SECTION 4  OIL SPILL RESPONSE STRATEGIES AND ASSOCIATED IMPACTS

Quick Links to Section 4 Content
Summary and Key Messages
Introduction
Knowledge Status - Impact of OSRs
  Natural attenuation
  Mechanical recovery and containment
  In-situ burning and chemical herders
  Improving dispersion of oil
Future Research Considerations
  Priority recommendations for enhanced NEBA applications in the Arctic
Links to Further Information
  Authors
  References

Summary and Key Messages

Four main oil spill response (OSR) strategies exist: natural attenuation, mechanical recovery and containment, in-situ burning, and physical and chemical dispersion of oil. All four are often used in combination and can be used in the Arctic. Selection and application of an oil spill response strategy should be based on both the effective removal of oil for the specific oil and weather conditions and consideration of the information on potential impacts to valuable ecosystem components (VECs) since application of response options will influence the fate of oil in the environment and concomitantly potentially alter the impact to different VECs. The influence of chemically and/or physically dispersed oil on pelagic species is well documented, but biological responses to oil at interfaces (air/water, ice/water, sediment/water and shorelines) has been less documented. Understanding the consequences of OSR actions on the impacts and resilience of VECs within these interface layers needs to be further developed in order to strengthen our ability to select a preferred OSR strategy under each spill scenario using the net environmental benefit analysis (NEBA) process (see Section 9).
Environmental effects related to OSR options have been studied extensively. In order to readily synthesize information that is already available on exposure potential, sensitivity and resilience of VECs, this information should be collated for each OSR technology and corresponding VECs that these technologies potentially impact to improve application of NEBA processes in the Arctic. This compilation of technical data will also facilitate the identification of remaining uncertainties.

Introduction

This chapter explains the characteristics of the main OSR technologies and summarizes the current knowledge on the potential environmental impacts of the various OSR options to an oil spill in the Arctic region. The focus is on the impact of an at-sea response (as opposed to shoreline clean-up) to support the NEBA process. The response techniques discussed are: natural attenuation, mechanical recovery and containment, in-situ burning (ISB, with and without the use of herders), and physical and chemical dispersion. The equipment and strategies used for these techniques have been reviewed in detail in a recent publication (Potter et al. 2012). Strategies and techniques for recovering and remediating oil in ice have been extensively studied over the past 45 years (Dickins 2004). Two oil spill research projects conducted in the Canadian Beaufort Sea from 1974 to 1981 contributed to the acceptance of in-situ burning as a primary response strategy to deal with spills in ice (Norcor 1975; Dickins et al. 1981). Examples of previous field experimental studies and accomplishments are presented in Table 1-3). Of note, is a recent program, oil spill contingency for Arctic and ice-covered waters (JIP on Oil in Ice; Sørstrøm et al. 2010) conducted several large scale field experiments assessing the complex interactions of oil, water, and ice with state of the art data collection techniques (Photo 1-4).

This review focuses on the effectiveness and associated environmental impacts of these response options when deployed under a variety of Arctic conditions and identifies areas for future research. Special attention is paid to how responses in the Arctic may differ from non-Arctic areas of the world. Increasing collections of experience and data will provide a broader foundation for spill response decisions and help to reduce the overall environmental consequences of a spill.

The main sources of information were technical documents and incident reports supplied by CEDRE’s library, NewFields, and documents available at the Norwegian Environment Agency within the Norwegian Ministry of Climate and Environment.

These documents were categorized into:

1. Review or synthesis documents dealing with issues of Oil Spill management in Arctic, or with research needs on the same topic
2. Experimental studies of OSR actions that targeted the effects of those responses in cold environments
3. Recorded case stories of incidents relevant to assessing impacts of response technologies or Arctic geographies.

