Paper #8-3

BEHAVIOR OF SPILLED OIL – CURRENT PRACTICE/OPERATIONAL AND TECHNOLOGY CONSTRAINTS, AND OPPORTUNITIES

Prepared for the

Technology & Operations Subgroup

On March 27, 2015, the National Petroleum Council (NPC) in approving its report, *Arctic Potential: Realizing the Promise of U.S. Arctic Oil and Gas Resources*, also approved the making available of certain materials used in the study process, including detailed, specific subject matter papers prepared or used by the study's Technology & Operations Subgroup. These Topic Papers were working documents that were part of the analyses that led to development of the summary results presented in the report's Executive Summary and Chapters.

These Topic Papers represent the views and conclusions of the authors. The National Petroleum Council has not endorsed or approved the statements and conclusions contained in these documents, but approved the publication of these materials as part of the study process.

The NPC believes that these papers will be of interest to the readers of the report and will help them better understand the results. These materials are being made available in the interest of transparency.

The attached paper is one of 46 such working documents used in the study analyses. Appendix D of the final NPC report provides a complete list of the 46 Topic Papers. The full papers can be viewed and downloaded from the report section of the NPC website (www.npc.org).

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# Topic Paper (Prepared for the National Petroleum Council Study on Research to Facilitate Prudent Arctic Development)	
8-3	**Behavior of Spilled Oil - Current Practice/Operational and Technology Constraints, and Opportunities**
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SUMMARY
The oil industry, Federal government, and oil spill response community have been conducting research to understand the processes controlling the behavior of oil spilled into ice environments for over 40 years. This research provides a strong basis for understanding how oil behaves in ice and how to develop strategies to safely respond to spills. This white paper provides a summary of how weather conditions, ice cover, and oil-ice interaction will influence the fate of oil spilled in Arctic environments.

Recommendations
1. Perform additional field tests studying the behavior of oil in ice.
2. Perform broken ice tests at Ohmsett to study the behavior of oil in ice and identify and validate best available technologies and methods for containment, recovery, and/or treatment

The oil industry, Federal government, and oil spill response community have been conducting research to understand the processes controlling the behavior of oil spilled into ice environments for over 40 years. There have been several landmark field experiments primarily in the US, Canada, and Norway (Glaeser, 1971, McMinn, 1973, Norcor, 1975, Dickins et al., 1981, Comfort and Purves, 1982, Nelson and Allen, 1982, Buist et al., 1983, Buist and Dickins, 1987, Singsaas et al., 1994, Vefsnmo and Johannessen, 1994, Ohtsuka et al., 2001, Ivanov et al., 2005, Dickins et al., 2008, Sørstrøm et al., 2010). This research provides a strong basis for understanding how oil behaves in ice and how to develop strategies to safely respond to spills.

This white paper provides a summary of how weather conditions, ice cover, and oil-ice interaction will influence the fate of oil spilled in Arctic environments. There are a number of reviews and assessments that provide more details on the behavior of oil spilled in Arctic environments (Fingas and Hollebone, 2002, Brandvik, 2007, SL-Ross et al., 2010, Dickins, 2011).

Oil in ice-covered environments

The oil industry is in the early stages of evaluating new opportunities for oil production in Arctic marine waters. It will likely be more than a decade before any new oil production occurs in these areas. Prior to this, industry's focus in the offshore Arctic will be on exploration drilling. Currently, exploration drilling in Arctic waters will be mostly restricted to the open water and shoulder seasons that occur in the summer. Thus, the greatest risk of oil spills during this evaluation phase of oil development will be during the open water season. During this time, oil will behave as it would in other open water regions with the advantage of significantly more hours of daylight in which to conduct operations. Because there is a large body of knowledge on oil behavior in open water this discussion will focus on oil behavior in ice.

