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Countermeasures for ice covered waters*

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Abstract: This chapter describes the state of knowledge regarding the most applicable countermeasures to deal with oil on, in or among ice. Countermeasures are discussed in the context of seasonal variations in ice conditions and observations of oil fate and behaviour in a variety of different situations. The behaviour of oil spilled in ice covered waters is governed largely by the ice concentration in the case of broken ice, and the processes of encapsulation and subsequent migration in the case of solid (fast) (ice). Each season presents different drawbacks and advantages for spill response. During freeze-up and break-up, drifting ice and limited site access tend to restrict the possible response options and significantly reduce recovery effectiveness. Mid-winter, although associated with long periods of darkness and cold temperatures, provides a stable ice cover that not only naturally contains the oil nearshore within a relatively small area but also provides a safe working platform for oil recovery and transport. For the case of spills under or on fast ice, there are a range of effective countermeasures options which can result in very high recovery effectiveness. Countermeasures to deal with spills in moving pack ice are much more limited and likely to result in highly variable recovery values depending on a variety of natural conditions and logistics constraints.

OIL FATE AND BEHAVIOUR IN ICE COVERED WATERS

Strategies and techniques for dealing with oil in ice have been studied intensively in the United States, Canada and Norway during the past 20 years (e.g. [1,2,30,40]). Two of the largest field experiments took place in the Canadian Beaufort Sea in 1974–75 and 1980 [3,4]. The Norcor project involved eight spills of two different crude oils totaling 330 barrels under ice ranging in thickness from 17 to 70 inches. A later experiment in the same region simulated a subsea blowout by injecting compressed air and Prudhoe Bay crude oil under landfast ice [4]. Field spills under controlled conditions in broken ice are more limited in scale, and include a single trial off the East Coast of Canada in 1986 [5], and several offshore trials in Norway [6].

These field studies in conjunction with laboratory and tank tests, and actual arctic spill experiences have led to a good understanding of the basic processes controlling the behavior of fresh and emulsified crude oil, with and without gas, in a variety of ice conditions including landfast and broken pack ice [e.g. 13,17,33,34,41]. Dickins & Fleet [7] contains a comprehensive summary of all known references on the subject of oil-in-ice fate and behavior, including analytical studies, tank and basin tests, spills of opportunity, and experimental spills at sea.

The following discussion summarizes the key processes governing the fate and behaviour of oil spilled into polar waters in the presence of different forms of sea ice. While many of the processes and countermeasures strategies are applicable to freshwater ice environments, the focus here is on saline conditions representative of the arctic continental shelf regions (e.g. Chukchi Sea, Beaufort Sea, Barents Sea) and marginal ice zones and subarctic areas such as the Bering Sea, Labrador Sea and Sea of Okhotsk.

The physical distribution and condition of spilled oil under, within or on top of the ice plays a major role in determining the most effective response strategies at different stages in the ice growth and decay cycle.

The fate and behaviour of oil in ice covered waters is governed by a number of important processes, several of which are illustrated above in Fig. 1 (after [8]) and discussed below.

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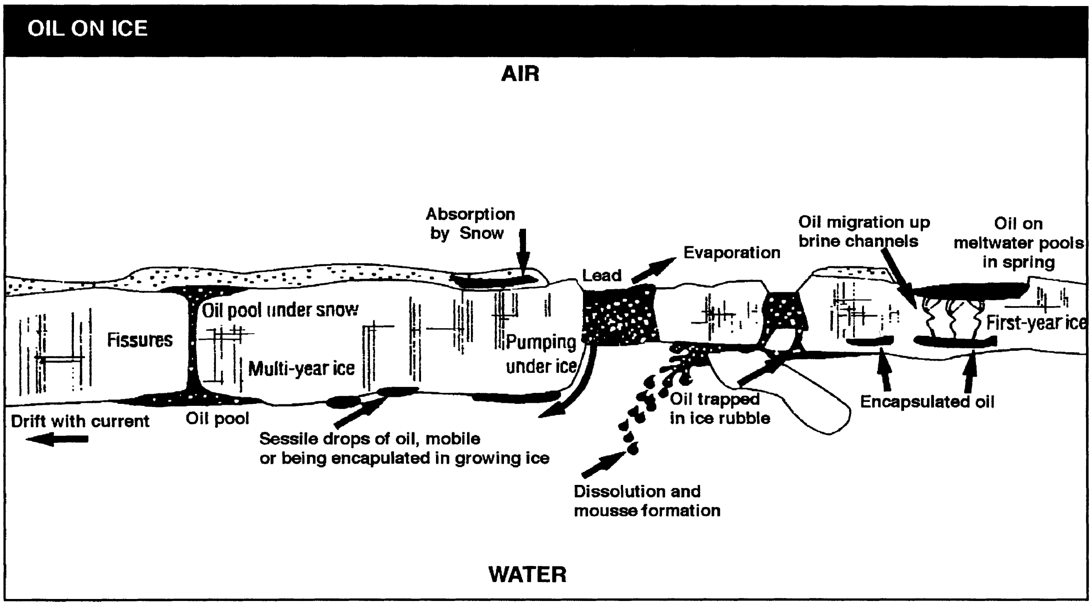

Fig. 1 Illustration of oil and ice processes.

Oil spreading

In broken-ice

In broken ice, oil spills tend to spread far less and remain concentrated in greater thicknesses than in ice-free waters. In ice concentrations greater than 'close pack' (over 6/10 of the sea surface ice covered), the ice floes themselves provide a high degree of natural containment and serve to physically limit oil spreading. As the ice concentrations become more open, the oil spreading gradually increases until it reaches close to an open water state in very open drift ice (less than 4/10). There are a number of simple empirical models that predict the spreading of oil in broken ice by modifying the open water spreading (Fig. 2 [39]) as a function of ice concentration.

For example, a 1000 m^3 spill in 6/10 ice cover after 12 h would be estimated to have spread to 0.8 km^2 (2 km^2 from Fig. 2 multiplied by 0.4).

Under solid ice

Even large spills (tens of thousands of barrels) of crude oil underneath or on top of solid (or fast ice) will usually be contained within hundreds of meters from the spill source, depending on under-ice currents and ice roughness. Natural variations in first-year ice thickness provide huge natural 'reservoirs' to effectively

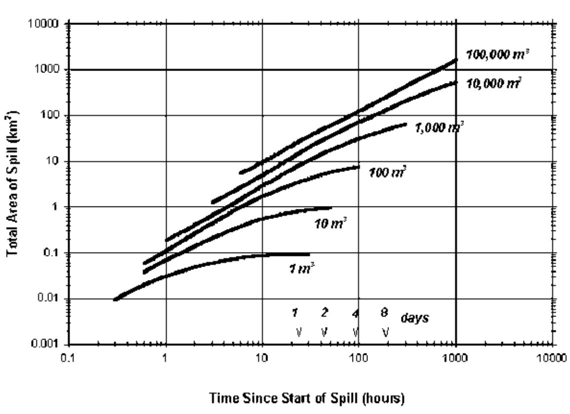

Fig. 2 Hypothetical slick dimensions vs. time after spill, for spills of various volumes on water [39].

