Regional Considerations Influencing Oil Spill Response in Arctic Offshore Environments

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Abstract

There are a number of locations around the world that may need the ability to respond to oil spills in ice-covered waters resulting from present and future activities related to the exploration, production, or transportation of hydrocarbons. These locations include the Azov Sea, Baltic Sea (including the Gulfs of Finland and Bothnia), Barents Sea, Beaufort Sea, Bering Sea, Bohai Sea, Caspian Sea, Chukchi Sea, Cook Inlet in Alaska, Gulf of St Lawrence, Laptev Sea, Kara Sea, offshore Eastern Newfoundland, Pechora Sea, Northern Sea of Japan, and the Sea of Okhotsk. Arctic and sub-arctic environmental conditions will present logistical, operational and technical challenges to effective oil spill response operations. This paper presents an overview of the effects of regional ice type and seasonal scenarios on the fate and behavior of a spill and those spill response technologies and strategies that may be most effective in minimizing environmental damages after an oil spill.

Introduction

There are several comprehensive references that discuss oil spill response in arctic environments (e.g., Owens, 1996; Owens et al., 1998; Dickens et al., 2000; Alaska Clean Seas, 2001). The main purpose of this paper is to present a general discussion of some of the many regional similarities and differences that will affect offshore oil spill response in waters with ice and relate scenarios to the options available for response. The discussion focuses on aspects related to the type of ice present and the progression of the ice season at a given location. Arctic and sub-arctic conditions hamper OSR efforts from the logistical perspective (ability to get safely to the spill site, ability to work outside for extended periods, visibility, etc.). However, these conditions may also reduce the spread of oil, help retain it as thick layers, contain it on, in or under ice and snow, reduce its chances of reaching sensitive biota and shorelines, and limit its penetration in onshore environments. In dynamic pack ice and during freeze-up and break-up of ice in bays, unstable ice conditions can significantly reduce the chances of reaching and recovering spilled oil in a safe and effective manner. A combination of response tactics may be necessary in these situations. Each technique will have limitations as described below. When active response cannot be safely accomplished, oil spill drift may be monitored to facilitate later cleanup efforts.

Characteristics of Ice and Impacts on OSR

Each arctic and sub-arctic region has it own unique combination of environmental characteristics. Ice parameters that may impact oil spill response strategies include the characteristics of landfast, transition, and pack or drift ice regimes; the ice season duration and decay cycle; ice concentration, ice type, thickness and growth rate; ice drift velocity; currents; the physical and mechanical properties, and others (Poplin, 2000). Aspects of an oil spill response that may be affected by these characteristics include: the degree of natural containment provided by the ice; the proportion of oil likely to be present on the water versus on top of or underneath ice floes; the ability of support vessels to maneuver through the ice field while supporting possible over-the-side countermeasures; the ability to put people and equipment on the ice for oil recovery operations and for sampling and monitoring; the ability to maintain effective visual surveillance of the oil distribution in the ice; and the likelihood that oil will rise naturally to the ice surface prior to break-up (Dickins, 2003). Depending on the nature of the spill and the means available to respond to it, differences in ice conditions between the spill location and the response mobilization base will also need to be taken into account.

A map showing the Northern Hemisphere Polar region and arctic oil and gas development areas (present and potential future opportunities) is shown in Fig. 1. Areas covered with sea ice at the time the map was created are shown in yellow while areas with snow are shown in white. Note that in addition to potential hydrocarbon exploration and development activities there will be transportation activities related to the energy industry as well as those required for maintenance of commerce in the Polar Regions shown (e.g., through the Baltic and Gulf of St. Lawrence).