The presence of ice, the harsh environmental conditions, and remoteness adds challenges to oil spill assessment and response in the Arctic. Ice cover and cold temperatures, however, may provide a critical advantage. Oil spill responders understand that "speed is the key" for a spill in open water. This is because of the very dynamic nature of oil on water. It can rapidly spread, drift, break into smaller slicks, interact with natural sediment / vegetation, weather, emulsify, and strand on shorelines before response equipment can be deployed. In contrast, ice cover can immediately contain oil to limit spreading thereby keeping the oil thick. Ice cover can limit the energy of waves and thereby limit emulsification. Cold temperatures and the thicker oil will limit the rate of evaporation and dissolution. Oil evaporation, dissolution, and emulsification increase the viscosity of the oil generally making it more difficult to treat or recover. Further, land-fast ice can protect shorelines from oil stranding for many months of the year. Thus, ice conditions may give response personnel more time to bring response strategies into play and this advantage may counteract some of the disadvantages caused by Arctic conditions and remoteness.

Oil Weathering

The two most important weathering processes for oil spills are usually evaporation and emulsification. These two processes tend to be the most rapid in most spill scenarios, although Arctic and ice conditions can limit the rates and magnitude of these processes. Viscous oil is more difficult to treat by all response options. Emulsification adds an additional challenge by increasing the volume of the spill. This is because emulsified oils can incorporate significant amounts of water thereby significantly increasing the volume of material requiring storage, treatment, and disposal.

Oil behavior in any environment is strongly dependent on the oil properties. In general light fuels such as gasoline and diesel are not persistent on the water surface in any environment given the high volatility, solubility, and tendency to naturally disperse. Light crude oils and condensates will have limited persistence as well for the same reasons. Incorporation of oil into ice may increase the persistence of any of these oils, however. Other crude oil and fuel oils will have greater persistence. These oils can remain on the water surface for longer periods of time so they may have more time to interact with ice.

Oil spilled in ice during initial freeze up has the potential to undergo evaporation, dissolution, emulsification, and natural dispersion. Many crude oil and light fuel oils spilled during initial freeze up will remain on the ice surface or quickly migrate to the surface where it can undergo significant evaporation (Dickins, 2011).

Oil evaporation is a function of the slick thickness, oil temperature, and the amount of volatiles within the oil. Cold temperatures slow evaporation. Ice containment also slows evaporation by keeping slicks thick. Snow interacting with surface oil to eventually cover it will also reduce evaporation rates.

Ice dampens the mixing energy needed to generate oil–in-water emulsions. Thus, emulsification is not expected to be as prevalent in ice covered water. Further, natural dispersion of oil into the water column will not be as significant because of the wave-dampening effects of ice.

Ultimately, weathering requires the oil to be exposed to either the air, water, or both. Oil trapped under ice and exposed to the water can undergo both dissolution and natural dispersion. It is unlikely that there will be enough mixing energy to cause emulsification, although it is possible. Oil trapped within ice leads can undergo dissolution, natural dispersion, emulsification, and evaporation. Oil trapped within ice is isolated from the water and air, which limits to a very large extent any weathering processes.

Another important factor governing the behavior of oil in the Arctic is the oil's pour point. Oil with a pour point above the freezing point of water will rapidly cool and gel to become a semisolid when spilled into the environment. Depending on the cooling rate, the semisolid gelled oil could form very thick pools on or under the ice if the gelling occurs before the oil has time to spread. Oil is a shear-thinning fluid (i.e., viscosity is reduced when the oil is being disturbed, e.g., moving, spreading, bending with waves), so the gelling is a function of how much movement the oil is undergoing. Oil subject to the motion of waves may not gel until it cools significantly below its pour point.

Oil Interaction with Ice

Figure 1 shows some of the possible configurations of oil in, on, and under ice. The rough underside of continuous ice is expected to limit the mobility of oil trapped under it. Even large spills of crude oil underneath solid or continuous ice cover will usually be contained within a relatively small area compared with the equivalent volume spilled in open water. If oil is trapped under ice in the winter, new ice will rapidly form under it even as late as May in the Arctic (Dickins et al., 1981). This encased oil is isolated from the marine environment until it is released by response activities or during spring melt. The encapsulation keeps the oil from weathering, emulsifying, and dispersing. Oil spilled under ice after May in the Arctic and April in the sub-Arctic may not become encapsulated due to insufficient ice growth.