Table 4-1. Landmark Field Studies
<table>
<thead>
<tr>
<th>Project</th>
<th>Year</th>
<th>Location</th>
<th>Spill Characteristics</th>
<th>Ice Type</th>
<th>Process or Response</th>
<th>Achievements</th>
<th>Authors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Interaction of crude oil with Arctic sea ice</td>
<td>1975</td>
<td>Canadian Beaufort</td>
<td>340 bbl/ 9 spills</td>
<td>Under fast ice</td>
<td>Burning &amp; Mechanical</td>
<td>Oil injected under ice, Oct – May. Oil spreading and entainment documented by divers and video. Assessed migration, degree of weathering and dissolution. Min oil thickness was 0.8 cm at ice-water interface. Also assessed currents under solid ice.</td>
<td>Norcor 1975</td>
</tr>
<tr>
<td>Oil and Gas Under Ice</td>
<td>1979/80</td>
<td>Canadian Beaufort</td>
<td>116 bbl/ 3 spills</td>
<td>Landfast Ice</td>
<td>Subsea Blow-out</td>
<td>Determined area impacted by a subsea blowout; assessment of in-situ burning as spill response option</td>
<td>Dickins et al. 1981</td>
</tr>
<tr>
<td>Baffin Island Oil Spill Project</td>
<td>1980</td>
<td>Baffin Island</td>
<td>2-8 m³</td>
<td>Seasonal</td>
<td>In-situ burning; natural recovery of shoreline</td>
<td>5 core studies; field based trials w 3 similar bays w untreated oil, treated oil, and control (included biological, chemical, and physical measurements; burning in melt pools; shoreline study w/ oil and emulsion in intertidal zone</td>
<td>Blackall and Sergy 1987</td>
</tr>
<tr>
<td>Behavior of crude oil in pack ice</td>
<td>1986</td>
<td>Canadian East Coast</td>
<td>18 bbl/ 3 spills</td>
<td>Pack ice, leads, between floes</td>
<td>Burning</td>
<td>The presence of ice dramatically reduced the spreading of oil compared to open water.</td>
<td>Buist IA, Dickins DF 1987</td>
</tr>
<tr>
<td>Emulsions in Ice</td>
<td>1983</td>
<td></td>
<td>192 L</td>
<td></td>
<td></td>
<td>Emulsions were stable; did not inhibit ice formation; retarded natural migration through ice sheet</td>
<td>Buist et al. 1983</td>
</tr>
<tr>
<td>Marginal Ice Zone</td>
<td>1993</td>
<td>Norway; Barents Sea</td>
<td>164 bbl</td>
<td>Marginal between floes</td>
<td>Oil Tracking in Ice</td>
<td>Applied oil spill trajectory model (OILMAP™) to forecast trajectories of oil in pack ice. When wind was off-ice wind speed drift (2.5%) with Ekman veering angle of 35°; with on-ice wind drift was 1.5%, veering angle of 60°</td>
<td>Singsaas et al. 1994</td>
</tr>
<tr>
<td>Under-Ice Spill</td>
<td>2001</td>
<td>Sea of Okhotsk</td>
<td>Light oils</td>
<td>Under ice floes</td>
<td>Vertical Migration</td>
<td>Oil fills under-ice cavities; very small amount migrates to the surface (&lt;1% with 7 -10 cm rise)</td>
<td>Ohtsuka et al. 1999; Ohtsuka et al. 2001; Karlsson et al. 2011</td>
</tr>
<tr>
<td>Diesel and Fuel Oil</td>
<td>2005</td>
<td>Russian Arctic</td>
<td>Light Oils</td>
<td>Ice floe surface</td>
<td>Evaporation</td>
<td>Complete evaporation during spring and summer; photo-oxidation more significant with 24 h daylight</td>
<td>Serova 1992; Ivanov et al. 2005</td>
</tr>
<tr>
<td>Encapsulated Oil</td>
<td>2005</td>
<td>Svalbard</td>
<td>6 Crude Oils</td>
<td>Pack ice</td>
<td>Dissolution</td>
<td>Water soluble compounds diffused through 110 cm thick ice, but concentrations were low (6 ppb)</td>
<td>Faksness and Brandvik 2005</td>
</tr>
<tr>
<td>Predictive Modeling Algorithms</td>
<td>2004-2009</td>
<td>Canada, Ohmsett NJ</td>
<td>Alaskan crude oils</td>
<td>Cold water, ice</td>
<td></td>
<td>Thickness of oil on calm water; Spreading of oil; Equilibrium of oil thickness on ice; Oil Spreading on ice, on snow; Evaporation on ice, under snow, among drift ice</td>
<td>Buist et al. 2008; Buist et al. 2009</td>
</tr>
<tr>
<td>Weathering of Oil in Ice</td>
<td>2009</td>
<td>Svalbard</td>
<td>Statfjord crude</td>
<td>0, 30, 90% coverage</td>
<td>Natural Weathering</td>
<td>Oil in 90% ice had &gt; slick thickness, reduced evaporation; wave dampening reduced emulsification; oil ignitable and chemically dispersible after 60 h</td>
<td>Brandvik and Faksness 2009</td>
</tr>
</tbody>
</table>
In general, the majority of the reviewed documents dealt with the feasibility of the response options under various conditions and the methods that were used or tested to optimize the efficiency of response techniques. It is noted that very few papers focus on a comparison of effects between different environmental compartments as a result of the response action while this is one of the main challenges in NEBA. Next to the potential impacts of oil and oil residues, NEBA should also look into the impacts of the response action itself, which may include access to vulnerable areas and impacts related to logistics.

Environmental Uniqueness of the Arctic Region in Relation to OSR

The Arctic region is characterized by the presence or absence of ice at different times of the year which generates a seasonal regime of ice coverage and ice thickness (AMAP 2007, SL Ross 2012b, Wang et al. 1999). When spilled, the oil fate and behavior will depend on a combination of the ice growth stage and coverage area which together can reduce or stop the weathering processes and limit the spreading. In some cases, the oil can be trapped by the ice and remain fresh and unweathered until the melting season.

The extent and nature of ice coverage also greatly affects the OSR options that might be considered and their operational effectiveness (SL Ross 2011). While shorelines and lagoons are not unique to the Arctic these are critical environmental compartments that have seasonal congregations of valuable ecosystem components that create significant risks to populations (refer to Sections 2, 7 and 8). The importance of these seasonally used compartments and the logistical challenges of positioning manpower and equipment at remote locations that ultimately limit response feasibility and/or timing suggest that response options need to be selected to avoid contact with these environmental compartments during those seasonal uses (refer to Sections 7, 8 and 9). Surface or subsurface oil releases will be influenced by the presence of ice (refer to Section 3) and will impact both environmental compartments and key species groups differently depending on location and density of the ice cover and seasonal use of those environmental compartments by VECs (refer to Section 2). Depending on the season of the year and the site of released oil, an incident may result in different types or magnitudes of environmental impacts. Generally speaking, “Arctic habitats are characterized by extreme seasonal change, which drives extensive migrations on land and at sea. The seasonal patterns of movement to, from, and within the Arctic determine to a large extent the vulnerability of Arctic ecosystems to oil spills. These patterns of seasonal activity and movement must be taken into account in selecting response strategies designed to reduce or avoid environmental impacts from oil and gas activities” (AMAP 2007).

Arctic species are subject to potentially dense concentrations (e.g. for birds, mammals, and fish) according to migrations patterns and corresponding ice regime. Ice edges are important locations for concentrating marine mammals and birds as a result of high biological activity. In addition, possibly due to the low ambient temperature, there is a low turnover for many species and consequently population recovery can be slow. As an example, some Arctic fish spawn under ice in winter; their eggs incubate under ice and hatch when ice begins to melt and plankton blooms occur. An oil spill in such spawning areas and during early life stages could severely reduce that year’s recruitment (AMAP 2007). The presence and the movements of the different species in both localized and regional areas is generally not known to the extent needed to make some of the important tradeoff decisions when selecting spill response options. Baseline studies are often conducted as part of the Environmental Impact Assessment (EIA) process that is undertaken in areas where oil and gas production is envisaged or in the process of being developed. Mapping (spatial and temporal) the ecologic: Return to Quick Links habitats in these areas will contribute significantly to regional oil spill response planning.
Natural Attenuation

Several field tests with experimentally released oil have been completed in the Arctic (see Potter et al. 2012 for an overview). However, except for the Baffin Island Oil Spill (BIOS) experiment these tests were devoted to studying the behavior and environmental fate of the oil in icy conditions and not the environmental impact at the spill location or other ECs. Nonetheless, this information helps frame the physical and chemical factors that affect the nature of oil released in an Arctic environment and help to identify the challenges to be encountered in implementation of any type of OSR activity. In fact, this sets the basic expectations for what might occur if natural attenuation were the only response option implemented.