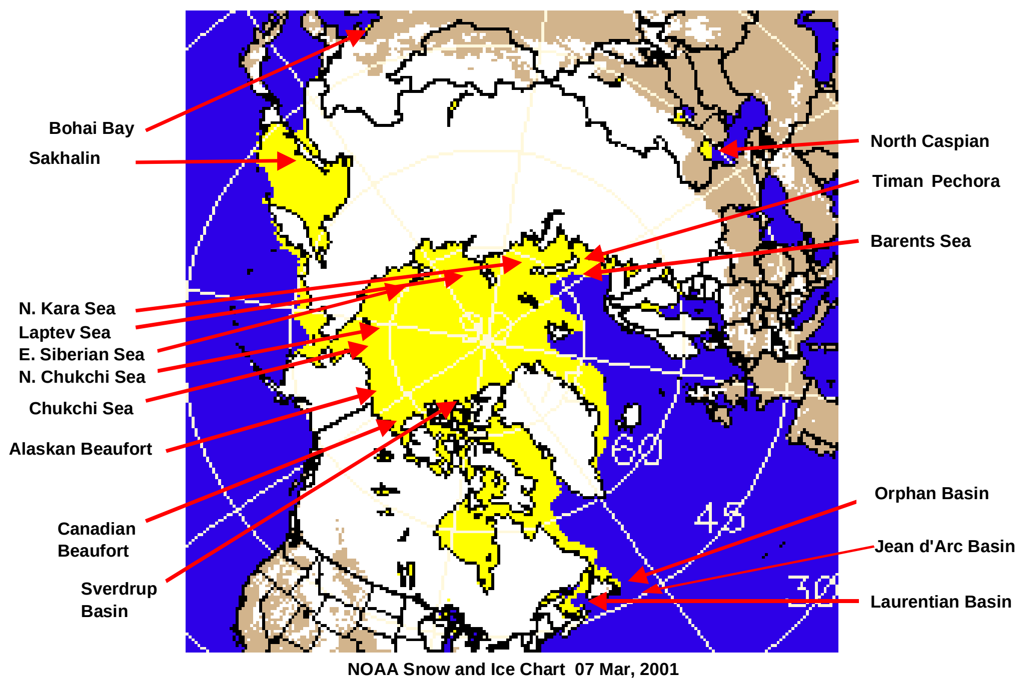

Figure 1. Arctic Offshore Opportunities -- Present and Potential Future

Ice Formation and Aging

Depending on the latitude, climate and ocean dynamics, regions may develop different types and forms of ice. First-year ice may be present as landfast ice (either floating or bottom fast), grounded ice (such as rafted ice in shallow water) and as pack ice. As ice ages, brine channels will form in the ice that can act as conduits for oil lying beneath the ice to travel to the ice surface (most prominent in warmer regions such as the Caspian and during spring). Once on the surface, this oil may collect in melt pools. Oil that spills into melting/rotting ice may adhere to the porous surface of the ice and be more difficult to remove. Multi-year ice will generally be thicker than first-year ice and will be smoother and less porous since brine channels have filled with melted ice and re-frozen over time.

Salinity affects the crystal structure of ice and the distribution and formation of brine channels as the ice begins to melt. This will affect the rate and extent of oil surfacing through the ice (more saline ice will have more channels for transport of oil). Oil spilled under brackish ice in nearshore bays and lagoons may remain trapped until just before the ice disintegrates leaving little time to recover or remove the oil before it enters the water. Conversely, oil spilled under sea ice offshore will likely surface weeks before the ice finally breaks up providing more time for recovery operations to be completed before the oil is released into the water (Dickins, 2003). The most likely response option for oil on melt pools is *in situ* burning.

Frazil and grease ice present one of the paradoxical challenges to spill response in ice-covered water. Spreading of oil will be greatly reduced by the ice crystals in the water, creating oily slush. This will reduce the area impacted by the spill and provide natural containment. If the grease ice/oil mixture freezes into a landfast ice sheet, then the oily layer could be mined from the ice. However, if the grease ice freezes into a dynamic ice pack, then the oil could be inaccessible for recovery by any method other than physically picking up ice floes and melting them. When the ice field diverges as the ice pack moves, oil could be spread over a wide area by the time the ice pack melts.

