Spill Response in the Arctic Offshore

Prepared for the American Petroleum Institute and the Joint Industry Programme on Oil Spill Recovery in Ice

February 2, 2012
FINAL

Authors:

Stephen Potter, Ian Buist and **Ken Trudel** - SL Ross Environmental Research Ltd.

David Dickins – DF Dickins Associates

Ed Owens – Polaris Applied Sciences

Edited by:

Debra Scholz
SEA Consulting Group

Preface

This publication has been prepared jointly by the American Petroleum Institute (API) Arctic Oil Spill task group and the Joint Industry Programme on Oil Spill Recovery in Ice (JIP).

The JIP is aimed at creating international research programmes to further enhance industry knowledge and capabilities in the area of Arctic oil spill response and to raise awareness of existing industry OSR capabilities in the Arctic region.

The JIP is sponsored by nine international oil and gas companies: BP, Chevron, ConocoPhillips, Eni, ExxonMobil, Shell, Statoil, North Caspian Operating Company, and Total making it the largest pan-Industry project dedicated to this field of research and development.

This report is intended as a compendium to describe the tools available for use by industry for response to an oil spill in the Arctic. The JIP will undertake various research projects that have been identified to improve industry capabilities and coordination in the area of Arctic oil spill response. Throughout this report, reference is made to other useful documents on specific aspects of spill response including conference proceedings and publications from organizations involved with spill response research.

This Page Intentionally Left Blank.

Table of Contents

Appendices

List of Tables

List of Figures

This Page Intentionally Left Blank.

Introduction

Recent years have seen increasing interest in offshore oil exploration in the Arctic and other frontier regions. While these activities may seem like new developments, Arctic oil exploration and in some cases production has been taking place for many years in these regions. Close to 100 wells were drilled in the Canadian Beaufort Sea and in the Canadian High Arctic in the 1970s and 1980s. Five wells were drilled in U.S. waters in the Chukchi Sea during this same period. The Cook Inlet basin has seen oil production for 50 years, and production on the Alaskan North Slope began over 30 years ago, mostly from on-land wells but also from several offshore islands in shallow water. More recently, oil and gas production commenced from fields offshore Sakhalin Island off eastern Russia and in the Pechora and Kara Seas. Further offshore exploration is ongoing or is proposed in other Arctic areas such as the Alaskan Beaufort Sea, Chukchi Sea, West Greenland, and the Barents Sea.

This report describes the tools the industry will use in the event of a spill in the Arctic. For the purposes of this document, it can be noted that conditions similar to those found in the “Arctic” involving sea ice and cold temperatures may exist for all or part of the year in such areas as Sakhalin, the Baltic Sea, the Caspian Sea, and Labrador.

Oil spill response is demanding under any circumstances, and Arctic conditions impose additional environmental and logistical challenges. At the same time, unique aspects of the Arctic environment can in some instances work to the responders’ advantage.

The first and most obvious challenge is dealing with the presence of ice. As far as the effective use of spill countermeasures is concerned, ice in its various forms can make it more difficult to detect oil, and to encounter, contain and recover oil slicks with booms, skimmers, and any vessel-related activity. On the other hand, the natural containment provided by ice may offer significant advantages. In open water, slicks can spread and drift so quickly that shoreline impacts occur before a response can be initiated. Ice, however, can contain oil spills and provide time to mount a response. As well, the cold temperatures and reduced wave energies in an ice field mean that spilled oil will weather more slowly, which will extend the window-of-opportunity for some types of countermeasures.

This report discusses some of these challenges and describes how they have been met through research, technology development and experimentation to develop effective techniques for dealing with spills. In some cases these techniques have been modified from standard response techniques developed for temperate climates, but in many cases the techniques have been specifically developed for use in the Arctic. Some of these techniques have been recently developed, but several have been the subject of research activities for over 30 years. In all cases, the techniques continue to be refined and improved in the laboratory and in the field and additional research and development is planned for coming years.

Section 1

Fate and Behaviour of Oil in Arctic Conditions

The following discussion summarizes the key processes governing the fate and behaviour of oil spilled in Arctic conditions. While many of the processes and countermeasure strategies are applicable to freshwater ice environments, the focus here is on salt-water conditions representative of the Arctic continental shelf regions (e.g., Chukchi Sea, Beaufort Sea, Barents Sea), marginal ice zones and sub-Arctic areas (e.g., the Bering Sea, Labrador Sea and Sea of Okhotsk).

Oil Spreading

On Ice and Snow

The spreading of oil on ice is similar to the spreading of oil on land. The rate of spreading is controlled mainly by the oil viscosity, so the cold temperatures will tend to slow the spreading rate. The eventual total area that is contaminated will be dictated by the surface roughness of the ice. Even smooth first-year sea ice has considerable surface roughness, and discrete ice deformation features such as rafting, rubble and pressure ridges can lead to localized increases in roughness up to tens of metres in elevation above sea level. Any oil spilled on the surface of rough ice may be completely contained in a thick pool bounded by ridge sails and ice blocks. As a result, slicks on ice tend to be much thicker and orders of magnitude smaller than equivalent slicks on water.

Figure 1 shows estimates of oil holding capacity. If ice is covered with a layer of snow, snow, snow will absorb the

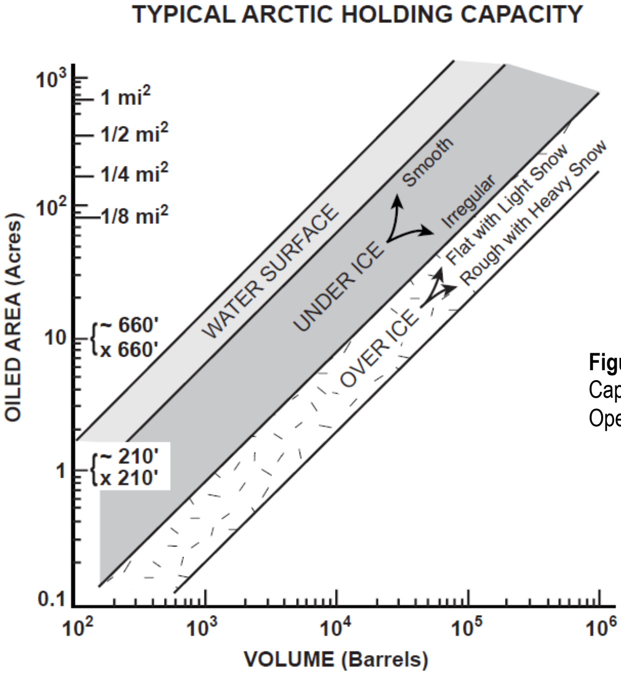


Figure 1: Typical Arctic Oil Holding Capacity (Alaska Clean Seas Operations Manual, Tactics R-14).

spilled oil, further reducing its spreading. Oil spilled onto a snow pack will flow down to the ice layer, then slowly outwards under the snow.