The specific challenge encountered in the Arctic during OSR is the presence of permanent or seasonal ice, which has many consequences (Potter et al. 2012). Ice reduces the sea surface agitation which coupled with the low prevailing temperature, slows down the spreading of the oil slick reducing physical weathering and emulsification that occurs with more active surface water disruption. Ice also limits oil spreading when it is between ice blocks, or when beneath or on top of the ice. This helps keep the oil relatively concentrated reducing the rate of oil weathering. Large quantities of oil can be trapped either in snow, or on or under the ice within spaces found in the unevenness of the ice surface. When ice is forming, oil can be encapsulated in the new ice and thus kept unaltered during the winter season. Oil trapped in ice can then be released to surrounding waters when the ice melts, possibly reappearing as fresh, unweathered oil. Oil has been observed to migrate through the ice, at a rate that is dependent on oil viscosity. Experimental studies have determined that oil components separate within the ice and undergo degradation during the winter in the ice brine channels, as discussed below and in Section 5.

Potential Environmental Impact of Untreated Oil

If spilled oil is not recovered or treated, heavier oils may persist on the surface of water or surface of ice and can affect biological communities that are utilizing these interfaces, especially birds or mammals with fur (due to the potential loss of thermal insulation) whereas lighter oils may naturally disperse into the water column. A reduced rate of oil weathering may occur if oil is encapsulated by ice and the oil may not be biologically available until the spring thaw. Another unique attribute of the Arctic is that oil can strand on the shore during the ice-free season, whereas at other times the shoreline may be protected by landfast ice, which prevents oil from coming ashore. Oil stranding on shoreline substrates during the ice free period is subjected to the strong erosional forces of the ice on shoreline substrates during the next ice build-up and ice break-up seasons. Only deeply buried oil that might occur in intertidal cobbles would be sequestered for extended periods of time (e.g. decades). Therefore in many cases the persistence of oil onshore will be governed by the physical erosional forces that occur in many shorelines which minimize its retention. However, the weathering and recovery processes may be longer (e.g. occupy those area for more than one year) in cases where oil is sequestered in spaces among cobbles or boulder fields or where oil may be trapped in isolated nearshore water bodies. The practicalities of staging recovery operations in remote locations are also a consideration.

The effect of oil that is left to natural attenuation on the shoreline depends upon:

- The environmental resources of concern that are present when the oiling occurs and during subsequent seasons when extended oil exposures could be possible.
• The duration certain ECs of shoreline contamination, which may not persist for more than one year in while in others it may be extended for longer periods.

• The resiliency of the populations of various species that were impacted as a result of the spill and treatment methods that were used. The resiliency of these populations and communities of organisms is controlled by fecundity, immigration from unaffected areas, and the diversity of organisms present within the affected habitats.

McAuliffe et al. 1980 reported on the effects of oil on under-ice meiofauna as a part of the BIOS project (McAuliffe et al. 1980). Effects of this experimental spill on ice algae are summarized in a report by SL Ross (2010b). In that study, the bottom 10 cm of ice had decreased density of meiofauna, no adverse effects were observed on the ice algal community, and under-ice invertebrates showed no mortality but did drift away from the oil impacted area for days following the spill. All the findings of the BIOS Project are summarized in Li et al. (1992).

A separate study conducted on first-year sea ice off Svalbard showed that there is a migration of bioavailable water soluble components (WSC) from encapsulated oil through the ice to the underlying water (Dickins et al. 2008, Faksness et al. 2012). The estimated toxicity of these dissolved oil components in the ice was calculated using toxic units and the findings indicated that the concentration of WSC in the brine channels might be acutely toxic to the ice fauna. Results from another field study of an experimental release of 7000 L crude oil in the Barents Sea showed low concentrations of dissolved hydrocarbons (maximum concentrations were 4 ppb dissolved hydrocarbons and 32 ppb total hydrocarbons) in subsurface water. Predicted toxicity to the exposed community in the upper layers of the water, expressed as toxic units, was 0.11 or less, indicating that the potential for acute toxicity was low in subsurface bulk water (Faksness et al. 2012). However, the effects of surface oil on organisms using the surface layer, polynyas, ice-edges or adjacent shorelines where oil compounds can be re-concentrated was not assessed.

These studies indicate that there could be effects on the local ice biota if the oil is encapsulated in the ice or trapped underneath the ice. The organisms associated directly with the ice could be exposed to potentially toxic dissolved hydrocarbons over the course of several months, causing potentially toxic oil components to enter the Arctic marine food web. On the other hand, the measured concentrations of dissolved hydrocarbons in the water column, or underneath an untreated oil slick, have been lower than potentially toxic concentrations, perhaps indicating that severe effects to organisms residing in the water column would be negligible. However, this does not take into account the reconcentration processes that occur at interfaces such as the surface of the water, at ice water interfaces, convergence zones and shorelines (refer to Sections 2 and 3).

Conclusions on Natural Attenuation

Oil remaining in Arctic habitats without treatment will behave similarly to non-Arctic situations, although chemical processes such as dissolution, volatilization, and biodegradation may occur at a slower rate resulting in increased persistence. In non-ice periods oil spills on the sea surface will remain at the sea surface and be transported in slicks by winds and currents to shorelines, convergence zones, and offshore surface waters. During that process some of the oil will dissolve into the water column or be physically dispersed into the water column as droplets, some will volatilize into the atmosphere, while the majority of the oil may remain on the surface where it will weather, biodegrade, emulsify and accumulate in zones of reconcentration. Subsurface releases of untreated oil will generally rise towards the sea surface but during that transport it may also be rapidly biodegraded based on the increased surface area of oil droplets created by the turbulence of the release. Oil that remains on the sea surface can be stranded on shorelines or concentrate in convergence zones but the oil may also be encapsulated
by ice as it forms. In order to facilitate the forecasting of the seasonal dynamics of oil in these compartments, it is important that data are available for NEBA evaluations. This will facilitate the decision making process regarding the most appropriate response option under various conditions.

Such a NEBA process would evaluate the trade-offs of untreated oil containment by ice and treatment efficiency with decreased impact on pelagic environments by dispersant treated oil in non-ice environments. In addition the increased effects of surfaced oil as it is captured and released by formation and melting of ice on seabirds, marine mammals, annual ice fauna and flora should be evaluated. Also the biological significance of overwintered oil and ice must be determined.