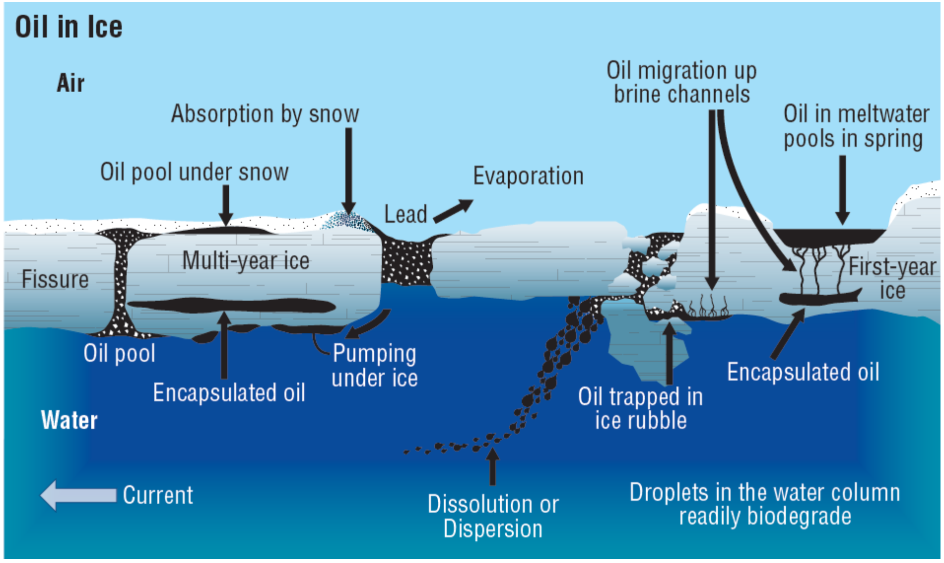

Figure 1. Depiction of oil interacting with ice (adapted from A.A. Allen).

Sea ice includes multiple vertical brine channels that form as brine is excluded from ice as it freezes. These channels allow the brine to migrate down to the base of the ice where it is released to the water below. When oil interacts with sea ice, it migrates up these natural brine pathways because it is less dense than both the brine and seawater (Dickins et al., 1981). For thicker ice, winter brine channels only allow oil to migrate through the bottom 10 – 20 cm of ice as these brine channels close on the colder surface ice. Vertical migration accelerates in the spring as the ice melts, resulting in the oil pooling on the ice surface in melt pools (Figure 2). Oil in these natural melt pools is more readily available to responders prior to ice breakup.

Oil located on top of continuous ice will likely undergo limited spreading due to the roughness of the ice surface and snow. This oil can be covered by snow as well. Further, cold temperatures will increase the viscosity of the oil, and this reduces spreading. The oil on top of ice will ultimately be much thicker and cover a smaller area than the same oil spilled on open water. The end result is that in many cases ice will allow responders time to mount a response while the oil is still accessible.

Figure 2. Melt pools (water only) formed on top of ice during spring melt in the Arctic. Oil trapped in ice will flow to the ice surface and float in these melt pools prior to ice break up.

Snow is a good absorbent for oil. It combines with oil on the surface of ice to the point that the resulting mixture can be as much as 80% snow (McMinn, 1973). Additional snow will tend to cover the oil-snow mixture. Snow ice mixtures contain the oil and keep it from spreading. Oil-snow mixtures are easily handled by shovel, bulldozer, etc. if the ice is stable enough, but it may not be burnable depending on the amount of snow.

Oil trapped in ice leads and fissures is also contained by the ice depending on the amount of ice cover. Estimates are that in less than 30% ice cover, oil can spread and behave in much the same way as in open water. In greater than 50% ice cover, ice will begin to provide containment that will restrict spreading. The degree of containment will increase as the amount of ice cover grows. This containment keeps the oil thick, which can enhance response efficiency. Two experimental field releases conducted in 1989 and 1993 illustrate the restricted spreading caused by ice cover (Vefsnmo and Johannessen, 1994). Both experiments used the same Sture Blend crude oil. The 1989 experimental release 30 m^3 of oil into open water while the 1993 experiment released 26 m^3 in 70 – 90% concentrations of broken ice. After 10 hours of spreading the thickest portion of the open water slick covered an area of 2 km x 50 m (100,000 m^2) with a 13 km sheen "tail." After 10 hours the spill in broken ice covered only 100 m^2.