The time it takes for the oil to be incorporated into the growing ice sheet will depend on the region. Some areas, like the Beaufort Sea, have a very short time frame before a solid ice sheet is formed. Other more temperate or more dynamic regions (Sea of Okhotsk, Caspian Sea) have an extended period during which new ice could be forming on the water. Mechanical recovery methods will have limited utility in frazil and grease ice and will recover the ice along with the oil – potentially causing blockages and jams in the hose and piping systems. Sorbent materials may be useful for small spills. *In situ* burning may be the best method for removing oil from frazil and grease ice.

It is important to consider the potential negative effects of active response during the early stages of near-shore ice sheet formation. For example, if an oil spill were distributed over grease or pancake ice during initial freeze-up in the Beaufort Sea, then recovery of the oil and ice with skimmers will not likely lead to any significant recovery of oil before the entire surface freezes. Mechanical response activities in this environment could hamper subsequent cleanup efforts by mixing the oil into the growing ice layer. If the oil and ice are left alone, oil that falls on the forming ice in a thin layer should remain on the ice surface until it is incorporated in the ice or absorbed by snow.

Whether oil is spilled on top of the water and is incorporated into a growing ice sheet during formation of young ice, is released on ice and covered by snow, or is incorporated into the growing underside of an ice sheet as a result of an underwater release, the encapsulated oil will be very difficult to remove. Accessibility will determine the response options available. When the ice is thick enough to provide a working platform (see landfast ice discussion, below), clean-up options could include excavation, *in situ* burning or scraping (mining) the ice surface and removing the oil for recovery or burning. (Dickins et al., 2000). If the working platform (i.e., ice floe) is offshore, it may be possible to bring equipment to the site via icebreaking vessels and to cut and remove contaminated ice for melting and oil recovery onshore. Safety of people conducting operations on the ice will be of primary importance.

As ice floes decay in the spring, oil released from within or beneath the floes into melt pools or onto the water may be recovered as access allows - either with the techniques developed for ice-covered waters or using conventional open water techniques if ice concentrations are below three-tenths. Instability of the ice will be a primary concern when determining applicability of mechanical techniques from the time spring over-flood occurs (possible where rivers enter bays) until access via boats is possible.

Landfast Ice

In regions such as the Alaskan Beaufort, where a thick layer of landfast ice is present during much of the winter, strategies for spill response in ice have been well-developed (Alaska Clean Seas [ACS], 2001). Once the landfast ice is thick enough to safely support people and equipment, the ice provides a platform from which to mount the spill response effort. In fact some exploration and production operations are timed to occur while there is extensive landfast ice so that the ice will contain and facilitate response to a surface spill event, if one were to occur. Manual response methods employing shovels, bulldozers, graders/scrapers, snow blowers and other equipment can achieve recovery of oil from the surface of the ice (or in snow) – ACS, 2001, Tactics R1 to R3. In addition, surface mining equipment can be used to "mine" encapsulated oil from within a frozen ice sheet – ACS, 2001, Tactic R5 and R29. In the event of a subsurface release beneath a landfast ice sheet, procedures have been demonstrated for containing the oil and for recovering the oil by drilling holes or trenches in the ice to allow use of mechanical recovery devices – ACS, 2001, Tactic R13 and R14.

If there is a strong current moving beneath the ice (such as for landfast ice across a river or in coastal areas with strong tidal action), then the oil may be swept out from beneath the landfast ice into nearby leads or pack ice.

If warm or hot oil spills on top of landfast ice or large ice floes, a melt pool may be formed on the surface of the ice that would act to contain the oil. If the pool is large enough, and if it is accessible to equipment, open water oil spill response techniques may be applicable in the melt pool. Otherwise, it may be possible to burn the oil *in situ*.