Many data that serves as a basis for such evaluations is already available, but improvement of the information base would result in further reduction of uncertainties. Suggested topics for such studies are:

1. Biodegradation
   - Measure the biodegradation of oil in ice and trapped within leads or under ice over a winter season. Compare to biodegradation of oil in pelagic waters and surface layers during non-ice periods.
   - Does frazzle ice increase biodegradation of oil released from ice by physical grinding and disturbance of oil, creating larger surface area for microbes to degrade the oil?

2. Presence of VECs
   - Determine avoidance behavior for fish and invertebrate VEC’s associated with oil trapped with ice. Indications are that they will move away from oil.
   - Evaluate the use of polynyas or leads by VEC fish, invertebrates, sea birds, and marine mammals and the potential for oil effects in these critical habitats. Compare oil within broken ice fields and open waters as an attraction to seabirds, marine mammals, fish and invertebrates.
   - Summarize the same types of information for seabirds, shorebirds, marine mammals.

3. Considering the uniqueness of Arctic shorelines influenced by landfast ice, it will be important to understand the dynamic processes controlling the fate and persistence of oil on such shorelines. This will require an assessment of the potential for lingering oil releases and the assessment of the natural decontamination rate resulting from different responses

**Mechanical Recovery and Containment**

When oil is spilled on the surface of the water or rises from a deep water discharge and then accumulates on the surface it is possible to concentrate the oil by placement of booms in the pathway of the oil transport. As the oil accumulates next to the booms it can be recovered by pumping the captured oil into collection containers. Oil can also be collected e.g. using boats and surface water booms that accumulate the oil as the vessels travel through oil slicks. The success of these processes depends on the encounter rate and efficacy of the mechanical collection techniques and the success of containment or accumulation. Ice can act as a natural boom that allows oil to collect along its edges, within leads, under the ice in pockets, and within polynyas. Ice can also hold the oil for extended periods of time, allowing mechanical recovery to occur over more extended periods of time from its formation to when it begins to melt. Many of the tools used for mechanical recovery are not unique to application in the Arctic but for some adaptations have been made to collect oil mixed with ice (Broje
Environmental impacts from Mechanical Recovery and Containment

Moving ice, either as ice floes or frazzle ice can interfere with containment and recovery equipment deployment and operations (SL Ross 2012b, EPR 1998). On the other hand, ice can also slow the spreading of oil on water, keeping a slick thicker during recovery, which increases the efficiency of this type of response activity. Environmental impacts of mechanical recovery are usually considered in terms of emissions of response equipment, noise, and the impacts of the presence of large numbers of personnel. However, it is important to consider that mechanical containment and recovery is a slow, tedious, and challenging response method. Mobilizing and supporting such activities in remote areas adds further inefficiencies and time constraints. Impacts from a containment and recovery response effort are: the impact from oil that is left behind (oil that escapes containment), and impacts from the activities necessary to reclaim or dispose of the recovered oil and associated oily debris.

The impacts considered with natural attenuation are also associated with the residual oil left behind from mechanical recovery. Historically, mechanical recovery in open water spills is often reported as less than 15% of the spill volume and in most cases less than 5%, although specific performance can vary widely from incident to incident (EPR 1998). Thus, for this report, impacts considered under MNR will also be a large part of any mechanical containment response scenario. Our consideration of the ISB, dispersants and OMA and herder technologies will therefore compare tradeoffs using either mechanical response or naturally attenuation as their baselines.

Conclusions

Mechanical recovery in an Arctic spill situation may have marginal improvements in effectiveness due to the presences of some types of ice conditions, or may have additional inefficiencies brought on by different types of ice. Impacts of residual oil left in the environment due to the low effectiveness of mechanical recovery can also serve as the baseline assessments for evaluating tradeoffs for ISB (with or without herders), chemical and physical dispersants. The areas of proposed work are the same as those included in the natural attenuation section of this report.

In–Situ Burning and Chemical Herders

The in-situ burning (ISB), also referred to as controlled burning, has been the subject of extensive research, development, and testing over the past 30 years in temperate and sub-arctic water (SL Ross 2012b). The basic premise for effective and efficient burns is to collect and/or concentrate the oil slick to a thickness greater than 2 mm and provide an ignition source that can start the burning of surfaced oil. The oil must not be weathered or emulsified to such an extent that there are not enough lower molecular weight compounds (LMW) and available oil to sustain combustion (Fingas and Punt 2000).
ISB can be effective in rapidly removing large quantities of oil from the marine environment. Ideally, about 85 to 95% of the burned oil becomes carbon dioxide and water. The rest, 5 to 15% which is not burned efficiently is converted into particulates (soot) and a few percent is converted into organic compounds and combustion products that remain in the marine environment (Potter et al. 2012). The burn residue from a typical efficient ISB operation is in the order of less than 15% (SL Ross 2010). ISB seems well suited to Arctic conditions and the presence of ice (Photo 4-5). The presence of significant ice formations can keep oil from reaching water (burning of oil on ice) or limit the spreading of the oil on water (burning thick patches of oil on water contained among ice formations).

In-situ burning is an efficient process that removes ~80% of the oil (SL Ross 2010). However, the residuals of these burns include unburned volatile materials that are released into the air, soot particles that are also mobilized and transported into the air, and the modification of oil compounds into new products or the addition of agents (e.g. herders) and their burn products for release into the air or water. These residues of the burning process (smoke, volatiles, soot particles, additives and unburnt oil) are the potential materials that can pose environmental and human health effects. In addition there is a small risk of causing secondary fires that could threaten human life, property and natural resources; this risk is, however, easily manageable.

Chemical herding agents are products used for thickening an oil slick and concentrating oil on the water surface in order to reverse the effects of spreading. The increase in thickness may facilitate oil combustion during an in-situ burning operation. Several herding agents are listed on the National Contingency Plan registry as approved for use during oil spills, including Thickslick 6535 and Siltech OP-40. A third herder employed by the US Navy (USN herder) has been tested under arctic conditions. The USN herders (65% Span-20 and 35% 2-ethyl 1-butanol) and silicon based herders have been used under Arctic conditions and have been shown to work in cold open water environments as well as in broken ice (Buist and Nedwed 2011).

Potential environmental and human health effects of ISB residues and unburnt oil

Generally an efficient burn leaves 5 to 15% of the initial oil as residual or unburnt oil (SL Ross 2010). The residual is mainly composed of high molecular weight (HMW) oil compounds which are similar to those in highly weathered heavy fuel oil. The physical properties of burn residues depend on burn efficiency and type of oil. Factors that determine whether residues float or will sink are: water density, oil chemical properties, thickness of slick, and efficiency of the burn (Buist et al. 1995). The residual ash may also settle on the surface of the surrounding ice or sea where it may come into contact with surface dwelling organisms.