contain oil spilled underneath the ice within a small area. Late-winter (April) under-ice storage capacities have been estimated to be as high as 400 000 barrels per km^2 from surveys of fast ice along the Alaskan North Slope [9,28]. Early winter values have been computed to be about a half as great reflecting the smoother ice at that time. Subarctic regions with greater snowfalls (e.g. Labrador) would be expected to have a greater local variability in ice thickness earlier in the season. The implication is that any mid-winter spill under ice would be naturally contained within a relatively small area when compared to an identical volume spilled on open water

Winter under-ice currents in most arctic nearshore areas are not sufficient to spread spilled oil much beyond the initial point of contact with the ice under surface. Exceptions may be in fjord-like areas with strong tidal currents. Several studies have determined that, with roughness values typical of undeformed first-year sea ice, the threshold current speed needed to initiate and sustain movement of an oil lens or pool along the ice under surface is approximately 0.9 ft/s or ~0.5 kt [3,10,11].

As the natural containment increases with ice thickness, the area needed to contain a given spill volume decreases steadily throughout the winter, as shown in Fig. 3.

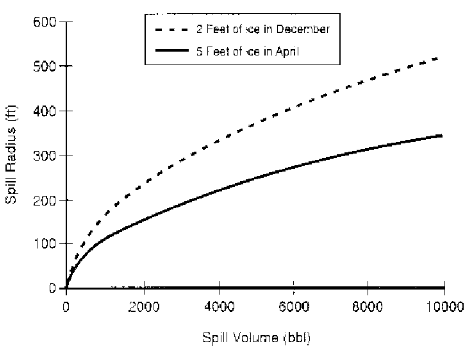

Fig. 3 Predicted radii of spills of a given volume spilled under landfast ice [12].

The average oil layer thickness under the ice can range from several centimetres for spills in early winter to tens of centimetres in April for a spill under ice at the end of the ice growth cycle. The maximum oil thickness in the deepest pools could vary from 10 to over 30 cm, respectively. Actual values will depend on the local ice conditions at the time of the spill.

Natural variations in ice thickness comprise the most important physical characteristic limiting the spreading of oil from a subsurface release. In the case of a small leak, the formation of a lip of new ice at the outer perimeter of the spilled oil will also act to further limit spreading in the case of unusually smooth ice (see following discussion).

On-ice

The spreading of oil on ice is similar to spreading of oil on land or snow. The rate of spreading is controlled by the density and viscosity of the oil, the final contaminated area being dictated by the surface roughness of the ice. Oil spilled on ice spreads much more slowly than on water and covers a smaller final area, thus slicks on ice tend to be much thicker than equivalent slicks on water. Figure 4 shows the final area of spills on ice as a function of spill size and ice roughness (after [1]). Smooth first-year sea ice has a roughness in the 0.01–0.1 ft range. Discrete ice deformation features such as rafting, rubble and pressure ridges can lead to localized increases in roughness up to tens of meters in elevation above sea level (in the case of extreme grounded ridges along the seaward edge of the fast ice). Any oil spilled on the surface of rough ice may be completely contained in a thick pool bounded by ridge sails and ice blocks.

Oil movement

Spills on and under ice will generally not move independently of the ice, but remain in the vicinity of the spill site; if the ice is drifting, the oil will drift with it. The exception is oil under ice in currents exceeding 0.5 knots. The rate at which oil moves under ice under the influence of high currents is a complex function

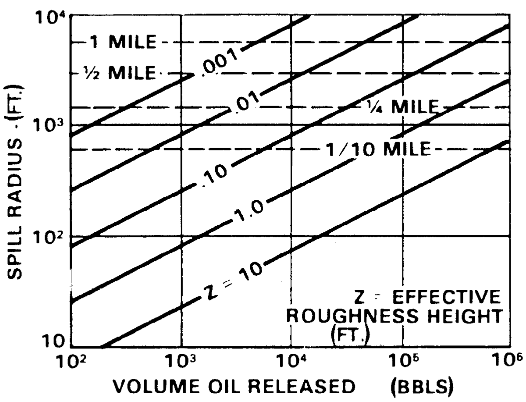

Fig. 4 Spreading of oil spilled on ice [1].

of oil and ice properties [13]; it generally involves the progressive filling and draining of under-ice cavities with oil. In general, the oil is swept under the ice until it has filled enough under-ice cavities to account for the volume spilled. The volume of oil that can be retained by under-ice cavities decreases as the current speed increases; the speed at which oil moves between cavities increases with increasing current speed and decreases with increasing oil viscosity. Under perfectly smooth ice oil will be moved along at 1.7–2.7 knots by two to three knot currents; under smooth sea ice with a roughness of 0.1 ft, two to three knot currents would move oil at a velocity of 1.4–2.1 knots [13,14].

Oil spilled among broken ice will move with the ice. Both the ice floes and the oil will move at a small percentage of the wind speed [5]. A value of 3% is commonly used as a general rule to estimated drift speed, but floe tracking experiments have shown that a value of 5–7% is not uncommon nearshore [42]. Due to the Coriolis effect, a turning angle of 10–20° to the right of the wind can be applied to better estimate the direction of oil moving with high concentrations of ice. Oil trapped in converging broken ice, will be thickened as the ice concentration increases; in extreme cases, rapid compression can force some of the oil in the water under or on top of adjacent floe edges. The majority of the oil which was floating on the water or in slush ice between floes prior to compression, will be incorporated into the raised crushed ice edges as the floes contact and grind against one another under the wind generated pressure [5].

Oil weathering

The major weathering process that occurs for spills on ice or among broken ice is evaporation. Dispersion rates are very low in the presence of ice due the effective wave damping of the ice floes. Oil spilled under ice is quickly encapsulated by the growing ice sheet and does not evaporate or weather to any significant extent during the winter period [3,4]. During the spring melt, the encapsulated oil is exposed on the ice surface in a close to fresh state, at which time normal evaporation will occur as the oil floats on melt pools.

At any time during the winter when response crews pump or burn oil brought to the surface from a trapped layer under or within the ice, they will be dealing with almost fresh crude, even months after the spill occurred.

Oil encapsulation and migration

In a batch release of oil beneath a solid ice cover, new ice will completely encapsulate the oil layer within 18–72 h, depending on the time of year [4]. Oil spilled under the ice after May in the Arctic, or after April in subarctic regions, may not become encapsulated due to insufficient new ice growth before the onset of melt.

After the oil has spread under the ice and been encapsulated, it will remain trapped until the ice sheet has reached its maximum thickness, at which time a process of vertical migration will begin with the gradual warming of the ice sheet. The rate of vertical migration depends on the degree of brine drainage within the ice (a function of internal temperature), trapped oil pool thickness, and oil viscosity. During the period from freeze-up to mid-winter when the sheet is cooling and growing rapidly, there are very few passages for the oil to penetrate into the ice sheet. Vertical migration of the oil in this period is limited to several centimetres of initial penetration through the porous skeletal layer (new ice crystals) at the ice/water interface.