On Cold Water

A large number of researchers have performed experiments to investigate spreading on cold water and among pack ice. Some found that warm water oil spreading equations did not reasonably predict the results for cold, viscous oils and proposed a “viscosity correction factor” or substituting oil viscosity for water viscosity in spreading models (SL Ross and DF Dickins, 1987; Buist et al., 2009). They also noted that if the ambient water temperature approached the

Pour Point *is the temperature at which oil will cease to flow.*

POUR POINT of the oil, spreading would cease. Because of this increase in viscosity, an oil slick on cold water is usually thicker and occupies a smaller area than it otherwise would in a more temperate climate.

Spreading Under Solid Ice

A combination of analytical studies, laboratory tests, and field spills has been used to develop a better understanding of the spread of oil and natural gas under an ice sheet (Keevil and Ramseier, 1975; Chen et al., 1976; Yapa and Dasanayaka, 2006; Rytkonen et al., 1998). Laboratory tests have aided in understanding the processes involved and have produced data to define key spreading parameters. Field tests have provided information at a large scale that has helped to develop a better understanding of the expected spreading behaviour.

Even large spills of crude oil underneath solid or continuous ice cover will usually be contained within relatively short distances from the spill source (compared with the equivalent volume spilled in open water), depending on under-ice currents and ice roughness characteristics. Natural variations in first-year ice thickness, combined with deformation features such as rubble and ridging provide large natural "reservoirs" to effectively contain oil spilled underneath the ice within a relatively small area (**Figure 2**).

Spreading In Pack Ice

A number of studies have been completed on the spreading of oil in pack ice. In pack ice oil spills tend to spread far less and remain concentrated in greater thicknesses than in ice-free waters. In ice concentrations greater than 60 to 70%, the ice floes touch each other at some point and provide a high degree of natural containment (see **Figure 3**). This was first documented in a series of experimental spills off the coast of Cape Breton in 1986 (SL Ross and DF Dickins, 1987). As the concentration of the ice floes diminishes, the potential for oil spreading among the more

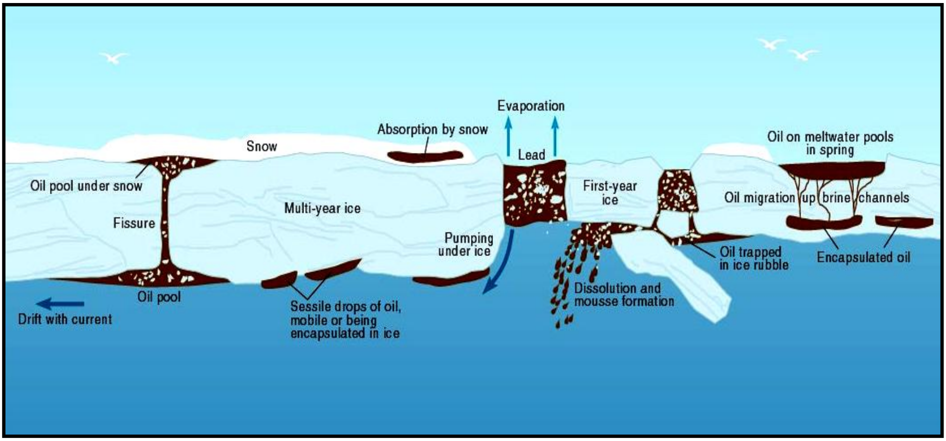


Figure 2: Illustration of oil and ice processes (adapted from A.A. Allen)

Figure 3: Close pack ice would provide natural containment of spilled oil (D. F. Dickins)

separated floes gradually increases until it approaches an open water state in very open drift ice (30% and less).

During an experimental spill in 1989, 30m^3 of North Sea crude oil was released on open water in the Norwegian Sea. After 10 hours of spreading, the oil formed an elongated slick with a sheen “tail” up to 13 km long. The thickest portion of the slick measured 2km by 50m (100,000 m^2). Then in 1993, another experimental spill involving 26 m^3 of the same oil was conducted in the Barents Sea marginal ice zone off the coast of Norway (Singsaas et al., 1994; Reed and Aamo, 1994; Jensen, 1994). Ten hours after the release this oil slick occupied an area of about 100m^2.

Following these initial tests, it was concluded that high concentrations of pack ice (90% initially, declining to 70% at the end of the experiment) during the field experiment in 1993 significantly reduced the spreading of the slick and kept it immobile for an extended period of time (days) which, in combination with cold temperatures and the dampening of wave action by the ice, significantly slowed the oil weathering processes. The reduced spreading rates, thicker slicks, and decrease in weathering processes associated with spills in close pack ice were also documented in detail in a series of experimental spills in the Norwegian Barents Sea in 2009 (Sørstrøm et al., 2010).

Oil Movement

Spills on and under sea ice will generally not move independently of the ice, but will remain in the vicinity of the initial contact area; if the ice is drifting, the oil will drift with it. Experiments have shown that the currents required to move oil along the undersurface of ice will range from about 5 cm/s with smooth freshwater ice to 15 to 30 cm/s (0.3 to 0.6 knots) under typical sea ice (Buist et al., 2008). Winter under-ice currents in most Arctic areas are not sufficient to move spilled oil beyond the initial point of contact with the ice under surface. Exceptions may be in fiord-like areas with strong tidal currents or close to the fronts of major deltas such as the Colville, Mackenzie, and Lena river systems. Even then, the under-ice roughness is generally sufficient to restrict any large-scale spreading or movement.

The Buist et al., (2008) study showed that oil spilled within pack ice will generally move with the ice. In open drift ice, the oil and ice may move at different rates and directions under the variable influence of winds and currents. See further discussion of this topic in Modelling of Potential Oiled Ice Motion under ***Section 2 - Response Options: Monitoring and Detection.***

The presence of ice and low water temperatures reduces the rate of spreading and drifting of spilled oil. Evaporative and emulsification processes will also be reduced in ice-infested waters. Similarly, land fast ice will keep offshore oil from impacting shorelines from freeze-up to break-up, up to 9 months in many areas. As a result of these influences, individually and combined, the time available for an effective response, referred to as the window-of-opportunity, can be greater in Arctic conditions.