In general, oil spilled on or under ice or within concentrated ice coverage will move with the ice if it is drifting or remain near the spill location for land-fast ice or ice that isn't drifting. Research has shown that currents ranging from 15 – 30 cm/s (0.3 – 0.6 knots) are needed to move oil under typical sea ice that isn't moving (Mar-Inc. et al., 2008). In more open ice conditions, oil and ice can move at different rates and directions because the oil may be under greater influence by the wind and the ice more influenced by the currents.

The above discussion was primarily focused on oil behavior in first-year ice. Oil behavior in multi-year ice may be somewhat different. A single field release was performed in 1978 to study oil behavior under multi-year ice (Comfort and Purves, 1982) – this ice was likely second-year ice at the start of the experiment. No oil was found at any of the study sites four years after the releases based on surface investigations and analysis of core samples. These results were surprising given that multi-year ice has fewer brine channels to allow migration of oil.

The under-ice storage capacity of multi-year ice is estimated to be greater than first-year ice, which could lead to thick individual pools and even less mobility of the oil. Oil under multi-year ice can also encapsulate although the process will be much slower due to the slower growth rate of multi-year ice. Multi-year ice has low salinity and therefore has fewer brine channels to allow vertical migration of oil. Further, multi-year ice is more stable than first year ice and can survive the summer ice breakup more readily than first-year ice. Thus, oil trapped in multi-year ice may persist within the ice for more than one year.

A final point on oil behavior in ice is its fate during spring melt. Oil trapped in ice during the winter and not recovered or treated will eventually be released during the spring melt. Spring melt requires multiple weeks to occur (Dickins, 2011). Oil trapped in ice will likely be relatively slowly released during this melt process, and depending on the motion of the ice, the release could occur over a significant area. The slow release and the movement of the ice will reduce the amount of oil transferring to the water column and water surface at any location. The encapsulated oil will be close to fresh and the slow release will encourage maximum spreading of the oil to a thin sheen assuming the ice melt has progressed to the point of providing significant open water. The combination of fresh oil and thin sheens will facilitate natural dispersion and evaporation.

Natural Biodegradation

Petroleum biodegradation is a natural process where microorganisms break down crude oil to mostly carbon dioxide and water. Petroleum degrading microorganisms have been found in almost all ecosystems (Margesin and Schinner, 2001, Prince and Clark, 2004). This includes Arctic marine water, sediments, and terrestrial soils. Oil is a concentrated energy source and can support a range of microorganisms. Arctic petroleum-degrading microorganisms are adapted to the cold temperature allowing them to efficiently degrade oil at much lower temperatures than similar microbes in warmer climates (McFarlin et al., 2014).

Natural seeps are another source of information on oil behavior in the marine environment. Indicators of hydrocarbon seepage have been found in almost every marine region mapped by side-scan sonar or high-resolution reflection seismic (Hovland, 1992). Natural seeps have occurred for millions of years, and the environment has developed natural mechanisms to degrade oil through biodegradation.

Seeps are fed by underground reservoirs of oil and gas, and the Arctic Ocean is estimated to have between 16,000 to 36,500 barrels of natural oil seepage annually. The Arctic Council's Arctic Oil and Gas Assessment estimated that 80-90 percent of the petroleum based hydrocarbons that enter the Arctic environment are from natural seeps (AMAP, 2007). Geologists believe that natural oil seeps are the largest source of oil entering the oceans (Kvenvolden, 2003), contributing annually between 4 and 14 million barrels. In the U.S., an estimated 1.1 million barrels of crude oil seep into marine waters, which is the single largest source of oil released into the environment (Etkin, 2009).

Petroleum-degrading microorganisms have evolved to exploit the energy source provided to them by natural seeps. Seeps also provide a sustained energy source to maintain at least a small population of these microbes. Without these natural mechanisms to remove oil from the environment, the world's oceans and beaches would have a much different appearance.

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