As ice temperatures gradually increase, brine trapped between the columnar sea ice crystals begins to drain down, leaving vertical channels for the oil to eventually rise to the surface. The first evidence of natural oil appearance on the surface has been observed as early as late May in experiments on the Beaufort Sea coast. In subarctic areas such as Labrador, this process will be advanced by about one month depending on air temperatures. Oil released under two metres of ice in one experiment on 21 May reached the ice surface within 1 h [3].

The rate of oil migration increases rapidly once daily air temperatures remain consistently above freezing. During the same experiment mentioned above, up to 50% of the oil originally trapped within the ice became exposed on the ice surface between 10 June and 20 June. Oil slick thickness in the melt pools on the surface increased from 0.04 inches (0.1 cm) to over 0.4 inches (1 cm) during a one-week period. Figure 5 shows the timing of oil exposure as measured from three different experimental spills during the course of one winter [4].

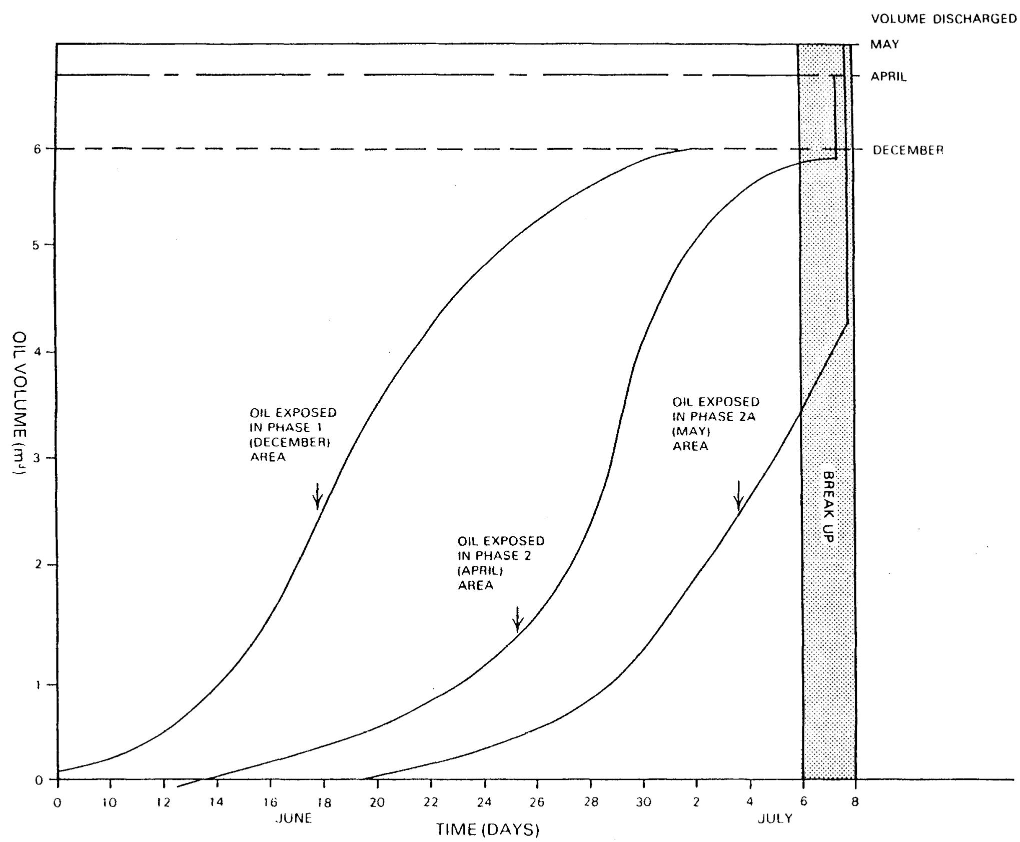

Fig. 5 Timing of oil exposure on the surface in spring following winter spills under ice [4].

Natural melt of the ice from the surface down acts as a competing process to expose encapsulated oil. When this melt reaches the level where the ice was growing at the time of the spill, the oil is exposed. In most situations of a concentrated thick oil layer in the ice, natural migration will bring most of the oil to the surface before the surface melts down to meet it. Oil released subsurface in the presence of gas (e.g. blowout) may be distributed as fine droplets which surface much more slowly. Both processes are combined in Fig. 5 [4].

Once the oil reaches the ice surface, it lies in melt pools or remains in patches on the melting ice surface after the surface waters have drained. Winds herd the oil into thicker layers against the edges of individual pools. Spring observations during experimental spills in landfast ice in the Canadian Beaufort have shown the following size distribution of melt pools containing oil which has naturally migrated to the surface (Table 1). This type of information is important in determining how much of the oil can be effectively burned through ignition of individual pools by either Heli-torch or manual ignition (refer to following discussion).

Table 1 Average oil pool size distribution, McKinley Bay NWT, 1981

	All	10 ft^2	50 ft^2	100 ft^2	200 ft^2	1000 ft^2
Number of pools per acre greater than a given size	32	24	12	6	1.6	0.8
Percent of oil in pools greater than a given size	100	95	85	75	45	40

DETECTION AND MONITORING OF SPILLS ON/IN/UNDER ICE

Although spills in ice covered waters are generally contained within a much smaller area (compared with open water spills) the presence of ice in conjunction with limited daylight greatly complicates both the initial detection and mapping and subsequent monitoring/tracking. Wotherspoon [15] summarizes the state of the art based on field trials and laboratory research.

Spills on ice

The detection of oil spills on ice immediately following a spill is reasonably easy since the oil is generally thick and visible in sharp contrast to the snow. Aerial reconnaissance is the best technique, supplemented, if possible, with aerial remote sensing (video and IR or FLIR) [15]. Difficulties can arise when a fresh snowfall at the time of spill covers the oil before aerial observers can arrive on site. It may then be necessary to take snow cores in a grid pattern, or shovel radial strips from a known source point to delineate the extent of the contaminated area.

In the spring, oiled snow will melt faster than the surrounding snow due to the increased solar heat absorption. As the melt progresses, sediment on the ice (particularly in nearshore areas) combined with the light and dark patterns characteristic of a deteriorated ice surface can easily be confused with weathered oil. It may be necessary to 'ground truth' the visual observations close to break-up to confirm what is being mapped as oil.

Spills in broken ice

Airborne systems such as the laser fluorosensor operated by the Canadian Government [15], as well as IR sensors, have shown some potential for detecting and mapping oil among drifting broken ice. The latest generation of high resolution radar satellites can potentially be used to map large spills in an open pack condition but radar signatures of new ice, oil and calm water can be very confusing. Further work is needed in this area before satellite imagery can be recommended as an operational tool. Visual airborne reconnaissance remains the most effective method (subject to the usual weather and daylight constraints).

Spills under ice

The detection and mapping of oil spilled under ice is a difficult undertaking since the oil is hidden from view beneath a (generally) thick sheet of ice. Several techniques have been developed for spills in landfast ice; all of these depend on knowing the general location of the oil beforehand.