Pack Ice

Pack ice may be found in many forms. The size and concentration of ice floes and the speed at which the pack is traveling will be a function of the region, the season, and the current tidal and meteorological conditions. Oil that is spilled on top of large floes will be difficult to recover. However, *in situ* burning may be used to remove a large fraction of the oil from the marine environment, especially if the ice is thin and unsafe for manual techniques used on landfast ice. Oil that is spilled beneath large floes may have several likely fates. If the subsurface of the ice is smooth and there is differential movement between the water and the ice, then the oil could be swept from beneath the floes and into leads - facilitating response. However, natural variations in the ice under-side provide huge natural reservoirs to effectively contain oil spilled underneath the ice within a small area. This will be especially true for locations where there is rafting and ridging of ice. The ice keel may provide a significant trap and barrier to oil movement. It may be possible to recover oil trapped in this manner by deploying skimmers in trenches or holes cut through ice, deploying rope mop skimmers under the ice, or pumping through holes augered into the oil pool. If the under-ice current is fast enough to cause the oil to escape, trenches or barriers may effectively trap the oil as long as the current is not so fast that oil flows under the barrier. When the pack ice is composed of small floes and brash, oil spilled beneath the surface is likely to end up in the leads between floes as the floes move. Several methods have been proposed for sweeping oil that remains trapped beneath small floes out into leads for recovery, e.g., prop wash, and pneumatic bubble booms (Rytkönen, 1999; Rytkönen, Sassi and Mykkänen, 2003; Owens, Spring and Wigton, 2003). A relative water flow of more than 20 cm/s is needed to initiate and sustain oil motion under rough ice (Cox and Schultz, 1980)

When oil is between floes in an ice pack (in the leads), there are several types of equipment that can be used to recover the oil from the water (e.g., oleophilic rope mop, rotating brushes or disk skimmers, small over-the-side skimmers). However, the limiting factor for a response of this nature will be the accessibility of the equipment to the spill. The size of the floes, overall ice concentration, weather conditions and availability of suitable vessels are a few of the factors impacting the response operation. To the degree that high ice concentrations contain the oil there is a possibility that once the response equipment gets to the spill it will be able to quickly pick up the localized oil. However, conventional booms can not be used in ice to gather large areas of a slick toward a collection point, so the oil encounter rate of the response equipment will generally be low. ExxonMobil is working on a pneumatic diversion boom that could be used to improve the oil encounter rate of mechanical equipment in ice-covered waters (Owens, Spring and Wigton, 2003). However, this project is still in the development and feasibility testing phases.

Wind and currents will normally cause oil to accumulate downdrift along the edges of ice floes. If there is access, skimmers can be used to collect oil at such locations. Likewise, *in situ* burning could be used to remove the oil (NORCOR, 1975; Dickins and Buist, 1981). Since the wind and currents may change and allow oil to escape before mechanical methods may access and recover it, *in situ* burning of oil (which can remove oil faster than skimmers) should be considered if conditions are right.

In some regions the speed at which the ice pack is moving may be a consideration for spill responders. For example, the East Coast of Sakhalin Island (Sea of Okhotsk) and the Cook Inlet of Alaska have pack ice that moves rapidly and presents additional operational and logistics challenges for spill responders. In 1994, SakNIPI used Argos buoys to measure long-term ice drift east of Sakhalin Island (Kalinin and Truskov, 1995). One buoy traveled in a net southerly direction at an average speed of 0.37 m/s while the other traveled at a net average speed of 0.30 m/s. Tides in Cook Inlet may move the ice at 3.5 to 4 m/s, though the net drift is much lower than this. In Cook Inlet, the primary response tactic in high ice concentrations is for the response vessel to drift along with the ice and oil and deploy oleophilic-rope skimmers onto the surface of the water and ice via a crane on the vessel (Lentsch, 2003).

