocosms and analysed for chemical composition at different layer depths. For microbial community analysis, the total DNA and RNA were extracted from each sample to determine the microbial community structure and structure of active counterparts of microbial assemblages. Bacterial community composition was investigated, as well as microbial numbers, presence of oil degrading microorganisms and microbial activity.

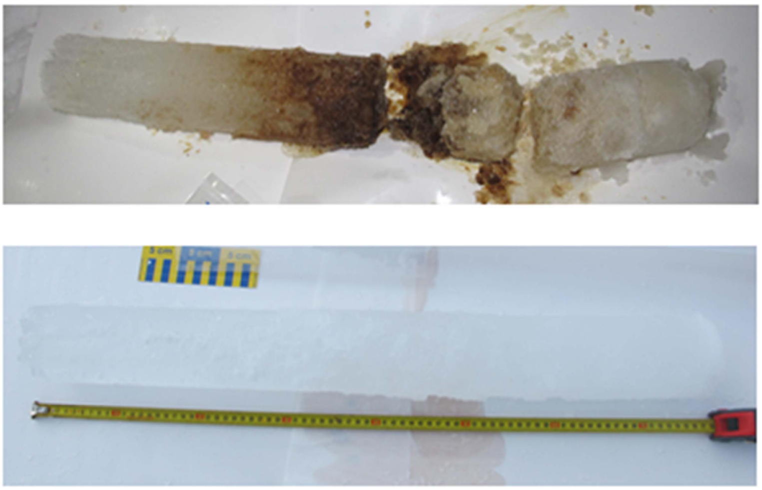

Figure 4. Ice cores taken from crude oil exposure (top) and control mesocosm (bottom)

For all treatments, changes to the chemical composition of the oil slick trapped in the top layer of the ice were minor, indicating that oil remained relatively fresh throughout the ice period and confirming results from previous studies. (Norcor 1975; Brandvik et al. 2006). Still, changes in alkane composition suggests that while not significant in terms of volume in a response context, some biodegradation and evaporation takes place while the oil is frozen into the top layer of the ice.

A slow dissolution of soluble light PAHs (i.e. naphthalene) into the ice and the water column underneath the ice was detected from the oil frozen into the ice upper surface. This effect was enhanced when dispersant was premixed with the oil. As expected in-situ burn residues liberated only small concentrations of PAHs into the ice and not into the water, reflecting the fact that most of the light components of the oil are burned off in the combustion process.

Arctic microbial communities in ice shift in response to oil within the first month of exposure. Bacteria related to known oil biodegraders (Oleispira + Colwellia) were present and active in the sea-ice layers for the oiled mesocosms. The differences in the structure of the biological communities in the oil and dispersant mixture mesocosms compared to the other mesocosms indicated that oil may have diffused through the ice layer to the seawater, where oil biodegraders used it as a food source. Very low levels of hydrocarbons were detected underneath the ice for these treatments.

• Oil trapped in ice undergoes minimal change over time. A fraction of the lightest compounds (HAPs and alkanes) are dissolved and migrate through the ice; • Dissolution and migration kinetics of lightest compounds through ice are higher with dispersant than without; • In the arctic environment, microbial communities are active and are able to degrade petroleum compounds; • A higher number of microorganisms are found in the ice and seawater in presence of oil; • Microbial communities shift towards abundant oil-degrading organisms when exposed to oil, and these changes happen faster in the presence of dispersant; • Incubation experiments showed that bacteria present in sea ice were able to respond to and degrade petroleum hydrocarbons

Table 2. Summary findings on biodegradation

Sea ice communities

The objective of the study was to assess the exposure potential and effects to ice associated ecology that plays a key role in the energy built-up and transfer in early spring. This included ice-algae forming at the water/ice interface, under ice micro and zooplankton, and fish.

<u>Ice algae</u>

To assess the effects to the development and production of ice algae, at T1, T2 and T3, light penetration through the ice was measured inside the mesocosms and bottom-ice cores (5 cm) were taken for the determination of nutrients, chlorophyll a, the elemental composition of organic matter, the taxonomic composition of microalgae as well as the estimation of primary production rates.

No evidence was found that the presence of oil in the upper layers of sea ice had an adverse impact on nutrient availability in bottom ice. The oil in this experiment had no effect on the upward supply of nutrients from the water to the algal layer in the bottom few centimetres of the ice.

Low light conditions underneath the ice inside the mesocosms made it difficult to discriminate between effects of the treatments on ice-algae, but analysis of ice algae growth indicated that the responses in the control and ISB residue treatments were similar while reduced growth of ice algae was observed in the natural attenuation or oil and dispersant mixture treatments. The ISB treatment had a lesser ecological impact on ice algae than the oil and oil mixed with dispersant, either through toxic action or light attenuation.

Under ice micro- and zooplankton

Under-ice phyto- and zooplankton communities were sampled and monitored for effects in winter (T1) and spring (T3). Water was sampled from each mesocosm at the sea ice/water interface through drilled holes in the ice. This water was used for micro plankton and copepod exposure studies executed in the laboratory of UNIS in Longyearbyen. Over a 14 day period micro plankton development was followed as well as effects on zooplankton (*Calanus glacialis*) fecal pellets and egg production, egg hatching success and post hatching development.