Backlighting

Powerful lights placed beneath the ice by divers can be used to delineate the extent of oiling under or trapped in an ice sheet [2]. Removal of the surface snow is required for the technique to be successful. The North Slope Spill Response Team in Alaska uses high intensity quartz halogen fixtures lowered through a hole in the ice to illuminate the ice under surface [12].

Ice coring

Ice cores can be taken through the ice at spaced intervals across an area of suspected oil contamination. Care should be taken in using this technique near the site of a subsea blowout since the gas also pools under the ice and can present a safety hazard to personnel [4].

Diver observations

Divers can be used to delineate the extent of an under-ice spill once the general location is known. In general they can operate within about 100 ft of a dive hole cut through clean-ice and require surface directions to maintain their bearings [2,4]. Difficulties arise when the divers enter the water several days after a spill, by which time a layer of new ice may have formed beneath the oil and make detection and mapping more difficult.

Other

Although research is continuing on remote sensing and detection of oil under sea ice, no field-proven technology presently exists. One technique that seems promising and may be further developed is the detection of oil beneath ice using acoustics.

Tracking of oiled ice

The tracking of oil spills on, in or under ice generally involves techniques for tracking the ice movement. Several types of satellite-tracked or radio-transponder buoys are commercially available for this purpose. The latest generation of GPS tracking buoys can provide near-real time positions to better than 50 m accuracy to computers in a command centre [35]. In addition, successive visible or radar satellite images can be used to track the motion of large, distinctive ice features to gain some idea of the regional ice motion trends over 24–72-h periods. In the absence of airborne visual checks or buoys on site, rough estimates can be made of the likely drift of oiled ice by applying a standard factor such as 3–5% of the wind speed with a 10–20° turning angle to account for Coriolis forces. Nearshore ice drift can be complicated by long-shore tidal residuals and boundary effects. It is not unusual to see deep draft ice features (e.g. old multiyear floes) moving into the wind in response to currents at depth [42].

The tracking of oil under ice in areas with high currents is particularly difficult. Measuring under-ice currents could be used to assist in selecting likely downstream areas for coring or diver observations to intercept the moving oil. Fortunately, this condition will not normally be encountered along open arctic coastlines such as the Beaufort Sea. Arctic fiord environments which can give rise to significant under-ice currents may present a more difficult problem. Computer models (e.g. [14]) exist that attempt to predict the motion of oil under ice in high currents, but these have not been verified in field tests.

INFLUENCE OF ICE CONDITIONS ON CLEAN-UP STRATEGIES

Of all the factors affecting the choice of response actions to deal with a marine spill in a polar environment, the combination of ice and weather conditions largely determines which countermeasures can be considered practical. Examples of important ice conditions affecting the choice of countermeasures include thickness, stability, bearing capacity and concentration. Figure 6 shows a typical cross section of mid-winter sea ice moving from shore through the fast ice zone to the moving pack ice. All ice covered areas incorporate some of the features shown with the main difference being in the extent of fast ice. Depending on bathymetry, the fast ice may vary from narrow band along shore less than 100 m in width, to a vast area of relatively smooth ice stretching for tens of kilometers.

Ice thickness

Ice thickness dictates the available site access, load-bearing capacity for staging equipment and surface

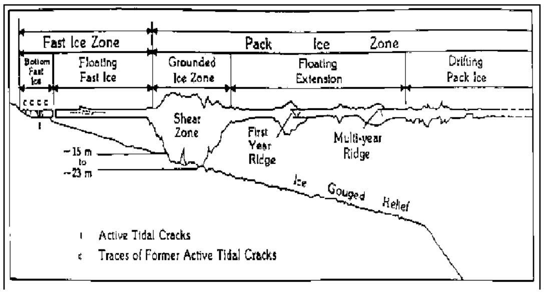

Fig. 6 Typical arctic sea ice cross-section.

travel to and from the spill site. Depending on location and time of year, sea ice will support heavy equipment, such as trenchers, end-dumps, backhoes, ditch witches, and bladders for temporary storage and/or transport of liquid oil pumped from within the ice. If necessary, the ice thickness along a selected route can be built-up by spraying to support heavier loads than the natural sheet is capable of carrying (ice roads). Figure 7 illustrates the relationship between ice thickness and mid-winter loading capacity used to guide response operations on Alaska's North Slope. In the case of warming ice in the spring, or cracked ice, loads need be reduced substantially.

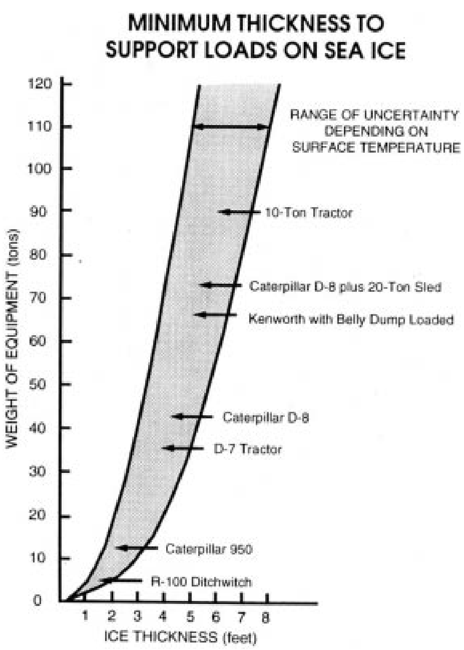

Fig. 7 Load bearing capacities of sea ice [Source: Alaska Clean Seas Training Manual].

The shoulder seasons of freeze-up or break-up represent the greatest challenge to arctic logistics in that surface transport is usually not possible [16]. High concentrations of broken ice can prevent non-ice strengthened vessels from reaching the spill site. In these cases, countermeasures are often restricted to those strategies which can be carried out remotely from helicopters (e.g. *in-situ* burning with a Heli-torch). Possible alternatives involve air cushion vehicles which have demonstrated an ability to move heavy loads (up the 30 tons) over newly forming ice at freeze-up and over melting ice in the spring.

Ice stability

The term ice-stability relates to the potential for large ice movements in response to storm winds. Periods of most concern for oil spill response are freeze-up from October through December, and break-up in June and July. During early winter when the ice is less than 60 cm, the fast ice sheet can be broken up by sustained storm winds. As a result any oil trapped in the ice at this time can be rapidly dispersed over a wide ocean area as the fragments of the former fast ice are blown out to sea and along the coast. By mid-December in most ice covered areas, the fast ice becomes relatively stable and usually remains intact until May or June.

Once the ice has deteriorated during spring melt, another short period of instability occurs during the transition from a continuous ice cover to predominantly open water. During these 'unstable' months, response operations may encounter the possibility of oil trapped in, or on top of the ice, moving at drift rates close to one knot in periods of sustained storm winds.