In addition to naturally formed floes discussed above, brash and small ice floes may be generated from shipping traffic and associated icebreakers. The channels formed in this manner will generally have smaller ice pieces and lower ice concentrations than the original expanse of pack ice. Therefore the sides of the channel may provide natural containment to keep the spill within the channel, while the smaller ice pieces and lower ice concentrations will make accessing the oil easier. The Finns have spent considerable effort on developing response techniques and equipment to facilitate recovery of oil from this type of ice in the Baltic. They have developed several types of skimmers suitable for operations in ice-covered water (e.g., Rytkönen, Sassi and Mykkänen, 2003). The MORICE project also produced a prototype skimmer that may be suited for operations in this type of ice environment (Jensen, Mullin and McHale, 2002).

Ice Concentration

The effect of ice concentration on oil movement has been observed in field studies, laboratory and tank tests and actual arctic spill experiences. Differences in natural containment as a function of ice concentration directly affect the selection of spill response strategies (Dickins and Buist, 1999). Oil spilled into pack ice with less than four to six-tenths cover will tend to spread and move independently of the ice. As the coverage increases above six-tenths, oil will be confined and concentrated between ice floes and drift with the ice. Oil spilled into grease ice, slush, or brash will be contained by the small ice pieces in close proximity to each other and will move with this ice. As increasing ice concentrations confine a spill in ice and keep it from spreading, they will also facilitate response operations such as use of *in situ* burning by keeping the slick thick enough to ignite.

Table 1 shows the variation in average ice cover throughout the ice season for various locations. These data were extracted from the National Ice Center (NIC) sea ice maps for 1972-1994 (National Ice Center, 1996) using ICE 98 (a program developed by CANATEC Consultants Ltd.). Some seas have a significant gradient of ice concentration from North to South or extending out from shore - especially at the beginning and end of the ice season. Therefore, coordinates of a location within each sea for which data were collected are shown. The average number of weeks per year with a given ice concentration were summed using average ice concentration data for two-week periods over the twenty-three year period covered by this data set. It can be seen from the data that the Kara, Laptev, and Beaufort Seas have greater than five-tenths ice coverage for three-fourths of the year or more. In contrast, the Baltic Sea and Aniva Bay (south of Sakhalin Island) have less than five-tenths ice cover for the majority of their ice season.

Table 1. Variation in Weekly Average Ice Cover by Region

Location	Open Water	Weeks < 5/10	Weeks > 5/10	Weeks > 8/10
Chukchi Sea (68°N, 170°W)	14	6	32	28
Beaufort Sea				
-- Alaskan Sector: North of Prudhoe Bay (70°30'N, 148°W)	0	12	40	38
-- Canadian Sector: North of Mackenzie Bay (69°30'N, 137°W)	0	14	38	32
Gulf of St. Lawrence (48°30'N, 62°W)	34	8	10	4
Baltic Sea				
-- Bothnian Bay (63°30'N, 21°E)	26	16	10	0
-- Gulf of Finland (60°N, 26°E)	30	12	10	0
Barents Sea				
-- East of Svalbard (77°N, 30°E)	8	10	34	24
-- South of Svalbard (75°N, 20°E)	18	20	14	0
Kara Sea (77°N, 75°E)	0	10	42	36
Laptev Sea (77°N, 125°E)	0	0	52	42
Sea of Okhotsk				
-- NE Sakhalin (53°N, 144°E)	24	8	20	14
-- Aniva Bay (46°30'N, 143°E)	32	16	4	0

National Ice Center data are available for the Bohai from 1997-2004 (National Ice Center West Arctic Web Page). These data show that the ice season in the Bohai Sea region is relatively short (mid-December to March) with ice thickness rarely exceeding 70 cm. Ice accumulation generally starts in the eastern and northern part of the Bohai Sea (Liaodong Bay) with ice developing westward along the coast in more severe years. Full freezing of the Bohai Sea is generally not reached, but significant ice concentrations may be present in Liaodong, Bohai and Laizhou Bays at the peak of the ice season.