Oil Under First Year Sea Ice

For a release of oil beneath growing sea ice, new ice will completely encapsulate the oil layer within a few hours to a few days as the ice continues to grow downwards (i.e., thickens), depending on the time of year. Encapsulation has been observed in laboratory and field experiments when the air temperature was sufficient to promote ice growth. However, oil spilled under the ice after May in the Arctic, or after April in sub-Arctic regions, may not become encapsulated due to insufficient new ice growth.

After the oil has spread under the ice and been encapsulated, it will remain trapped until the ice layer under which the oil has been encapsulated begins to experience spring thaw. 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. As ice temperatures gradually increase, brine trapped between the sea ice crystals begins to drain leaving vertical channels for the oil to eventually rise to the surface (see **Figure 2**). Oil appearance on the ice surface has been observed as early as late May in experimental spills off the Beaufort Sea coast (Dickins and Buist, 1981). In sub-Arctic areas such as Labrador, this process will be advanced by roughly one month depending on air temperatures.

The rate of oil migration increases rapidly once daily air temperatures remain consistently above freezing. During one series of field experiments, up to 50 percent of the oil originally trapped within the ice became exposed on the ice surface between June 10 and June 20 (Dickins and Buist, 1981). Oil slick thickness in the melt pools on the surface increased from 1 mm to over 10 mm during a one-week period. Once the oil reaches the ice surface, it floats on 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 melt pools. As will be discussed later in ***Section 3 - In-Situ Burning***, the appearance of oil in melt pools prior to the disintegration of the ice sheet provides a good opportunity for removal of the oil by burning.

__Ablation__ is the natural melt of snow and ice from an ice surface downwards through various processes, including evaporation, temperature increase, and wind erosion.

Ablation can refer either to the process of removing ice and snow or to the quantity of ice and snow removed.

Natural melt of the ice from the surface down (called **ABLATION**) acts as another process to expose encapsulated oil. When ablation reaches the level where the ice was growing at the time of the spill, the oil is then exposed. In situations involving a thick layer of low-viscosity oil in the ice, natural migration through brine channels will bring most of the oil to the surface before the surface undergoes ablation. In the course of field experiments, low-viscosity oils have been observed to have undergone little additional weathering since their initial encapsulation. Conversely, the renewed exposure of encapsulated viscous oils (e.g., fuel oils and emulsions) will more likely occur through the process of ablation.

The exposure of oil on the ice surface through migration was also observed in field experiments in 2006 on Svalbard

(Dickins et al., 2008). The results from this experiment compare well with the Beaufort Sea experiments of 1979/80 described above. For example, oil from the first spill in December 1979 rose through a similar ice thickness (60 to 70 cm) to reach 100% exposure on the ice surface in approximately 40 days. Like the earlier Beaufort Sea experiments (**Figure 4**), the oil appeared on the ice surface well before breakup, thereby allowing time for effective countermeasures.

Figure 4: Oil appearance in melt pools during spring melt (Balaena Bay experimental spill 1974/75, Norcor/D.F. Dickins)

Oil Spilled Under Multi-year Ice

Oil spilled under old ice (either second-year ice or multi-year ice) will be retained by under-ice roughness features, as it would be under first-year ice. The under-ice oil storage capacity of old ice appears to be greater than smooth first-year ice, and could lead to very thick individual pools of oil: thicknesses up to 19 cm have been measured in the field (Comfort and Purves, 1982). As is the case with oil encapsulated under first-year ice, the oil encapsulated in old ice would not weather significantly.

With the much lower salinity of multi-year ice, there are fewer and smaller brine channels present so the trapped oil will migrate much more slowly. Oil spilled under multi-year ice may appear on melt pools at the surface, but this is likely to be much later in the melt season than for first-year ice. The behaviour of oil under old ice was studied in a single field project in the Canadian High Arctic (Comfort and Purves, 1982). Three pools of crude oil were placed under what was thought to be old ice 2.5 to 2.9 m thick on June 1, 1978. Oil first appeared on the surface by late August of the same year, and 90% to 99% of the oil originally placed under the old ice had surfaced by September of the following year. These results may not be truly representative of likely behaviour under multi-year ice (older than 2 years) as the test ice sheet was relatively thin and may have been second-year ice.

Effects of Winter Conditions on Oil Weathering

The main oil weathering processes include evaporation, emulsification, natural dispersion, dissolution and biodegradation. In general terms, the combination of cold temperatures, and reduced wave energy due to the presence of ice results in a reduced rate of weathering and an extended window-of-opportunity for effective response (Sørstrøm et al., 2010).

Evaporation

Evaporation *is the preferential transfer of light- and medium-weight components of the oil from the liquid phase to the vapor phase.*

EVAPORATION typically plays a significant role in the natural weathering of spilled oil and oil products. Following a discharge, most crude oils and light products (e.g., diesel, gasoline) undergo significant evaporation relative to heavier more viscous oils (bunker fuel oils and emulsified oils). However, oil spilled in sub-freezing temperatures evaporates more slowly than oil at higher temperatures. Furthermore, oil spills covered with snow exhibit even lower evaporation rates.

Numerous experiments in laboratories and in the field have shown that oil spilled in pack ice will evaporate more slowly than an equivalent spill on open water, primarily due to the greater thickness of the oil in pack ice.

An important oil property change that may take place with oil spilled on ice in winter is the gelling of the oil as it cools and evaporates, resulting from the precipitation of dissolved waxes in the oil. Oils that may be fluid in warmer temperatures can gel when the ambient temperature falls below their pour point. The pour point of oil will also increase as the oil loses light ends to evaporation. Gelled oil will evaporate very slowly, and may develop a non-sticky, waxy surface coating.

Oil encapsulated in an ice sheet will undergo virtually no evaporation during winter months (Dickins and Buist, 1981). When it is once again exposed on the ice surface during the spring melt, the oil will be in a nearly fresh state, at which time evaporation will begin as the oil floats on melt pools. Oil on melt pools tends to be herded by the wind against the edge of the pools to a thickness of several millimetres. The resulting thick oil layer will evaporate more slowly than the much thinner slicks typical of open water conditions.