Ice concentration

The influence of ice concentration on oil spreading was discussed earlier. In the context of countermeasures, the ice concentration often becomes the governing factor in making decisions about equipment selection and deployment in the spring and summer. Depending on the concentration, broken ice can act to hinder or help clean-up operations [16]. The possibility of drifting pack ice at any time between break-up and freeze-up in many arctic areas can limit the effectiveness of conventional open water oil recovery systems. The value of 3/10 is significant in that it represents a generally accepted upper limit for deploying conventional booms and skimmers without unacceptable interruptions from drifting ice [16,20]. At the same time, high concentrations of ice can be used to advantage by naturally containing the oil to allow direct *in-situ* burning [5].

Ice concentrations between 3/10 and 6/10 represent the greatest problem for oil spill cleanup. Conventional booms may be collapsed, overrun, or damaged by drifting ice. At the same time there is insufficient ice to naturally contain the oil into sufficiently thick patches to burn *in-situ* without firebooms.

CONTAINMENT OF OIL SPILLS ON/IN/UNDER ICE

As with any marine response, containment is generally the first step in cleaning up an oil spill in ice covered waters. The key objectives of containment are:

- to limit the spreading of the spill, thereby limiting the area affected; and/or
- to contain and thicken the spill to increase the effectiveness of subsequent countermeasures such as recovery or *in-situ* burning.

This section describes the containment of oil spilled on, in, and under ice, summarizing the natural containment afforded by the ice itself (discussed earlier) and introducing other mechanical options.

Summary of natural containment mechanisms

Compared with spills on open water, spills involving ice have the advantage of being contained in many cases by various ice features such as floes, snow, and ridges.

Oil on ice

An ice surface has a significant oil retention capacity which tends to limit the spread of an oil spilled on it [1]. This retention capacity is a result of both major features such as ridges and hummock fields as well as smaller surface roughness features (see Fig. 4).

In addition, any surface snow will tend to absorb oil; in fact, snow may absorb up to 20–40% oil by volume [2]. Nonetheless, light oils such as diesel and condensates may spread along the ice surface under the snow for considerable distances beyond the spill source [29,31].

Oil among ice floes

Oil spilled among broken ice will be naturally contained to some extent depending on the ice concentration [5]. Ice concentrations between 5 and 7 tenths will greatly reduce oil spreading (as compared with a slick on open water), and concentrations greater than 7/10 will effectively contain oil from spreading at all. Oil among ice will become mixed among the floes by wave action and the grinding together of floe edges, and will tend to coat the exposed surfaces of the ice pieces.

Although low concentrations of ice offshore may afford little natural containment of an oil slick, the process of compaction of loose floes pressed against a shoreline through wind action will act as a buffer in temporarily preventing much of the oil from directly contacting the beach.

Oil under ice

The underside of smooth sea ice is somewhat wavy, with depressions from 2 to 10 m in diameter reflecting differences in surface snow cover. Superimposed on these containment features, linear roughness features called ridges create under-ice berms which can block oil movement or spreading for distances of kilometers or more.

Both the under-surface waviness and ridge features will prevent oil from spreading any significant distance from a seabed spill source in most cases [2,3]. Under-ice currents will not move the oil unless they exceed about 0.5 knots (an unlikely occurrence in most arctic areas). Spills under ice during fall, winter and early spring will be quickly encapsulated by the downward-growing ice. This process takes as little as one day in early winter and up to four days in March [4].

Containing spills on ice

The main technique for containing spills on ice is to use surface barriers or berms made of snow and/or ice.

Ice/snow berms

Snow can be scraped from the ice surface to form a barrier that would contain a spreading oil slick. If the ice will support heavy equipment, loaders and graders can be used to move large volumes of snow quickly. For small spills, manual shoveling is adequate.

Spraying the snow berms with water will result in an ice crust on the berm, enhancing its durability and permeability to oil. Spray-ice berms can also be constructed on ice by flooding selected areas from submersible pumps dropped through holes in the ice, a technique which is well established over several decades of building ice roads in Alaska, and Canada (Fig. 8).

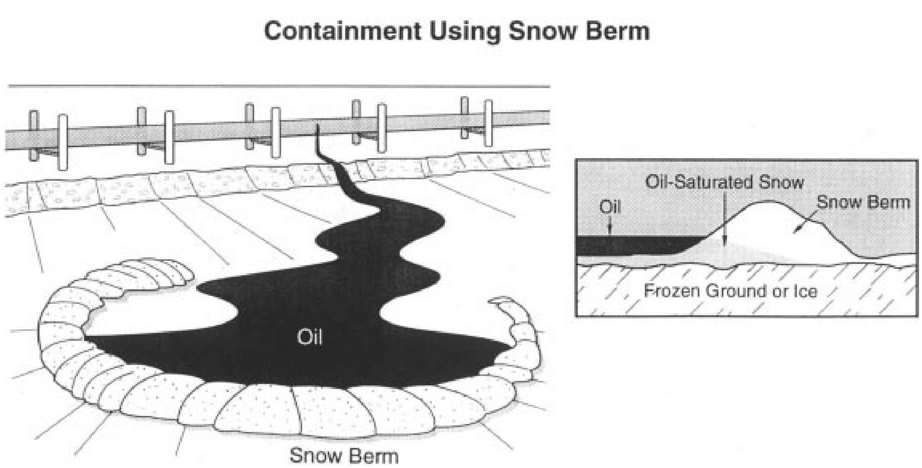

Fig. 8 Snow berm construction for winter oil spill containment [12].

Barriers

If sufficient snow is not available to construct an effective containment barrier, other materials such as sandbags, sorbent booms or any available material could be used. Water sprayed over the material will enhance its durability and impermeability to oil. In addition, conventional booms can be frozen into slots cut in the ice to provide surface and subsurface containment of oil (and ice if the location provides a stable ice cover). This technique has been used on a number of experimental spills to contain the oil for permitting purposes [3,34].

Containing spills under ice

The following subsections describe several techniques for containing oil spilled under ice. Each technique attempts to enhance the natural containment afforded by the under-ice surface by creating a sub-surface barrier or trough that will limit the movement of a spill.

Trenching

Several techniques can be used to cut holes or slots in the ice to trap or divert oil [17]. For spills under sea ice or river ice where there is a significant water current, the slot can be angled to the current direction so that oil captured in the slot will flow to a collection point [40]. For most spills under sea ice there is little or no measurable subsurface water current and there will be little lateral movement of the oil spill from the source location. In this case, cutting a trench around the spill area would be done only to provide an extra degree of insurance in containing the oil within the immediate area. For winter spills under sea ice, the most likely scenario is that holes and trenches will be cut directly through the spill area to attempt immediate recovery of oil with pumps and skimmers [19]. Fast ice in shallow water with only a few feet between the ice under surface and the seabed can be grounded through surface flooding to both remove the issue of bearing capacity and produce a dry trench for easier recovery operations.

Barriers

Depending on the volume of the spill and the under-ice water currents, it may be possible to enhance the containment capability of a trench by inserting a through–ice barrier. The barrier can be made of plywood, plastic, or even standard open-water containment boom. Stakes and floats may be required to position the barrier until such time as it is frozen in place [20].