Ice conditions for the Caspian are summarized in Dickins (2003). A few highlights of this summary are that:

- The North Caspian Sea is characterized by relatively thin ice lasting for a small proportion of the year, typically 40-50 cm maximum for three months of the year;
- Ice cover varies significantly from winter to winter and the southern ice boundary is extremely variable; and
- In an average year, the region north of a line from the Tuleny islands to the Kulali islands has greater than eight-tenths ice coverage.

Oil Fate and Response

The fate of oil in different types of ice as it relates to spill response options has been discussed above in a very general fashion. It should be clear that there will be many site-specific and scenario-specific factors that will impact spill response operations. The impact of ice type and spill scenario on mechanical recovery options has been mentioned in a number of examples above. However, this environment presents many limitations to operability of equipment, safety of personnel, and efficiency of mechanical response. Response with "hands-off" techniques such as *in situ* burning and application of dispersants may result in a much more efficient response to a spill event and a reduced overall impact to the environment. Recent research has demonstrated applicability and efficiency of *in situ* burning (Brown and Goodman, 1986; Guénette and Wighus, 1996; Buist et al., 2003) and dispersants (Owens and Belore, 2004) in select ice environments and additional efforts are underway to improve understanding of the applicability of these techniques to various spill scenarios in ice-covered waters. Additional discussion of spill response techniques and when they are most applicable is included below.

Spill Response Techniques

Proven techniques that can be used under various ice conditions and for shoreline cleanup in cold regions have been developed from laboratory and field tests as well as field applications. Their description can be found in recently published field guides and manuals, such as the Field Guide for Oil Spill Response in Arctic Waters (Owens et al., 1998), Technical Manual by Alaska Clean Seas (Alaska Clean Seas, 2001), and Field Guide for the Protection and Cleanup of Oiled Arctic Shorelines (Owens, 1996). The suitability of a particular response strategy is critically dependent on the state of the ice when the strategy is to be employed.

As a general rule, conventional OSR options, such as mechanical containment and recovery, *in situ* burning, and dispersant application, may be used when there is minimal ice coverage, i.e., less than three-tenths. At higher ice concentrations, *in situ* burning has been recognized as an effective countermeasure when the natural containment of oil provided by the ice occurs.   Mechanical recovery of oil may be possible with equipment specially designed for ice conditions, but additional work in this area is required to improve efficiencies. Dispersants may be applicable if sufficient mixing can be provided via wave action (suppressed in heavy ice) or via vessel induced agitation to assist in dispersion of oil into the water column. In the case of landfast oiled ice, conventional winter response procedures (ice trenching, excavation, ice mining, etc.) can be implemented when the ice thickness is generally greater than 50 cm.

Due to the short daylight hours, extreme cold temperatures, and potential dynamic ice conditions, any oil spill response in the Arctic during the winter could be hazardous. The health and safety of responders should be the primary concern and extra care and caution should be exercised. Personnel and equipment should not be sent out under any unsafe conditions. Ice class vessels are required for offshore operations in ice-covered waters with more than three-tenths ice.

Summaries of the state-of-the-art for response options that may be employed after a spill in ice-covered water, are provided below. Containment is discussed as are mechanical recovery, *in situ* burning and dispersants. Related issues such as tracking of spills in ice and shoreline cleanup are only briefly discussed.

Containment

In general, containment is necessary for mechanical recovery and *in situ* burning. There are a number of ways to contain an oil slick under arctic conditions. Conventional booms will not be effective if employed in the same manner in ice-covered water as they are in open water response. For ice coverage greater than three-tenths, booms may be deployed and placed in open water leads between the ice sheets to deter spreading of the oil through the leads; however the boom must be allowed to drift with the ice and is in danger of being damaged by the ice. As in open waters, mechanical containment is only effective in relatively light seas (wave height less than 2 m, winds less than 10 m/sec, currents less than 40-50 cm/sec). While ice cover usually suppresses wave motion, ocean swells have been observed far into the ice pack when severe storms are present outside the pack (Marko, 2003).