In winter (T1), none of the considered treatments substantially affected the micro plankton communities underneath the ice. However, in spring (T3), the oil and dispersant mixture and natural oil attenuation treatment negatively affected the growth of several functional groups of plankton, potentially as a result of lighter oil fractions leaching out of the ice. A net population biomass in the oil and dispersant and oil alone treatment was about 50% lower compared to the control and ISB residue treatments. Locally, this may in turn affect the functioning of the microbial food web, but considering that even a very large spill is unlikely to impact more than a small fraction of an eco-system and that these communities are characterized by high resilience and recovery, ecosystem-wide impacts could be minimal and community recovery rapid.

Residues of burnt crude oil had the least harmful effects on the microbial communities. From the zooplankton study, no effects among the various endpoints could be demonstrated, however, hatched nauplii from females exposed to water from the oil mixed with dispersant treatment showed a tendency towards higher number of deformations.

Polar Cod

To study sensitivity and resilience of polar Cod to short term exposure, laboratory exposures were executed. Wild polar cod were collected in Svalbard fjords by bottom trawl and transferred to the laboratory in Tromsø (Norway). Selected treatments were based on a scenario of fresh oil being released into the environment and mixed within the water column. This scenario was different from what was chosen for the mesocosms, but assumed more realistic for polar cod. Four treatments of 48h exposure were tested in three replicates (mechanically dispersed oil, chemically dispersed oil, in-situ burn residues and a, control) followed by 6 month monitoring in uncontaminated water. The following parameters were recorded: survival, weight, length, sex, somatic, liver and gonad weights. Gonads were collected for histological analyses and determination of maturity stage. Otoliths were collected for age determination.

Limited to no long-term effects on survival, growth or reproductive investment were revealed in polar cod for a period of 7 months after short duration exposure to mechanically dispersed oil, chemically dispersed oil or residues of burnt oil. The lSB residue exposed fish showed a slightly increased interruption of maturation in female fish but this could not be explained by measured oil exposure concentrations.

Sea Surface Microlayer

A dedicated experiment was conducted to assess the sensitivity and resiliency of the sea surface micro layer. This very upper part of the water layer is a biologically active layer that supports transport across the air water interface. To test the effect of an oil spill and spill response options twelve small exposure systems for open water were installed to conduct a 5 day lasting experiment. Six pairs of rectangular holes were cut in the sea ice that served as experimental chambers (1 mm oil film, 1 cm oil slick, oil and dispersant, dispersant only, in-situ burn residue and control). The sea surface microlayer and the sub surface water were sampled over a 5d period and analysed for phytoplankton and bacterial abundance, bacterial community and hydrocarbons.

No difference between surface layer and underlying water in density of bacterial and pico/nanoeukaryotes as well as in bacterial community diversity was observed between surface layer and subsurface waters, regardless of treatment. The bacterial abundance was not different among the different treatments and no change was observed as a function of time over the course of the experiment. There was also no or little change observed in bacterial composition and diversity within and among the various treatments, except for some known oil-degrading bacterial species. The increase of oil degrading bacteria in the sea surface microlayer demonstrates that these organisms are present and have the potential to respond to hydrocarbon input within day.

Mesocosm Decommissioning

Final sampling (T4) and removal of the mesocosms was conducted July 4-10, 2016. When personnel arrived on site, 3 of the 8 mesocosms were detached from their anchors and were washed ashore. Those 3 mesocosms corresponded to the following treatments: 2 “control” and 1 “burnt residue” treatment. No oil was released and no pollution was observed, neither on the water nor on the beach. The mesocosms were recovered, cleaned using absorbent pads, decontaminated and steam-cleaned, disassembled and stored at Svea (Svalbard, Norway). 40L of emulsified oil was recovered and disposed.

IV. CONCLUSIONS

If an oil spill occurs late in the open water drilling season, there is a risk that with dropping temperatures, oil or oil spill response residues that are floating on the water surface get frozen into the top layer of the ice. Preferably oil spilled in open water should be dealt with at open water, because once oil reaches shorelines or interferes with ice biodegradation will be slowed down and the oil will persist in the environment longer. Experiments performed herein shows that, in case untreated or treated oil freezes into ice the risk of exposure to ice associated ecology is relative low during the winter period. Some light oil components may diffuse through the ice to the water (enhanced when oil is pre-mixed with dispersants), but exposure concentrations are generally below effect levels and are quickly degraded once in the water. Based on performed studies, no significant negative effects on the microbial community are expected: Oil-degrading microbes are not inhibited by oil or dispersed oil, they are active and actively degrading a small fraction of the oil. Low-levels of hydrocarbons will potentially leach out of the ice, but effects to the winter ice-ecology will be limited.

Important ecological processes start at the ice/water interface in spring at the same time that oil that was frozen into ice will be released. The released oil will still be relatively fresh. Close to the ice break-up, hydrocarbons and oil that gets released might impact the growth of ice-algae, and under ice plankton communities. Considering that even a large spill is unlikely to impact more than a small fraction of an ecosystem and that these communities are characterized by high resilience and recovery, ecosystem-wide impacts could be minimal and community recovery rapid.

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