Tests have been carried out on the burn residue of Alberta Sweet Mixed Blend which had been used in the Newfoundland Offshore Burn Experiment (NOBE). The water accommodated fraction (WAF) was prepared from the unburnt residue and tested on rainbow trout to assess the 96 h LC50 and on sea urchin for inhibition of fertilization (20 min contact). The maximum total petroleum hydrocarbon (TPH) concentration measured in the test solutions (WAF)
was 1.1 mg/L. All samples were not toxic to the tested species (Blenkinsopp et al. 1997). In another study, Daykin et al. (1994) concluded the toxicity of the residue should be lower than that of the initial oil. Other studies showed that the residue had very little or no acute toxicity to key indicator species in salt water and freshwater because an effective burn removes the lightest, most toxic components of crude oil (Blenkinsopp et al. 1997).

In a recent study by Faksness et al. (2010), the semi-volatile organic compounds (SVOCs) in a crude oil prior to and after ISB were analyzed. No volatile analyses were performed, but a removal of approximately 60% of the SVOCs, mainly the decalines and naphthalenes, had occurred during the ISB. Acute toxicity tests with the marine copepod Calanus finmarchicus exposed to the underlying water after ISB indicated no increase in toxicity when compared to WAF generated with unburned weathered oil. These findings were in accordance with the results presented by Daykin et al. (1994) as a part of NOBE. Concerning potential for exposures to the PAHs in burned oil residue, several studies have demonstrated that the concentrations of PAHs in the residue were lower than that in the initial oil.

While the toxicity from uptake of chemical components of the residue does not appear to be a concern to water column organisms, there is possible impact on surface dwelling species (by ingestion and/or direct smothering) and benthic species if the residues were to be stranded onshore or sink onto the sea bed. These risks are however considerably lower than when fresh oil remains on the surface or strands. Concern for such an impact arose during oil spill incidents involving ISB, e.g., the Honan Jade spill in South Korea (1983) and the Haven spill in Italy (1991) where the NRC (2005) reported that the burn residue was typically a semisolid, tar-like layer. The surface oils were burnt, removing the impacts in the surface waters but the burnt residues would sink where they affected the benthos. Such sinking residues consisted of scattered chunks rather than as a continuous mat covering a broad area. While this type of impact on the benthos is very hard to assess it must be considered as part of an overall assessment of potential benefits and impacts of ISB.

Oil combustion produces gas, smoke and soot into the atmosphere. Typically the smoke plume is composed of CO₂, steam, soot, CO, SO₂, NO₂ and VOCs including PAH and BTEX, dioxins and dibenzofuran (Tennyson 1994, Fingas et al. 1993). Despite the fact that VOC concentrations in the plume are usually lower than the accepted threshold value for human health concerns (Buist et al. 1999), responders put an exclusion zone in place to ensure there is limited exposure of downwind communities or wildlife populations to these compounds. Responders are also excluded from the immediate area of the fire and at more lengthy distances downwind of the fire.

In one assessment of the NOBE study Ross et al. (1996) found that burning of 1 Kg of oil produced 40 µg of PAH in the soot/particles while the original oil had 9.5 g/kg of oil. Therefore multiple authors have concluded the ISB residue would have a lower toxicity than the initial oil (Buist et al. 1999, Fraser et al. 1993, Garrett et al. 2000, Li et al. 1992, Lin et al. 2005). The potential effects that would occur with species living at the air/water interface or that break through the surface (e.g. seabirds and marine mammals) were unaddressed by these studies.

The production of smoke during an ISB, and the concentrations of smoke particles at ground or sea levels are usually of most concern to the public as they are highly visible from significant distances and can persist for several miles downwind of a burn. Concerns include human health and wildlife inhalation risks from particulates carried in the smoke plume. Particulate concentrations in the plume are greatest at the burn site, but they decline with increasing distance from the site, primarily through dilution, dispersion, and fallout, but also through washing out by rain and snow (API 2004). The species of greatest concern to atmospheric pollution or fallout of soot and particles will be downstream of the
burn and include marine mammals that must breathe at the surface of the sea or species and life stages that live within the very surface of the water.

Environmental Impact of Herders

The literature dealing with herders is rather old as these products have not been considered or promoted until very recently. Available data shows that most chemical herding agents are not soluble either in water or in oil (less than 1%; Hayward et al. 1995, MSRC 1993) and are used at low application rates; therefore, acute toxicity of these products to pelagic organisms is generally not considered to be an issue. Additional considerations may be required under special use conditions such as very shallow waters with low flushing rates and organisms abundant in early life stages, but exposures are still likely to be at very low concentrations (Walkert et al. 1999, MSRC 1993). The more recent documents deal with the efficiency or operations related to herder use (SL Ross 2010). As with dispersants, the toxicity information is limited to water column organisms and there is little information available on the toxicity of these materials to surface dwelling organisms.

Conclusions on ISB and Herders

Most of the available information on ISB deals with the efficiency of the technique and operational guidance. While there is some information regarding monitoring activities to ensure air pollution is not a human health or wildlife exposure issue, information on the environmental impact is more limited. Information on fate and effects studies could be compiled, taking into account the specificity of Arctic environment (species with the possibility of large concentrations of juvenile life stages, especially within the surface microlayer) and additional studies could be conducted to evaluate the persistence of these products and their residues where necessary.

Improving Dispersion of Oil

Chemical dispersants are most effective when applied during or quickly after a spill or sub-sea release event, before dilution, weathering and emulsification of the oil reduces the effectiveness of the dispersants. Modern dispersants are mixtures of solvents consisting of organic carbon chains that are oleophilic and surfactants that are hydrophilic. The combination of oleophilic and hydrophilic components change the surface viscosity of the oils and create small droplets of oil that are released from the surface water and move into the water column or from deep water releases into adjacent deep pelagic environments. These small oil droplets have greatly increased surface area that increases the rate of microbial degradation compared to the oil prior to dispersant application. Dispersant mixtures have been evaluated by numerous organizations to determine their toxicity and efficiency of dispersion under many different environmental conditions. By breaking up the oil and creating micron-sized droplets, chemical dispersion reduces the persistence of a surface slick or the potential for sub-sea discharges to reach the surface and thereby minimizes potential encounters by marine mammals and offshore bird populations. Application of chemical dispersant to sub-surface and to surface oil slicks reduces the amount of oil that becomes stranded on the shoreline and prevents oil from transforming into weathered oil-in-water emulsions that are resistant to further biodegradation (Lewis and Daling 2001).