When there are sufficient ice floes present, the ice itself can effect containment. Support vessels could assist by maneuvering ice floes into appropriate blocking positions. Ice booms have been used to entrap ice and encourage ice buildup in shallow water areas. The shapes and sizes of the ice floes, as well as wind velocity and currents, determine the feasibility and practicality of this method. Applicability of this method to specific locations will need to be determined on a case-by-case basis.

Mechanical Recovery

Owens et al. (1998) and Allen (2000) provide a summary of the state of the art for skimmers in ice and rules of thumb for their use. Most open water skimmers work effectively when ice coverage is less than one to three-tenths. At this point ice, concentrated by associated booming operations, begins to bridge the skimmer (preventing the oil from entering) or cause other operational problems. With higher ice coverage, portable oleophilic rope mops have been shown to be effective for recovery of oil in ice-laden waters (Solsberg and McGrath, 1992). These are typically deployed from a vessel by suspending the skimmer over the oil to be recovered. When properly designed, some of the brush and drum skimmers can recover oil in ice under favorable conditions (Johannessen et al., 1996; Solsberg and McGrath, 1992). Ice and cold temperatures will reduce the effectiveness of mechanical countermeasures, e.g., by reduction of maneuverability, ice clogging of receptacles, puncture of boom by ice fragments, freezing of recovery fluid, fuels and lube oils and brittle failure of equipment.

In above freezing temperatures, disk skimmers can be used where oil concentrations are thick and where the open ice leads allow deployment. This is also true for weir skimmers, provided the presence of brash ice or newly frozen ice will not prevent oil from flowing into the skimmer or clog the ports of the pumps.

The Finns have recently developed devices specifically for cleaning oiled ice and beaches (Liukkonen and Rytkönen, 1997; Rytkönen, 1992; Rytkönen, 1999) and these have been tested in ice conditions. Additional laboratory and field demonstrations are being performed as devices are improved and new ones conceived (Rytkönen, Sassi, and Mykkänen, 2003).

In Situ Burning

Due to the positive results of extensive research on *in situ* burning in the last twenty-five years, *in situ* burning has been recognized as a proven, effective, and efficient countermeasure for oil spill cleanup (Buist et al., 1994). *In situ* burning has been recognized as an effective countermeasure for oil spills in ice-covered waters when ice floes or ice sheets contain the spilled oil, maintaining thicker slicks (Bech et al., 1993). The contained oil can usually be efficiently burned (this will be a function of the slick thickness, oil type, degree of weathering and degree of emulsification). The burning of spilled oil also eliminates the need for storage containers and later disposal of the oil. *In situ* burning has been used successfully in numerous actual spill incidents in ice-covered waters (Buist et al., 1994; Johannessen et al., 1996).

Results from laboratory, meso-scale, and large-scale field tests have proven that the potential environmental impact of *in situ* burning is generally minimal and confined to the immediate localized area (Buist et al., 1994). However, when burning large oil slicks, the smoke plume may extend downwind several kilometers.

If conditions are right for burning, oil contained between ice floes and along floe edges may be burned at a rate faster than skimmers can recover it. Pools of free oil formed on top of the ice from a spill on ice, or oil that has migrated to the surface through brine channels from within or below the ice may also be burned effectively. Under certain conditions, ice-breaking vessels can be used to carefully break ice around a spill site in very close pack ice to expose trapped oil for burning. Ignition of oil in melt pools and oil in broken ice via helicopter can allow removal of oil under conditions where it would not be safe to have people working among the ice.

Dispersants

Dispersant application has been studied extensively for over 30 years (ExxonMobil Research and Engineering Company, 2000) and dispersants have been used successfully in many actual spills (Lessard and Demarco, 2000). However, because of cold temperatures and ice cover, the use of dispersants in ice-covered waters entails special consideration.