Insulation

Insulation (natural or artificial) can be used reduce the growth of ice along a strip to create an inverse barrier to the spread of oil [2]. Insulation can be provided by piling snow into a berm along the desired path, or by placing sheets of insulating material on the ice itself. The result will be a subsurface ice cavity that will contain oil spilled within a prescribed area. An alternative method would be to use a loader or scraper to continually remove snow along the desired strip. This will increase the rate of ice growth directly below the scraped area, and create a subsurface ice berm that would also limit the spread of oil. Such measures are only required if there is concern that free oil will be swept by current action under the ice before recovery can take place.

Icebreaking

Under certain conditions, icebreaking vessels could be used to carefully break ice around a spill site in very close pack ice (9 to 9+/10) to expose trapped oil for burning. This technique would be most applicable in deeper water (icebreakers commonly require drafts in excess of 12–15 m) outside the fast ice zone where the options of: (i) waiting for the oil to appear naturally in the spring; or (ii) using the ice as a platform to support surface recovery operations, are not available.

Containing spills in broken ice

As discussed, concentrations of ice over 6/10 already provide an effective means of reducing oil spill spreading. For spills in lesser ice concentrations, additional containment may be required.

Conventional booms

Most heavy-duty containment booms can be used in light brash-ice conditions and ice concentrations up to about 3/10 (for example, Ro-boom has been deployed and towed successfully in broken ice). The forces presented by moving ice pieces will exert a greater strain on the anchoring and tensioning components, and on the boom itself. Workboats may be used to deflect large ice pieces, and to periodically submerge the boom to release accumulated ice. A high incidence of damage to the flotation chambers and skirt can be expected in ice operation.

Herding with water jets

The force of a stream of water can be used to herd oil among low to moderate concentrations of ice. Herding with water jets might be used to collect a small spill among broken ice, or to provide temporary containment while a more permanent system is deployed [20].

REMOVAL OF OIL SPILLS ON/IN/UNDER ICE

Recovering spills on ice

The techniques available to recover oil spilled on ice include direct pumping of thick pools of oil, mechanized and/or manual scraping and the use of sorbents [1,2,27,38]. Propane torches have also been used with limited results to melt oil frozen at higher elevations in ice rubble and create pools for recovery at lower levels.

Portable skimmers can also be used to recover oil spilled on ice, generally by cutting a trench or hole in the ice to contain and concentrate the oil, and deploying the skimmer in the trench or hole (see Fig. 9). See also 'Burning oil on ice'.

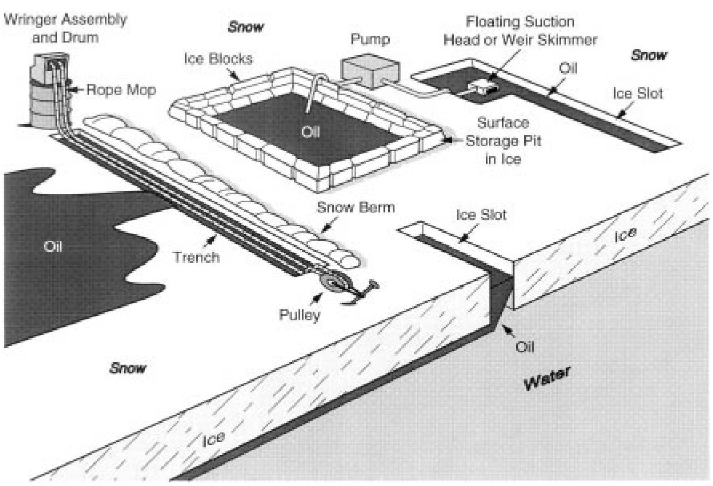

Fig. 9 Use of portable skimmers, slots and trenches with solid ice [20].

Recovering spills under ice

Regardless of the fact that oil spilled under solid ice is naturally contained within a small area and can be dealt with effectively when it surfaces in the spring, response crews will almost certainly be required to initiate recovery as soon as possible after the spill occurs. This can be accomplished by: direct pumping through holes augured into the oil pool, potentially the least effective method [2]; the deployment of skimmers in trenches cut through the ice [17,18]; or possibly the deployment of rope mop skimmers under the ice [19]. This latter technique requires that free oil be available to the rope mop, and is most applicable to spills in late winter when new ice is slow to form or does not form at all.

Where suitable heavy equipment can be brought to the site by ice road, it may be possible in the case of small spills to cut and remove all of the contaminated ice for melting and recovery onshore, leaving a residual amount for direct pumping/skimming from water surface in the resulting ice hole (Fig. 10).

Recovering spills in broken ice

The recovery of spills in broken ice involves the use of open-water skimmers deployed in the water amongst floes [16,20]. Field tests and studies in Alaska indicate that the capacities of these skimmers could be greatly reduced over their open-water performance due to a number of factors: lower oil

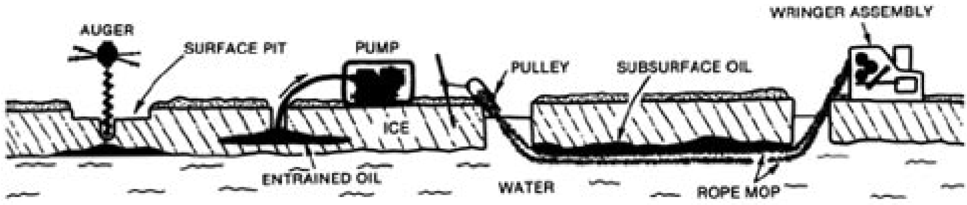

Fig. 10 Recovering spills under solid ice [source: ref. 20].

encounter rates because of limited boom effectiveness in ice; increased maneuvering and repositioning times to place the skimmer for optimum recovery among the floes; and, reduced skimmer speeds (for dynamic skimming systems). Conventional marine operations in broken ice are highly vulnerable to rapid changes in weather and ice conditions; a significant amount of downtime is likely as the drift ice converges and diverges in response to winds and currents.

The possible use of portable skimmers in broken ice, mounted on barges and vessels, is illustrated in Fig. 11.

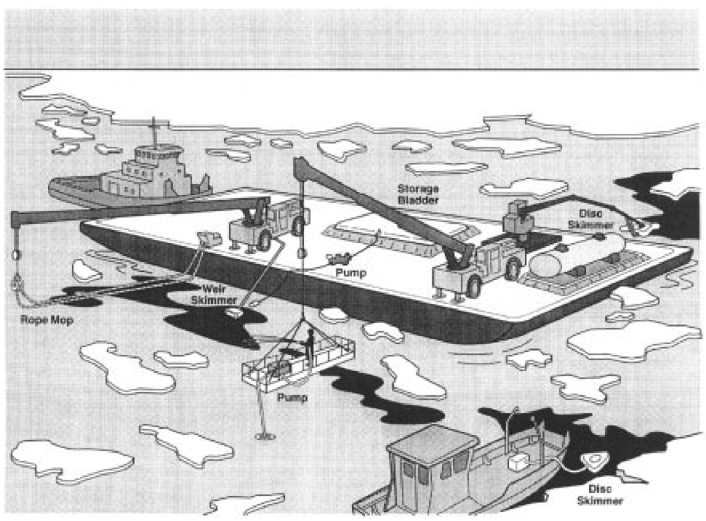

Fig. 11 Broken ice mechanical recovery [20].