However, dispersing oil into the water column from surface slicks or deep water releases is most effective when the oil is fresh and unweathered. Mitigating damage to the shoreline and to organisms
that may encounter surface slicks means exposing the near surface and shallow or deep pelagic communities to elevated concentrations of dispersed oil for short periods of time.

The literature reviewed focused on dispersant applied at the sea surface and it contains information on the toxicity of oil chemically dispersed into the water column and effects on those marine organisms from laboratory studies. Information on the behavior of dispersants applied below the upper surface layer during blow-out scenarios were sparse during this review period. However, it is expected that post-spill studies of the recent Macondo well blow-out and explosion that occurred in 2010 in the Gulf of Mexico will contribute greatly to our knowledge of subsea application of dispersants as well as natural dissolution and biodegradation processes that can occur in the deep ocean environment and at very cold temperatures that are similar to arctic temperatures.

There are limited holistic assessments that combine the toxicity of chemically dispersed oil data with information on specific assessments on toxic impacts associated with Arctic communities or the comparative damage resulting if oil persists on the surface or comes ashore. Therefore, the rationale for application of chemical dispersants should be based on the comparison of the possible extent and duration of impacts to the organisms living in the water column (e.g. fish, shellfish, plankton, etc.) resulting from the use of dispersants, and the extent and duration of potential damage which would result if dispersants were not used, i.e. from a persistent surface slick (e.g. effects to birds, mammals, and fish and invertebrates that live in the very surface of the water) and from the stranding of the weathered oil on the shoreline (e.g. effects to coastal shoreline species and benthic organisms). This type of information must be factored into the tradeoffs associated with Arctic dispersant use, and is considered in the section “Monitoring Natural Recovery (no active response)”.

**Impact of Chemically Dispersed Oil**

Most toxicity studies evaluate the impact of increasing the exposure of pelagic organisms to oil as a result of dispersing the material into the water column. Considering the toxicity toward water column organisms, it is recognized that the observed toxicity effects from chemically dispersed oil is due to the effects of the increased quantity of dispersed oil into the water and are not caused by the dispersant itself, as modern dispersant formulations are much less toxic than oils (Hemmer et al. 2011).

In assessing dispersed oil toxicity, determinants of adverse effects for a given species are exposure concentration and duration of exposure (see also a more detailed review of peer-reviewed literature presented in Section 6, Ecotoxicology of Oil and Treated Oil). A review of field studies found that small-scale field tests have demonstrated that the concentration of dispersant in water falls to less than 1 mg/L within hours (NRC 2005). The available data suggest that in general, maximum dispersed oil concentrations after a spill are less than 50 mg/L immediately after dispersion into the upper water column (top 3 m) and that dispersed oil concentrations dilute rapidly, dropping to 1 to 2 mg/L in less than 2 h throughout the water column (Cormack and Nichols 1977, Daling and Indrebo 1996, McAuliffe et al. 1980). These low concentrations are generally below estimated toxicity threshold concentrations derived from exposure experiments for most common water column organisms (McFarlin et al. 2011, Gardiner et al. 2013).

The BIOS experiment conducted in sub-Arctic nearshore areas in the 1970s studied oil dispersion impact on nearshore environments and concluded that the results offer no compelling ecological reasons to prohibit the use of chemical dispersants on oil slicks in nearshore areas (Potter et al. 2012). Secondly, the results provide no strong ecological reasons to undertake an intrusive effort to cleanup stranded oil (on certain shoreline types).
During an experimental oil spill in the Barents Sea in 2009, 2000 L of crude oil were dispersed six hours after release (Potter et al. 2012). Two hours later, measurements of oil in water were performed at depths of 1, 2 and 3 m. The maximum concentration of oil in water was measured to 5.5 ppm (at 2 m depth) with an oil droplet size smaller than 10 µm, 30 minutes after mixing energy was added by the ship thrusters. The monitoring indicated background concentrations were restored shortly after these measurements, as the plume had most likely drifted and diluted with the currents (Merlin and Le Floch 2012). After the Sea Empress incident, a major spill in nearshore waters at the port of Milford Haven, UK, dispersed oil concentrations were monitored and quantified in the field. Results showed 10 ppm dispersed oil immediately after the dispersant application, decreasing to 1 ppm 2 days after, 0.5 ppm 1 week after and 2 ppb 1 month after (SEEEC 1998).

Such a decrease can be modeled with the following relationship:

\[ C = C_0 e^{-1.35} \]  

**Equation 1**

Where \( C \) equals oil concentration at time (t in hours);  
\( C_0 \) is the initial concentration;  
\( e^{-1.35} \) represents an exponential decline in oil concentration

Application of the equation yields a half-life of 12 h for the dispersed oil concentrations [every 12 hours the concentration is divided by 2 (Merlin and Le Floch 2012)]. This reflects a dilution rate for a sustained spill response implemented over several days in a deep, but nearshore environment. In more recent toxicology studies carried out in several laboratories in North America (Aurand and Coelho 2005), the exposure duration was modeled after a single dispersant application to offshore, open water habitats establishing a half-life of 4 hours. These representations of ‘spiked’ exposures are more environmentally realistic (closer to real field conditions) than standard laboratory ‘constant’ exposures, and result in a reduced level of effects (Gardiner et al. 2013).

The effect and toxicity of a water soluble fraction (WSF) versus chemically dispersed oil was studied by using realistic exposure concentrations based on the WSF concentrations monitored during an offshore field experiment (i.e. initial TPAH concentration of less than 7 ppb; NRC 2005). The Arctic amphipod *Gammarus setosus* was used as test species in a continuous flow experiment. Body burden measurements showed higher level of PAHs in the gammarids exposed to oil and dispersant for 12 days than in those exposed to oil alone, consistent with the higher concentrations of oil that would be present when dispersant are used. Several biomarkers were monitored, and gammarids exposed to oil and dispersant also showed moderate signals of exposure after recovery in clean seawater.