Emulsification and Natural Dispersion

The formation of water-in-oil **EMULSIONS** (also known as “mousse”) and the natural dispersion of oil slicks into the water column are processes driven by wind and wave action causing a mixing of oil and water. As such, these weathering processes are much less prevalent in ice, except at an ice field’s open-water edge, or under conditions in which moving ice floes may add surface turbulence. Wind waves (as opposed to swell) are effectively damped by the presence of pack ice. Emulsification has been observed

***Emulsification** is the process of mixing water droplets into the spilled oil forming highly viscous mixtures that have reduced weathering capabilities and are usually more difficult to burn, disperse and mechanically recover.*

with oil in slush ice and pancakes in the laboratory when wave action is forced into the simulated ice field; it has not been observed to any great extent in field trials in ice or actual spills in ice, except when the ice field was dissipating and exposed to wind-generated waves.

Natural Dispersion *is the process of breaking waves forcing oil droplets into the water column, which can result in at least a portion of the droplets small enough to remain in the water.*

NATURAL DISPERSION of oil slicks is similarly unlikely in freeze-up ice conditions. The rocking action of larger ice floes or pancakes may temporarily disperse some oil into the water column around their edges, but, in most cases, the large majority of the oil droplets created are likely be too large to be permanently dispersed and will rise up to either re-coalesce with the surface oil or be deposited on the underside of the floe or pancake.

Dissolution

Dissolution *is the process where water-soluble compounds in a surface oil slick dissolve into the water column below.*

Crude oil contains a small amount of water-soluble compounds which may dissolve into the surrounding water. Components that undergo **DISSOLUTION** in sea water are the light aromatic hydrocarbons compounds which are also those first to be lost through evaporation, a process which is 10 -100 times faster than dissolution. Therefore dissolution is a relatively minor weathering process and would be relevant mostly for fresh oil finely dispersed in the water column. Dissolution rates in cold water are lower than those in warmer climates.

Once the oil is encapsulated in ice, a very small portion of the water-soluble components of the oil could diffuse down to the bottom of the ice sheet, but concentrations at the bottom of the ice will likely be very low (Faksness et al., 2011).

Biodegradation

Biodegradation *is the process where naturally occurring bacteria and other micro-organisms consume hydrocarbons to use as a food source.*

Oil discharged into the marine environment is also subject to **BIODEGRADATION**, the chemical dissolution of materials by bacteria or other biological means. Organic material like oil can be degraded aerobically with oxygen, or anaerobically, without oxygen. The biodegradation process reduces the adverse effects of the oil to the receiving environment by removing the hydrocarbons and also by degrading the more soluble components, which tend to be more toxic, first.

Petroleum is a complex mixture of many different types of chemical components primarily consisting of Carbon, Hydrogen, Oxygen and Sulphur. Interestingly these elements represent four out of the six principal elements, or chemical building blocks of living systems (Nitrogen and Phosphorus being relatively rare in petroleum). Carbon represents an average of about 85% of the petroleum by weight. Naturally occurring bacteria can utilize these elements as a “food source”. Hydrocarbon-degrading microorganisms have been found in almost all ecosystems (Margesin and Schinner, 2001; Prince and Clark, 2004). Biodegradation of hydrocarbons by microbial populations in the natural environment depends upon physical, chemical, and biological factors such as the composition, state, and concentration of the oil or hydrocarbons. Dispersion enhances the rate of biodegradation by increasing the surface area available for microbial attack and diluting the oil to the point that oxygen and available nutrients aren’t exhausted (Lee et al., 2011b).

Large quantities of naturally occurring bacteria are present even in pristine environments. Microbes respond to introduced petroleum compounds by rapidly increasing their overall abundance to degrade oil. There are natural indigenous microbial organisms that live not only within the cold Arctic waters but also those that live in the highly saline environments associated with sea ice brine channels. McFarlin et al. (2011a; 2011b) studied biodegradation of crude oil under Arctic conditions using indigenous microbes collected from the Beaufort and Chukchi Seas. Biodegradation of Alaska North Slope (ANS) crude was significant in all treatments at -1 to 2°C, and dispersants enhanced it. Other recent studies under low temperature conditions, including ice infested waters and in the deep ocean (Hazen et al., 2010; Lee et al, 2011a; 2011b), have also shown significant oil biodegradation.

Another source of information on oil behaviour in the marine environment is from the study of natural hydrocarbon seeps. Crude oil and gas are released into all of the world's oceans from natural seeps fed by underground reservoirs of oil. Natural seeps have occurred for millions of years (Ocean Studies Board, 2003). 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). Prominent geologists believe that natural oil seeps are the largest source of oil entering the oceans (Kvenvolden and Cooper, 2003) contributing annually between 4 and 14 million barrels.

A recent study of natural oil seeps offshore Santa Barbara, California, found that sediments down-current of the seep were saturated by hydrocarbons (Farwell et al., 2009). Estimates in this area alone are that natural seeps have deposited between 5 and 55 times the amount of oil spilled from the 2002 *Prestige* incident. Importantly, the researchers found that the oil had been substantially biodegraded even before it reached the sediment.

Processes Affecting Encapsulated Oil During Thaw Conditions

When an ice sheet deteriorates and breaks up, oil remaining in melt pools on the surface will be discharged onto the water in the form of thin sheens trailing from the drifting, rotting ice. Gelled oil could be discharged as thicker, non-spreading mats or droplets. Once exposed to significant wave action, fluid oil will begin to emulsify and/or naturally disperse. Since gelled oil forms are particularly resistant to emulsification and natural dispersion, these will survive much longer than slicks of fluid oil. However, sunlight will warm the gelled oil to a temperature above ambient and may result in the oil becoming fluid again. Once fluid, the oil will be subjected to potential emulsification, greater evaporation, and natural dispersion.

Oil spilled directly onto pack ice conditions in spring will weather much as it does in open-water conditions. Oil released under drifting floes will quickly surface through the porous ice and begin to evaporate. The floes themselves are rapidly decaying under the influence of wind and waves, and may release the oil as they deteriorate. The absence of large amounts of brash and slush ice between melting floes in spring conditions will permit the slicks to spread and evaporate more quickly than during freeze-up. Warmer spring temperatures will also accelerate evaporation. Once waves begin to act on the slicks, emulsification and natural dispersion will commence.

Summary Points

- How oil spilled in ice and snow behaves has been researched in the United States, Canada and Norway for the past forty years in numerous studies in the laboratory, in test tanks and in field experiments.
- The presence of ice and the cold temperatures can greatly reduce the spreading and weathering of spilled oil.
- Biodegradation, the breakdown of hydrocarbons by bacteria, occurs in all marine environments, and is a natural mechanism that reduces the adverse effects of oil discharges to the receiving environment. Biodegradation is enhanced if oil is dispersed in the water column in the form of droplets.
- Oil that is encapsulated in ice during freeze-up is typically returned to the surface during spring thaw through the processes of ablation or migration. Because this oil is found in the same state of weathering as before encapsulation, it is possible to remove this oil by in situ burning.