Burning

In-situ burning has always been considered as a primary arctic spill countermeasure, from the start of offshore drilling in the Beaufort Sea in the mid 1970s. Field trials at that time demonstrated that on-ice burning offered the potential to remove almost all of the oil present on the surface with only minimal residue volumes left for manual recovery [3]. Since then, a great many studies and trials have been undertaken to investigate and document burning of large crude oil slicks (both fresh and emulsified) in open water, slush ice, and broken drift ice and test basins. There is too large a body of experience to summarize here, other than to quote representative efficiencies in a number of different situations [15,25,32]. Buist *et al*. [21] provides a comprehensive evaluation and review of the state of knowledge surrounding the burning of oil spills at sea.

Oil on ice

In-situ burning is the countermeasure of choice to remove oil pools (created in the spring by vertical migration from an encapsulated oil layer) on ice or between ice floes for large spills. There is a high degree of knowledge on the ignition and burning of oil spills in a variety of ice conditions. Several of the operational techniques used to ignite oil on or in ice and are described below. The efficiency of these techniques in removing oil from the environment ranges from 30 to 99%, depending on the circumstances of the spill (e.g. film thickness, degree of emulsification).

Figure 12 illustrates the Helitorch aerial ignition system which can be used to remotely ignite oil on melt pools and in thick pools between floes in high ice concentrations [26].

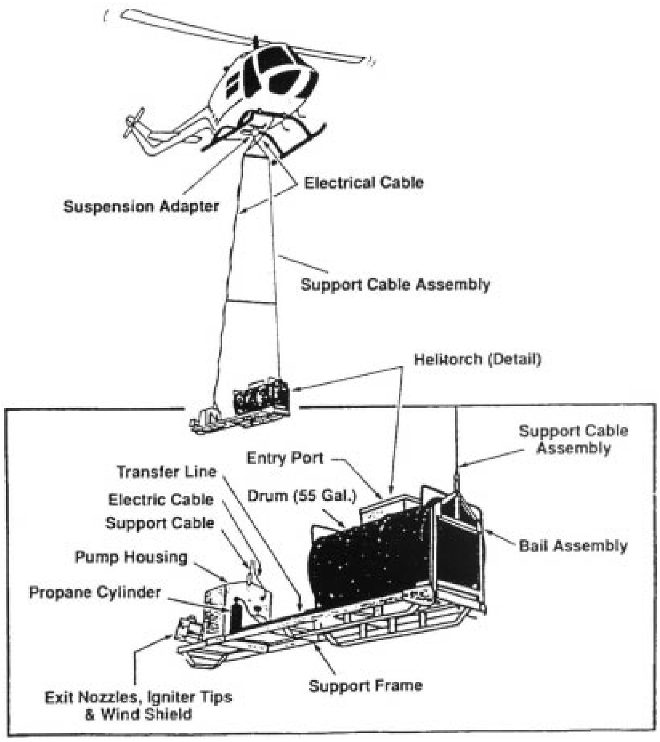

Fig. 12 Helitorch for igniting oil spills in ice and in firebooms [26].

In the case of oil initially spilled on the ice surface and mixed with snow, burning of oiled snow piles can be successfully achieved even in mid-winter conditions. Depending on the initial oil spill volume per unit area of ice, the technique of ploughing oiled snow into concentrated piles may be the only way of achieving successful ignition and burning. In many cases, waiting for the snow to melt could result in thin oil films incapable of supporting combustion and spread over a large ice area. Figure 13 illustrates the

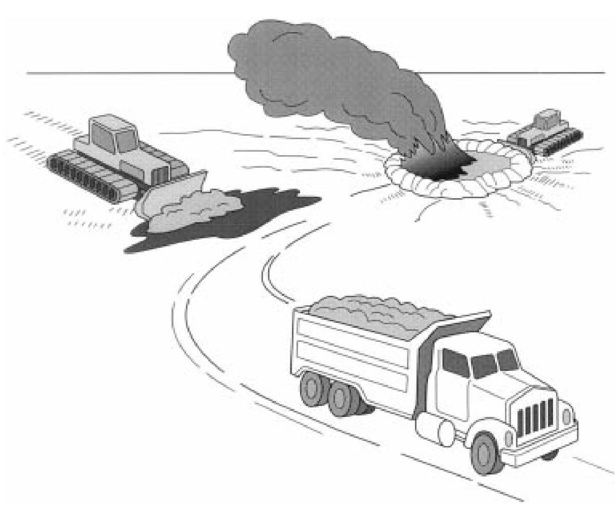

Fig. 13 Burning oiled snow on the ice surface combined with mechanical removal (where ice roads are available).

burning of oiled snow that has been scraped off the ice surface and placed into a volcano-shaped pile [12].

Oil on water among broken ice

Figure 14 illustrates the use of a fire containment boom to collect, concentrate and burn oil on water among broken ice. The use of this technique in the lee of an ice-deflecting structure (such as an artificial island) can extend its applicability to ice concentrations higher than the 3/10 value considered an upper limit for most conventional open water booms. The removal rates and limitations of *in-situ* burning at sea are covered in detail in ref. [21].

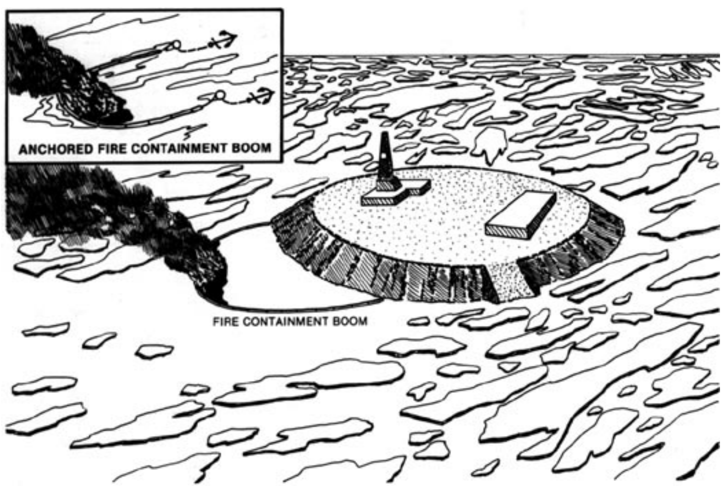

Fig. 14 Fire containment boom [source: ref. 20].

OVERVIEW OF SEASONAL RESPONSE STRATEGIES IN ICE COVERED WATERS

This section combines all of the countermeasures techniques (detection, mapping, tracking, containment and recovery) into a description of seasonal strategies for different combinations of ice and open water. The ranges of months quoted are representative of a North American arctic coastal condition but are also applicable to other arctic areas (e.g. Norway and Russia) at a similar latitude (~70°N) as well as coastal subarctic areas such as Labrador and the Bering Sea.