In a recent study on adult and juvenile fish and bivalve species conducted at elevated concentrations (up to 70 mg/L), the observed effects were sublethal and temporary. After 2 weeks, sublethal bioindicators did not show any differences between animals exposed to the chemically dispersed oil and mechanically dispersed oil (Merlin and LeFloch 2012). This demonstrates that exposure to chemically dispersed oil is not more toxic than the physically dispersed oil. However, the same research team reported that fish kept in a natural environment after exposure did show residual responses (persistent) in terms of growth (Merlin and Le Floch 2012). In conjunction with the previous study, experiments conducted with herring embryos in a wave tank showed abnormalities after constant exposure to elevated concentrations (to 10 ppm), but no effect when a more realistic and rapid dilution exposure regime was generated (McIntosh et al. 2010).

Dispersant toxicity research has been conducted recently on specific Arctic species of concern as part of a laboratory toxicity testing program conducted in Barrow, Alaska. It was found that Arctic species that were tested have similar or greater tolerance to representative concentrations of dispersed oil
Compared to the numerous temperate species that have been tested (Word et al. 2014 in prep.). Also, the acute toxicity of exposures to dispersant alone only occurs at concentrations that are greater than concentrations proposed for application of dispersant products in OSR (McFarlin et al. 2011, 2014; Gardiner et al. 2013). For most species that have been tested, dispersed-oil acute toxicity thresholds are on the order of 1 mg/L based on laboratory tests that expose test organisms for periods of 2 to 4 days. Water column concentrations above toxicity thresholds in an actual spill are limited to the top few meters and exposures at potentially toxic concentrations are limited in duration due to rapid dilution kinetics.

Conclusions on Chemical Dispersion

The available body of laboratory data, experimental field studies and monitoring following actual spills shows that dispersed oil may potentially cause environmental impacts but these will be limited to the organisms in the immediate vicinity of dispersed oil plume and in cases when the rate of dilution of the dispersed oil plume is slow. This would be the case for sensitive areas with limited water exchange, e.g. close to the shore. Even in such cases, these impacts would generally be limited to non-mobile organisms. For example, monitoring following dispersant use at major oil spill incidents over the past 40 years has never reported significant losses of mature fish populations at sea following dispersant applications.

Laboratory and field research as well as monitoring following actual incidents assessing the impact of use of dispersants in OSR, demonstrate that:

• The toxicity of oil/dispersant mixtures is related to the oil in the mixture and not the dispersant.

• The toxicity of the oil is directly related to the amount of oil that organisms are exposed to. That is, when dispersants are applied to oil the increase in response of pelagic organisms is directly related to the exposure concentration and duration of exposure to the oil.

• The toxicity of dispersed oil is relatively low and often not observable in real environment as long as there is no restriction to the rapid dilution process of the plume of dispersed oil (e.g. open-ocean).

• There is no evidence that Arctic species are more or less sensitive than other temperate climate species that have been tested with dispersed oil.

Dispersing Oil using Oil Mineral Aggregates (OMA)

The use of fine mineral particle (such as clay minerals) is an alternative response method to dispersant used to break up an oil slick into small droplets and stabilize the oil dispersion in the water column. When applied to physically dispersed oil, oil droplets aggregate readily with suspended particulate matter (SPM) such as clay minerals and organic matter to form [oil-SPM] aggregates called oil mineral aggregates (OMA; Le Floch et al. 2002). It is important to distinguish the use of OMA from sinking agents. Rather than bind to bulk oil as dense sediment and cause the oil droplets to sink, OMA will cause the oil to be suspended in the water as micron-sized droplets associated with a complex of mineral material in much the same result as chemical dispersants generate micron sized droplets (Khelifa 2005, Khelifa et al. 2005). The simplest form of OMA consists of an oil droplet coated with micrometer-sized solid mineral particles that prevent the droplets from sticking to each other and reforming a slick. When OMA forms, the dense mineral fines (small but 2.5 to 3.5 times denser than most oils) adhering to the oil droplets will reduce the overall buoyancy of the droplets, retarding their rise to the surface but keeping them somewhat buoyant so they do not sink. This promotes oil droplet
dispersion throughout the water column to low concentrations, and ultimately enhancing their biodegradation by natural bacteria (Lee et al. 2011).

Positive lab and basin tests of the concept led to a field test in 2008 (Lee et al. 2011). The field test was designed to evaluate the concept of using an icebreaker’s propeller and application of mineral chalk fines with seawater to create OMA. Visual observations confirmed that the oil stayed physically dispersed in the upper water column and did not resurface (Potter et al. 2012). Attempts were made to combine chemical dispersant use with fine mineral application. The dispersant was added to promote the dispersion of micron-sized droplets into the water column while the addition of fines attempted to stabilize this dispersion. The result was not especially convincing, as dispersant presence seemed to inhibit the formation of OMA complex with the oil droplets.

Preventing the re-surfacing of the droplets under the adjacent ice in the Arctic would be a significant environmental benefit since OMA also enhances natural biodegradation of spilled oil. The application of fine minerals seems well adapted to ice infested conditions as the presence of ice reduces the sea surface agitation; chemically dispersed oil may tend to resurface over prolonged time periods if not stabilized by OMA formation. It is also beneficial that the types of fine minerals needed for OMA dispersion are those that are commonly stockpiled in oil exploration facilities as drilling mud components; consequently, a source would be readily available in the event of a spill.

**Environmental Impact of OMA formation**

Most of the studies on this topic were devoted to the mechanism and efficiency of the technique to optimize the application conditions; very few considered the environmental impact of the use of OMA. A lab study dealing with the use of dispersant in estuaries assessed the toxicity of dispersed oil with presence of Montmorillonite clay (Merlin and Le Floch 2012). It was shown that the presence of this fine grained material reduced the observed impact on biota exposed to the dispersed oil plume to the level of impact commonly seen from oil that is mechanically dispersed (without chemical dispersant addition). To date, sparse information has been identified on the environmental impacts and relative toxicity of OMA in the Arctic.

Laboratory and field research as well as monitoring following actual incidents assessing the impact of use of OMA in OSR, demonstrate whether:

- The toxicity of oil/OMA mixtures is altered or if the oil in the mixture is the predominant cause of any toxicity observed with OMA use.
- The association of oil and OMA may alter the toxicity of the oil by decreasing bioavailability due to the adsorptive process that occurs to the OMA.