- Encapsulated oil released to water as a result of spring thaw conditions will act much as oil spilled in open-water conditions.

Further Reading

AMAP Arctic Oil and Gas 2007. 2007. **Report to the Arctic Monitoring and Assessment Programme (AMAP),** P.O. Box 8100, Dep., N-0032 Oslo, Norway (www.amap.no).

Bobra, A.M. and M.F. Fingas. 1986. **The Behavior and Fate of Arctic Oil Spills**. *Water Science Technology*, 18(2): 13-23.

Buist, I., R. Belore, D. Dickins, A. Guarino, D. Hackenberg and Z. Wang. 2009. **Empirical weathering properties of oil in ice and snow**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical* Seminar No.32, Vol. 1, pp. 67-107. Environment Canada, Ottawa, Canada.

Chen, E.C., B.E. Keevil, and R.O. Ramseier. 1976. **Behaviour of crude oil under fresh-water ice**. *Journal of Canadian Petroleum Technology*.

Comfort, G. and W. Purves. 1982. **The behaviour of crude oil spilled under multi-year ice**. Environmental Protection Service Report EPS 4-EC-82-4. Environment Canada. Ottawa, Canada.

Dickins D.F., P.J. Brandvik, J. Bradford, L-G Faksness, L. Liberty and R. Daniloff. **Svalbard 2006 experimental oil spill under ice: remote sensing, oil weathering under Arctic conditions and assessment of oil removal by in-situ burning**. In: *Proceedings 2008 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA.

Dickins, D.F. and I.A. Buist. 1981**. Oil and Gas Under Sea Ice Study: Vols. 1&2**. Prepared by Dome Petroleum Ltd. for COOSRA, Report CV-1, Calgary, AB, Canada (also published In: *Proceedings 1981 International Oil Spill Conference*, Atlanta GA, USA.

Faksness, L-G., Brandvik, P.J., Daae, R.L., Leirvik, F., and Børseth, J.F. 2011. **Large-scale Oil-in-ice Experiment in the Barents Sea: Monitoring of oil in water and MetOcean interactions**. *Marine Pollution Bulletin,* 62 (2011): 976-984.

Farwell, C., C.M. Reddy, E. Peacock, R.K. Nelson, L. Washburn and D.L. Valentine. 2009. **Weathering and the Fallout Plume of Heavy Oil from Strong Petroleum Seeps Near Coal Oil Point, CA**. *Environmental Science Technology*, 43 (10): 3542.

Fingas, M.F. and B.P. Hollebone. 2002. **Behavior of oil in freezing environments: A literature review**. In: *Proceedings Arctic and Marine Oilspill Program* (AMOP) *Technical Seminar*. No. 25, Vol. 2, pp. 1191-1205. Environment Canada, Ottawa, Canada.

Hazen, T.C., E.A. Dubinsky, T.Z. DeSantis, G.L. Andersen, Y.M. Piceno, N. Singh, J.K. Jansson, A. Probst, S.E. Borglin, J.L. Fortney, W.T. Stringfellow, M. Bill, M.E. Conrad, L.M. Tom, K.L. Chavarria, R. Alusi, R. Lamendella, D.C. Joyner, C. Spier, J. Baelum, M. Auer, M.L. Zemla, R. Chakraborty, E.L. Sonnenthal, P. D’haeseleer, H. Ying, N. Holman, S. Osman, Z. Lu, J.D.V. Nostrand, Y. Deng, J. Zhou and O.U. Mason. 2010. **Deep-sea oil plume enriches indigenous oil-degrading bacteria**. *Science,* 330: 204-208.

Jensen, H. 1994. **1993 Norwegian experimental spill**. In: *Proceedings Conference on Oil Spill Response in Broken Ice*. DF Dickins Associates, La Jolla, CA, USA.

Keevil, B. and R. Ramseier. 1975. **Behavior of oil spilled under floating ice**. In: *Proceedings of the Conference on Prevention and Control of Pollution*. American Petroleum Institute. Washington, DC, USA

Kenvolden, K.A. and C.K. Cooper. 2003. **Natural seepage of crude oil into the marine environment**. *GeoMarine Letters,* v. 23, pp. 140-146.

Lee, K., Z. Li, B. Robinson, P.E. Kepkay, M. Blouin and B. Doyon. 2011a. **Field trials of in-situ oil spill countermeasures in ice-infested waters**. In: *Proceedings of the 2011 International Oil Spill Conference,* Portland, OR, USA.

Lee, K., T. Nedwed and R.C. Prince. 2011b. **Lab tests on the biodegradation rates of chemically dispersed oil must consider natural dilution**. In: *Proceedings of the 2011 International Oil Spill Conference*, Portland, OR, USA. 12 pp.

Margesin, R. and F. Schinner. 2001. **Biodegradation and bioremediation of hydrocarbons in extreme environments**. *Applied Microbiology and Biotechnology*, 56:650-663.

McFarlin, K.M., M.B. Leigh and R. Perkins. 2011a. **Indigenous Microorganisms Degrade Oil in Arctic Seawater** (Poster). In: *Proceedings of the 2011 International Oil Spill Conference*, Portland, OR, USA. 1 pp.

McFarlin, K.M., R.A. Perkins, W.W. Gardiner and J.D. Word. 2011b. **Evaluating the biodegradability and effects of dispersed oil using arctic test species and conditions: Phase 2 activities**. In: *Proceedings of the 34th Arctic and Marine Oilspill Program (AMOP) Technical Seminar on Environmental Contamination and Response*. Calgary, AB. Environment Canada, Ottawa, Ontario, Canada.

Norcor Engineering and Research Ltd. 1975. **The Interaction of Crude Oil with Arctic Sea Ice**. Prepared for the Department of Environment, Beaufort Sea Technical Report No. 27, Victoria, BC, Canada.

Ocean Studies Board and Marine Board. 2003. **Oil in the Sea III: Inputs, Fates and Effects**. National Research Council of the National Academies. National Academies Press, Washington DC, USA.

Prince, R.C. and J.R. Clark. 2004. **Bioremediation of marine oil spills.** In: *Studies in Surface Science and Catalysis*. Chapter 18, pp. 495–512, Elsevier B.V.