It has been shown that dispersants can be more than 80% effective in water colder than 5 °C and recent tank tests at -0.5 to 2.4 °C showed dispersants to be highly effective (82 to 99%) on two different crudes in both fresh and weathered states (Belore, 2003). The effectiveness of Corexit 9527 and 9500 has been tested successfully on a light crude oil in brash ice with good results (Brown and Goodman, 1996). In other experiments, performed in brash ice of varying concentrations under the influence of very low wave energy, the presence of the ice increased the effectiveness of dispersant over open water controls (Owens and Belore, 2004). However, the presence of ice has varying effects on dispersant performance. The pumping action of waves in brash and between ice floes may provide the energy required to allow oil to be dispersed into the water column. Conversely, large pieces of ice and slush can inhibit mixing by damping waves.

Dispersants may be applied via helicopter, airplane, or marine vessels. Therefore, dispersants may be applied under conditions where mechanical recovery is not possible. In addition, data are available suggesting that once dispersants have mixed with oil they will stay within the slick (not being lost to the water column as previously thought) and remain effective as long as the oil does not weather to the point where viscosity precludes effective dispersion. This suggests that dispersants may be applied prior to the optimal conditions for dispersion without significant loss of dispersant effectiveness (ExxonMobil, 2003). Additional research is needed to further explore the feasibility of chemically dispersing oil under various arctic scenarios.

Tracking

Tracking the oiled ice will become a priority when active response measures are not possible. This could be done at the spill source. Radio and/or satellite position buoys may be placed strategically in the deposition zone to monitor ice movements. Pylons affixed with light strobes may also be placed on ice floes in the oil slick to assist aerial tracking. Dynamic ice conditions will increase the difficulty in tracking ice and several techniques should be used at any one time.

Aerial reconnaissance can be carried out using visual observations and remote sensing using the airborne FLIR system (forward-looking infrared: may be applicable only during very low ice concentrations). RADARSAT imagery may also be available to assist in documenting ice conditions and in tracking significant ice features. Current remote sensing techniques can not reliably detect oil under ice, so manual detection methods (such as drilling cores through the ice) will need to be used in this case.

Shoreline Clean-up

In most instances, the presence of ice in the shore zone or on the adjacent nearshore water acts to prevent oil on the surface of the water from making contact with the shoreline substrate before the spring thaw. In the event that there is oil at the shoreline, oil/snow mixtures would be relatively easy to remove manually or possibly mechanically provided there is access. Flushing and collection may be useful if water does not freeze and encapsulate the oil. For pooled oil, sorbents, vacuuming, or burning can be used for cleanup. Sorbents and the shoreline cleaning devices recently developed, such as Lori’s Oil Recovery Bucket and Lamor’s Rock Cleaner, may be used to sweep ice surfaces. In addition to these, portable rope mops may be used to collect oil from cracks, crevices and leads.

During early winter, the shoreline freezes over in the tidal zone to form an ice edge or ice base. As it approaches the shore, oil in pure form or mixed with ice or snow will freeze and remain frozen until spring. If oil cannot be removed before it freezes and does not pose a major threat to the environment or human health and safety, the oil location should be marked so it can be cleaned up after solid landfast ice has formed or in the spring. The choice of a cleanup method for an oil-contaminated shoreline will depend on the type of shoreline, the quantity and type of oil, and snow and ice conditions. Net environmental benefit should also be considered when selecting a cleanup method. If the amount of oiled ice on shore is relatively small, it can be collected manually. In the spring, when water is no longer freezing, the oil on the surface of ice may be flushed into the water and then recovered or burned.

Conclusion

There are many different possible spill scenarios for arctic and sub-arctic ice-covered waters. Conditions in all regions vary dramatically through the ice season. These variable conditions preclude the selection of a single OSR technique as the optimum for all situations. In the event of a spill, the most efficient response will generally include a combination of techniques. Selection and implementation of each OSR measure will depend on the sea-state, weather and ice conditions, and ability to safely execute the response measure. Net environmental benefit should also be considered using knowledge of sensitive resources at risk and likely spill trajectories.

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