**Conclusions on OMA**

The environmental advantages of using OMA to stabilize oil dispersion in the upper water column are similar to those expected from the use of chemical dispersant. Mineral fines are nontoxic to marine life. The main impact expected from addition of the mineral fines could be a temporary increase of the sea turbidity which should be similar to the level of turbidity promoted by chemical dispersion. Other mechanisms of impact would be similar to the environmental/biological impacts discussed with chemically dispersed oil. The description of the flocculation of fines to the outer surface of small oil droplets leads to the following questions prior to its acceptance as an OSR option for the Arctic.

- What is the optimum rate of OMA application to oil to maximize its benefits (OMA may need a 1:1 ratio with oil to provide its benefits.
• Does OMA surface coating of oil droplets reduce potential microbial degradation or use of the oil droplets?
• Does OMA surface coating of oil droplets reduce the potential toxicity of the droplets or decrease the solubility and exposure of the more soluble/toxic components of the oil?
• Are OMA coated oil droplets available to suspension feeding organisms in an unweathered, potentially more toxic form?
• The remaining questions regarding the long term environmental fate of the OMA aggregates are: do they tend to sink progressively with time? What is the impact of settled OMA to the exposed area of bottom resources that could be large but at very diffuse concentrations? Does the mineral separate from the oil droplet? What is the impact of OMA or separated mineral exposures to dilute inorganic particulate matter and would it be any different than that endured from settling of ocean particulate matter?

**Future Research Considerations**

The review of the main oil spill response strategies to be used in the Arctic described by the authors in this section led to suggestions of further research which can reduce remaining uncertainties. The more generic suggestions compiled from this review are summarized below while recommendations that are important for improving Arctic NEBA are listed separately. Recommendations for further study captured previously within each response option section are summarized below.

1. **Expand effect data for non-water column species.** Data are available on impacts of OSR technologies on species living in the upper pelagic environment. Additional studies on species living in other ECs (e.g. deep sea, surface layers, ice/water interfaces, hard substrates) should be performed. Noteworthy limitations of the available data are:
   a. Most of the toxicological information provided for different response strategies is in terms of sensitivity to organisms that are exposed in the water column (generally the upper 10 m) and do not include species that are using deep water, surface layer, ice/water and shoreline interfaces.
   b. Models have been developed to predict the toxicity of a constant concentration of oil and dispersed oil components to these species based on a narcosis model associated with uptake into lipids. Other modes of action (fouling, epithelial damage, developmental abnormalities, and others) and exposure types (declining dose) need to be considered.
   c. Assimilated information on recent subsea processes is appearing in the peer-reviewed literature; these studies need to be reviewed and important trends summarized.

2. **Expand Assessment to Population-Level Effects, Resilience, and Recovery Potential.** Toxicity evaluations have been generally limited to studies on the acute impact on individuals of a single species and do not evaluate recovery times for the suite of species, at the population-level. The resiliency of a population to a stressor is built around the population’s ability to recover from the stress, *i.e.* it is dependent on how widely the species or population is distributed, its reproductive potential, its mobility, and ability to avoid exposure to the stressor. Knowledge of the length of recovery time for populations living in each environmental compartment is needed prior to evaluating the consequences of each response decision. Critical summaries of the biological attributes that extend or shorten recovery times need to be developed for populations residing in the different EC that would be affected by response actions.
3. **Examine persistent effects.** Investigations have been conducted on oil and chemical toxicity, generally focusing only on the acute and short term toxicity. In NEBA decision-making chronic sublethal effects are often treated as acute mortality levels. An analysis should be performed to better understand the role of chronic sublethal effects in NEBA decision making. This includes the change in bioavailability, toxicity and biodegradation potential of oil and its components as physical weathering and biodegradation occurs after treatment by OSR actions.

4. **Explore additional modes of toxic action.** There is little information on other types of effects of oil exposure other than toxicity due to water borne exposure and uptake into tissues; additional study of fouling and epithelial tissue disruption by oil or oil residues on organisms that reside or move through the air/water, ice/water or shoreline interfaces or breathe contaminated air above an oil slick is warranted. Smothering/fouling related toxicity, atmospheric contamination and interference with air breathing mammals and birds has not been well investigated.

5. **Evaluate potential for impact on the basis of habitat function.** The available information is often concentrated on individual species or groups of species rather than on habitat function. However, it is the effects on population or habitat which are important in the overall assessments of the consequences of selecting alternative response actions.

**Priority Recommendations for Enhanced NEBA Applications in the Arctic**

The recommendations presented below indicate where increased knowledge of OSR processes and consequences would result in reducing existing uncertainties in NEBA assessments. No prioritization has been made to the list; for some of the recommendations, surrogate data may be already available.

1. **Identify VECs and ECs that can be impacted by each OSR.** Develop structured overviews of all VECs that can potentially be impacted by each OSR technology with special focus on VECs at interfaces and on seasonality.
   a. Improve knowledge on the spatial distribution of the living resources and seasonal evolution in the Arctic because large movements of populations occur.
   b. The resources should be ranked in terms of vulnerability to the oil in its different forms: surfaced oil (fresh, weathered and burnt), dispersed oil, and smoke and soot (in case of burning), oil on the shore.

2. **Collate available data.** Identify data needs for all potentially impacted VECs to score exposure potential, sensitivity, resilience, recovery preferably on a population level basis, using ARCAT approach.
   a. The oiling mechanism on Arctic shoreline and related impact on living resources taking into account the uniqueness of Arctic shoreline which are subject to strong icing periods.
   b. Short and long term effects of dispersed oil on Arctic living resources, especially those which are the most vulnerable and which are identified to congregate locally at certain times of the year.
   c. Data on air emissions should be included as well as residues for ISB (fate, exposure potential, effects, biodegradation).

3. **Highlight uncertainties in data.** Identify data uncertainties and evaluate needs for additional studies such as:
a. Effects caused by surfaced oil (ingestion, fouling, smothering) to the different living resources of concern (birds, mammals, etc.)

b. Increased knowledge of the effects produced by-products (smoke, soot and un-burnt residue) of ISB towards the Arctic living resources subject to direct or indirect ISB contact

c. Effects of herding chemicals and OMA have not been fully evaluated to date. Investigation of the intrinsic toxicity of chemical herding agents towards Arctic species especially related to the possible exposure to early life stages.

Further Information

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References  [Link to Chapter 4 references in Access database]