Reed, M. and O.M. Aamo. 1994. **Real Time Spill Forecasting During MIZ’93**. In: *Proceedings of the Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 17, Vol. 2, pp. 785-797. Environment Canada, Ottawa, Canada.

Rytkonen, J., S. Liukkonen and T. Riipi. 1998. **Laboratory tests of oil spreading under the ice cover**. In: *Proceedings International Conference on Oil and Hydrocarbon*

Spills: Modeling, Analysis and Control. Southampton, UK. pp. 155-164.

S.L. Ross Environmental Research Limited and D.F. Dickins Associates Limited. 1987. **Field research spills to investigate the physical and chemical fate of oil in pack ice**. Environmental Studies Research Funds. Report No. 062. ESRF, Calgary.

Singsaas, I., Brandvik, P.J., Daling, P.S., Reed, M. and Lewis, A. 1994. **Fate and behaviour of oils spilled in the presence of ice - A comparison of the results from recent laboratory, meso-scale flume and field tests**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 17, Vol. 1, pp. 355-370. Environment Canada, Ottawa, Canada.

Sørstrøm, S.E., P.J. Brandvik, I. Buist, P. Daling, D. Dickins, L-G. Faksness, S. Potter, J. Fritt Rasmussen and I. Singsaas. 2010. **Joint industry program on oil spill contingency for Arctic and ice-covered waters: summary report**. SINTEF report A14181. SINTEF. Trondheim, Norway. www.sintef.no/Projectweb/JIP-Oil-In-Ice/Publications/.

Wilkinson J.P, B. Wadhams and N.E. Hughes. 2007. **A new technique to determine the spread of oil spill under fast ice**. In: *Proceedings 19th International Port and Oceans Engineering Under Arctic Conditions*. Vol. 2, pp. 855-867.

Yapa, P. and Dasanayaka, L. 2006. **State-of-the-art review of modelling oil transport and spreading in ice covered waters**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar* No. 29, Vol. 2, pp. 893-909. Environment Canada, Ottawa, Canada.

Section 2

Response Options: Monitoring/Detection/Tracking

Detection, monitoring, and tracking of oil are key needs for the appropriate allocation of resources during an oil spill response. Information from detection and monitoring on the location of oil identifies targets for immediate application of response technologies. Forecasting the future movement of spilled oil allows responders to adjust response plans for site specific factors, adapt to weather windows that may temporarily restrict operations, and to identify resources at risk so that appropriate protective measures can be applied. This section focuses on the potential for current and developing technologies to detect oil, map the boundaries of contaminated areas, and track the movement of oil in a range of oil and ice scenarios. The presence of ice can both facilitate and complicate the tasks of monitoring, detecting, and tracking oil. Broken ice often forms a natural containment that slows down the spreading of oil on the sea surface. The rough surfaces of pack ice also tend to localize spilled oil to a relatively small area. By slowing the movement of oil and restricting its spreading, the presence of ice reduces to some extent demands for frequent updates of sensor measurements. Oil located under ice or under snow may present a challenge for remote sensing and oil-ice interactions complicate the task of numerical modeling of oil transport. Given the limited real-life experiences in detecting actual spills in ice, assessments of individual remote sensing system capabilities draw where possible on the much broader range of experiences with remote sensing of spills in open water.

Much of the early research on spill detection in ice took place over an intensive ten-year period beginning in the late 1970s, largely in response to active Arctic offshore drilling programs in the Canadian Beaufort Sea. Researchers carried out analytical, bench tests, basin tests, and field trials with a wide range of sensor types in an effort to solve the oil-in-ice detection problem (Dickins, 2000; Brown, 2008; Goodman, 2008). Detection technologies tested include acoustics, radar, ultraviolet (UV) fluorescence, viewing trapped oil under UV light from a bare ice surface, infrared (IR) (including active heating with a laser), gamma ray, microwave radiometer, gas sniffers, trained dogs, and ground penetrating radar (GPR).

Following the demise of Arctic exploration drilling in the late 1980s, little new progress was made towards developing operational oil in ice sensors until 2004. At that time, a series of projects sponsored by the former US Minerals Management Service (MMS) and the oil industry in Canada, the U.S., and Norway began to evaluate and test next-generation GPR, acoustics (sonar), gas detectors, and Nuclear Magnetic Resonance (NMR). Research on these technologies is continuing along with the development of new observational platforms such as unmanned air vehicles and autonomous underwater vehicles.

Experience gained from research in this area indicates that no single sensor system meets all needs for oil detection, tracking, and monitoring in ice environments and that a flexible response strategy will require a combination of airborne, satellite-based, and surface-based technologies.

Current Technologies

Side Looking Airborne Radar (SLAR), Synthetic Aperture Radar (SAR) and IR cameras and sensors are proven remote detection technologies. The SINTEF Joint Industry Project (JIP) field experiments in 2008 and 2009 provided an opportunity to evaluate these technologies within the bounds of a specific scenario involving small, contained spills between floes in close pack ice (Sørstrøm et al., 2010). Airborne Laser Fluorosensors (ALFS) are unique in their ability to identify the presence of oil (Goodman, 2008), but airborne systems are not widely available due to their requirement for highly specialized aircraft.

The state of the art and Arctic applicability – both estimated and proven – for different sensors are summarized here according to the platform and detection technology being used.

Airborne Remote Sensing

The use of airborne remote sensing technologies, augmented by visual data collected by trained observers is the most effective method for identifying the presence of oil on water (Andersen et al., 2010). In principle, many of the existing airborne sensors can detect and map oil among ice in some situations, but their capabilities in these conditions have not been field tested.

Figure 5: Airborne surveillance aircraft with multiple sensors (Government of Canada)

Some governments operate surveillance aircraft with multiple on-board remote sensing technologies, among them Canada, Sweden, and Iceland (**Figure 5**) that is representative of the state of the art in marine surveillance aircraft currently available anywhere in the world. The current generation of airborne systems is considered likely to have a high potential for detecting and mapping large spills in very open drift ice conditions and limited potential in close to very close pack ice. Many non-radar sensors are blocked by darkness, cloud, fog, and precipitation; however, radar sensors are not affected by these conditions. Infrared technology is currently used widely for sensing oil spills. IR deployed from aircraft is inexpensive, widely available, and is capable of detecting oil on the water surface. However, IR detection is not unique in that false targets, such as seaweed and shorelines, can interfere (Fingas and Brown, 2011).