Fall and early winter response (October to December)

There are limited mechanical options for recovering large volumes of oil spilled under or among new and young ice in the fall months of October and November. A ‘Foxtail’ rope mop style skimmer can be deployed by crane over the side of a response barge or vessel to recover localized oil patches trapped in water and slush between floes. This is one of the few skimmers able to recover oil from leads and openings in heavy ice conditions [22,23]. In areas of heavy oil concentration near the coastline or in available open water leads, other portable skimming systems could be utilized, such as vacuum, drum and disc type skimmers. It may be possible to utilize weir type skimmers under building ice conditions for a short period as long as the skimmers are equipped with mechanical systems to handle debris and ice. Any skimming operations will likely be terminated within one to two weeks of initial freeze-up.

At the very early stages of new ice growth, many of the spill response vessels will remain operational for a short period. The jet powered vessels will become inoperative as the brash ice and slush thickens and begins to interfere with the exposed mechanical parts of the jet systems. Outboard powered vessels will also be taken out of service when the thickness of the forming ice begins to clog the water intake ports on the lower units. Screw driven vessels along with the tug and barge systems can potentially operate in about 15 cm of young ice which may amount to as little as two weeks following initial freeze-up. Fall storms can break-up the new ice sheet several times and delay by more than one month, the final date when conventional vessels must be laid up for the winter.

The most effective sustainable strategy during freeze-up conditions will likely utilize *in-situ* burning, with the ice providing natural containment and Heli-torches providing a remote ignition source. A number of tests have shown the feasibility of burning oil trapped in leads with and without the presence of brash ice and slush [5,24]. Depending on conditions, removal efficiencies over 90% were readily achieved. Weathering the oil up to 20% had no significant effect on the results.

The oiled ice may move short distances (thousands of feet) in October before becoming landfast. Oil, during this time, is effectively trapped within the ice and contained from spreading until response teams can gain access. During the early stages of freeze-up, a fringe of new landfast ice protects the shoreline from oiling.

Mid-winter response (January to March)

By late December, landfast ice is normally stable enough to support spill recovery operations in water depths out to the 10–15 m range (the seaward limit of fast ice typically occurs in 20–25 m of water). From this time until late May, the fast ice cover can provide a safe operating platform for support equipment, including trucks, bladders and portable trenching equipment to deal with nearshore spills. Depending on location, this period of on-ice operation can be extended in some years. For example, the ice cover in near shore areas can often support lightweight vehicles (with low pressure tyres) by November, and in many years the still thick ice (although deteriorated on the surface) can support substantial loads and work crews into late June. While stable winter ice allows for greater access to the spill site, severe winter arctic conditions may limit the feasibility of many countermeasures for a period of three months at least (January to March). Extreme low temperatures present a hazard to operating heavy equipment and other hydraulic systems, including helicopters. Realistic low temperature limits for most equipment are in the order of $-40\,^{\circ}C$.

In the case of a known reservoir of oil trapped within the ice sheet in mid-winter, direct pumping and ice road haul operations will result in almost complete removal of the spilled oil. In order to eliminate the final volume of contaminated ice the upper layer of clean ice can be removed prior to exposing the oil pool. Ice roads and pads can be built with spray ice to allow heavy equipment and vacuum trucks direct access to the oil pools. These trucks would recover oil directly into insulated tankers for transportation to waste disposal facilities. During extremely cold periods it may be necessary to use steam wands on the oil pools to facilitate recovery. Burning oil at the spill site (if allowed) would dramatically improve the oil removal rates. Final cleanup in June would likely use selective burning of remaining oil which may surface, followed by manual recovery of any burn residue. It is estimated that for most spills in fast ice, the remaining oil available to enter the marine environment will be less than 10% of the original spill volume.

Spring/summer response

The period between the first onset of surface snow melt (April to May depending on latitude) and the final deterioration of the landfast ice in June or July provides the best opportunity for *in-situ* burning of oil that naturally appears on the surface from a trapped winter spill, or remains on the surface following a winter cleanup operation. However, this period also marks the end of easy site access with any heavy equipment.

In-situ burning is an efficient and effective method of removing oil from a solid ice cover in late May and June, after ice roads have been closed to traffic. Tests have demonstrated that the oil on the surface of the ice can be successfully ignited and burned even after weathering for several weeks. Wind herding of the oil in small pools enables much thinner oil films to be burned than would otherwise be possible [4]. Fresh crude must be approximately 0.04 inches thick for ignition to take place, and weathered crudes in the range of 0.1–0.2 inches are readily ignitable. Weathering of the oil is not as critical as once thought. Ongoing work by SINTEF in Norway has demonstrated that it is possible to effectively burn fresh crudes with up to 25% emulsification (water in oil), albeit at a reduced efficiency [25,30]. ACS has conducted similar studies in the last few years concentrating on emulsions made of Alaskan risk oils and seawater [32]. During these studies bench testing was conducted utilizing various emulsion breakers and gelled fuel mixtures to enhance ignition of emulsions. Promising techniques from the laboratory were then re-evaluated during both small scale and meso-scale testing, producing similar results to the SINTEF studies [21].

Work in Alaska and elsewhere has proven that the Heli-torch (Fig. 12) is a highly effective tool in igniting multiple oil pools over large areas [26]. Slung beneath a helicopter, the Heli-torch is safe and efficient. Approved hand-held igniters can also be used by helicopter-transported field crews to ignite isolated pools of oil. Burning efficiencies in the order of 97% have been achieved in numerous large scale and meso-scale experiments [4].

In practical field applications, values tend to be lower because a proportion of the oil is contained in pools too small and numerous to burn, and not all of the oil is available in sufficiently thick films. As a general rule it is considered practical to burn 80% of all oil present in pools greater than 50 square feet, amounting to ≈68% of the total oil exposed on the surface using the pool size distributions shown in Table 1. Manual recovery of any burn residue or thin unburned oil films on the ice may increase the overall recovery effectiveness by up to 10%. In addition, natural evaporation can remove approximately 30% of any oil lying on surface melt pools prior to burning [4]. Realistic estimates for the amount of residual oil remaining after all cleanup and natural processes up to the point of final ice break-up range from 10 to 20% [4]. With appropriate safety precautions and a helicopter or amphibious vehicle in attendance, surface operations on the ice can continue until within a few days of break-up. The small amount of residue left after burning (typically a few percentage of the oil available for burning) can be recovered manually with crews on the ice and transported to shore with helicopter buckets.

As the ice begins to break up, the response options will depend largely on the rapidly changing ice concentrations as discussed earlier. There will be a period of several weeks when response operations will need to apply a mix of strategies at short notice as conditions allow: booms and skimmers operated from shallow draft barges in light to moderate ice, *in-situ* burning of thick oil trapped between the floes in heavier ice. As ice concentrations diminish to less than 3/10 (usually within one month of fast ice break-up) response operations will become increasingly less restricted by ice and more able to rely on traditional open water mechanical containment and recovery techniques [37].

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