***Synthetic-Aperture Radar** (SAR) is a form of radar that provides distinctive long-term coherent-signal variations that provide finer spatial resolution than is possible with conventional beam-scanning means. SAR originated as an advanced form of side-looking airborne radar (SLAR).*

Satellite Radar Systems

The area where the greatest advances in Arctic ice and marine surveillance technology have been made over the past 20 years involves all-weather **SYNTHETIC APERTURE RADAR** (SAR) satellite systems, which are unaffected by darkness or cloud cover. The latest generation of platforms launched since late 2007 are able to detect surface features down to approximately 1 metre. The capabilities of these new satellites in being able to assist with Arctic spill response are still not fully understood but it is thought that the demonstrated capability of SAR to detect and map large slicks at sea under moderate wind conditions should also apply to well-defined slicks spreading among very open pack ice. The first generation of SAR satellites monitored and mapped large slicks at sea during the *Nakodka*, *Sea Empress* and *Prestige* incidents (Hodgins et al., 1996; Lunel et al., 1997).

The main value of satellite radar imagery is likely in its ability to document the changing ice conditions in the vicinity of the spill, providing a valuable tactical planning tool for deploying vessels and recovery systems more safely and effectively. Satellite radar has the very important advantages that it can be used in darkness and foul weather and for searching very large areas. Although radar detection of oil on the water is not unique, as other phenomena can contribute to damping capillary waves on the water surface, it can serve to identify areas that may need to be investigated with more specific technologies. It may be possible to use SAR satellite imagery to detect and map slicks in the presence of ice, given the right combination of circumstances: floe size, ice concentration, slick dimensions, and wind speed.

Surface Systems

This section describes detection systems that may be deployed either from the surface of the water, by vessel, or from the surface of the ice. **GROUND-PENETRATING RADAR** (GPR) is a technology that can be deployed on the ice surface and from aircraft platforms. A series of tank tests and field experiments demonstrated that surface-based GPR could detect the presence of oil films of 1-3cm thickness both under ice and trapped as layers within the ice. (Dickins et al., 2005). This latter capability was successfully tested in an experimental spill on fjord ice in

Ground-Penetrating Radar *(GPR) is a form of radar s a geophysical method that uses radar pulses to image the subsurface. GPR can be used in a variety of media, including rock, soil, ice, fresh water, pavements and structures. It can detect objects, changes in material, and voids and cracks.*

Svalbard, April 2008 as part of the SINTEF JIP. The average oil thickness of 2cm was covered in a layer of hard-packed snow 5 to 20cm deep (Bradford et al., 2010). A commercially available radar unit was used, suspended beneath a helicopter (**Figure 6**) and flown over the test site at forward speeds up to 20 knots and altitudes up to 20m. Results from the testing indicate that readily available, commercial GPR systems can be used effectively in an airborne mode to detect crude oil spills within or under snow, and from the surface to detect oil spilled under ice. However, researchers in this area emphasize that the GPR response from oil containing systems is non-unique and that successful detection requires careful interpretation. (Bradford and Dickins, 2008). Work is underway to expand the capabilities of airborne GPR in these applications.

Figure 6: Airborne surveillance aircraft with multiple sensors (D. F. Dickins)

Low-cost, non-cooled, hand-held IR systems can detect oil under certain conditions, as demonstrated by a collection of images obtained from the vessel and helicopter in the SINTEF JIP (2009) field experiments. These experiments confirmed prior tests that distinguished slightly warmer oil from cold water and ice during an offshore spill in pack ice in 1993. In the 2009 tests, during daytime, the IR sensor was able to distinguish between oil, ice-free water, snow, and clean ice floes. These tests found that performance of hand held IR systems is more reliable during daylight and in the absence of fog.

Side-Looking Airborne Radar *(SLAR) is the first airborne (aircraft or satellite) radar system develop that uses a radar beam transmitted from the side of an aircraft for data acquisition; SLAR can be used either day or night and through cloud-covered areas.*

Global Positioning System *(GPS) is a satellite-based navigation system made up of a network of 24 satellites placed into orbit by the U.S. Department of Defense.*

Integrated Systems

The combination of multiple sensors combined with advanced navigation technologies can provide valuable tools for oil spill detection as well as for other applications such as marine search and rescue. An early effort (Looström, 1983) integrated **SLAR**, visual-light cameras, IR/UV scanners, and a navigational computer on an aircraft platform to produce geographically indexed images for spill surveillance. Modern systems employ advanced **GLOBAL POSITIONING SYSTEMS** (GPS) technologies that combine motion and position information from the navigation instrumentation on a vessel with advanced long range IR and digital video cameras equipped with internal orientation sensors. This combination of technologies provides such systems the capability to map the location of recorded images on an electronic chart system (see http://www.aptomar.com/technology/the-securus-system). Aircraft platforms have been developed that can access a wide range of sensors, with images providing data directly into geographic information systems (SSC, 2011).

Trained Dogs

The training and field assessment of dogs in detecting oil in snow and on ice was a highly successful part of the SINTEF JIP remote sensing program (Brandvik and Buvik, 2009). Realistic tests (**Figure 7**) conducted in April 2008 at SINTEF's research station near Svea on Svalbard followed positive early trials in Trondheim in 2007 and confirmed that dogs can be used to detect oil spills covered with snow and/or ice in harsh Arctic winter environments.

Figure 7: Trained dogs have shown promise in detecting oil covered with snow and ice (SINTEF)

Controlled field tests carefully documented with GPS transmitters on each animal showed that the dogs could reliably locate isolated small oil spills buried under snow on the ice surface and determine the approximate dimensions of a larger oil spill. The dogs also verified the bearing to a larger oil spill (400 litres, on top of the ice and covered in snow) at distances up to 5km.

Evolving Oil-in-Ice Detection Technologies

A number of new technologies (or next generation of existing technologies) could serve to expand remote sensing capabilities to a wider range of oil in ice scenarios in the near future. These include NMR imaging detection of oil under ice (Nedwed et al., 2008), next generation GPR, and additional work on deployment platforms such as unmanned air vehicles or autonomous underwater vehicles.

Tracking and Modeling Spilled Oil in Ice

Tracking and forecasting the position of spilled oil provides information that can be used to direct airborne and marine response resources at an appropriate time to respond to the spill, for example to burn oil that was incorporated in ice during freeze-up and that surfaces in the spring. Numerical models can forecast future movement of oil based on the location of spill sources, remote sensing observations of oil location, and data on winds, ocean currents, and ice conditions. Forecasts of oil position provide information on resources at risk of impact so that protective measures can be appropriately applied.

In addition to information from the detection methods discussed above, there are additional sources of information on the movement of ice and, by extension, the transport of oil that moves along with ice. These resources include:

- High-resolution satellite imagery;
- National ice services such as those in Canada, United States, Denmark, and Norway;
- Oceanographic and meteorological services;
- Surveillance aircraft; and
- Commercially available satellite tracking beacons.

Outputs from spill tracking activities involve:

- Maps of real time and predicted contaminated area boundaries;
- Vector representations showing movements of oiled ice; and
- Charts showing the detailed composition of the ice cover where the oil is located such as: mix of floe sizes, variability in ice coverage, boundaries of leads and **POLYNYAS**.

Polynya or Polynia *is an area of open water surrounded by sea ice; it is also a geographical term for areas in the Arctic which remain unfrozen for much of the year.*

Numerical modeling can be used to simulate the approximate movement of oil. In the absence of airborne visual checks or buoys on site, currently available models approximate oil movement in broken ice by assuming that the oil follows the ice in its response to winds and currents (primarily winds). Adjusting the starting locations of oil for simulations based on information remote sensing measurements can allow the models to make the best use of all available information for forecasting.

Several open water spill trajectory models include a component that models oil-in-ice behaviour (e.g., Spaulding et al., 1989; Venkatesh et al., 1990; Johansen, 1989). These models are based on open-water spill models and incorporate the presence of ice by applying a correction factor that is a function of ice concentration. Typical ratios of ice movement to wind speed are in the range of 4 to 5% of the wind speed in open drift ice to 3 to 4% in close to very close pack. A turning angle forcing movement to the right of the wind direction is applied to account for the effects of the **CORIOLIS FORCE**. More modern numerical approaches are the subject of current research and a recent workshop (Khelifa, 2011) identified a need to collect data sets for testing models and to conduct a comparative study of existing algorithms so that the 30-year-old “correction factor” approach can be updated.

__Coriolis Force__ is an apparent force that as a result of the earth’s rotation deflects moving objects to the right in the Northern Hemisphere and to the left in the Southern Hemisphere and is instrumental in the large-scale atmospheric circulation. The deflection is related to the motion of the object, the motion of the Earth, and latitude.

Summary Points

- Detection, monitoring, and tracking of oil are key needs for the appropriate allocation of resources during an oil spill response. Information from detection and monitoring on the location of oil identifies targets for immediate application of response technologies. Forecasting the future movement of spilled oil allows responders to adjust response plans for site specific factors, adapt to weather windows that may temporarily restrict operations, and to identify resources at risk so that appropriate protective measures can be applied.
- There is no one sensor that will work across a broad

range of oil in ice situations and weather conditions. Planning scenarios for Arctic spill response should include a flexible combination of sensors operating from diverse platforms including aircraft, satellites, vessels, helicopters, and on-ice teams. **Table 1** illustrates the range of applicability of different sensor technologies for oil spills.

- Tracking and forecasting the position of spilled oil, based on integrating remote sensing information, environmental data, and numerical modeling provides information that can be used to direct airborne and marine response resources.

Table 1: Applicability of sensor technologies for oil spills (Dickins et al., 2010)

Platform	Ice Surface		AUV	Shipborne		Airborne						Satellite
Sensor	**Dogs**	**GPR**	**SONAR**	**Radar**	**FLIR**	**GPR**	**Visible**	**UV**	**FLIR**	**SLAR**	**ALFS**	**SAR**
Oil On Ice												
Exposed on cold ice surface	Y	N/A	N/A	N	Y	Y	Y	N	Y	N	Y	N
Exposed on spring melt pools	Y	N/A	N/A	?	Y	N	Y	?	Y	?	Y	N
Buried under snow	Y	Y	N/A	N/A	N	Y	N	N	N/A	N	N	N
Oil Under Ice												
Smooth fast ice	?	Y	Y	N/A	N/A	Y	N/A	N/A	N/A	N	N	N
Deformed pack ice	?	?	Y	N/A	N/A	?	N/A	N/A	N/A	N	N	N
Oil In Ice												
Discrete encapsulated layer	?	Y	N	N/A	N/A	Y	N/A	N/A	N/A	N	N	N
Diffuse vertical saturation	?	?	N	N/A	N/A	?	N/A	N/A	N/A	N	N	N
Oil Between Ice Floes												
Low concentration	N/A	N/A	N	Y	Y	N/A	Y	Y	Y	Y	Y	Y
High Concentration	N/A	N/A	N	N	Y	N/A	N	N	N	N	N	N

Legend:
Y = Likely
? = Possible
N = Not likely
N/A = Not applicable
▭ = Blocked by dark/ clouds/fog/precipitation

Further Reading

Andersen, J.H.S., P.J. Brandvik, I. Singsaas, T. Buvik, J. Bradford, R. Hall, Mo. Babiker, K. Kloster and S. Sandven. 2010. **Remote Sensing for the Oil in Ice Joint Industry Program 2007-2009.** *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar.* Halifax Nova Scotia, Canada.

Aptomar. 2011. **The SECurus System**. Accessed 8/22/11 at http://www.aptomar.com.

Bradford, J.H., D.F. Dickins and P-J. Brandvik. 2010. **Assessing the potential to detect snow covered oil spills on sea ice using airborne ground-penetrating radar**. *Geophysics*, 75:2.

Brandvik, P.J. and T. Buvik. 2009. **Using Dogs to Detect Oil Hidden in Snow and Ice – results from Field Training on Svalbard April 2008**. SINTEFJIP-rep-no-14-Oildog-snow-ice[1].pdf. Accessed 8/22/11 at http://www.sintef.no/Projectweb/JIP-Oil-In-Ice/Publications/.

Brown, C. 2008. **Oil detection in/under ice**. Presentation by Environment Canada at the *Oil-in-ice Workshop* sponsored by the Atlantic Regional Environmental Emergencies Team (REET). St. John's, Newfoundland, Canada.

Coolbaugh, T. 2008. **Oil spill detection and remote sensing – an overview with focus on recent events.** In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar.* No. 31, Vol. 2, pp. 679-691. Environment Canada, Ottawa, Canada.

Dickins, D.F. 2000. **Detection and tracking of oil under ice**. Report prepared for the U.S. Department of Interior, Minerals Management Service, Herndon, VA, USA.

Dickins, D.F., J.H. Andersen, P. J. Brandvik, I. Singsaas, T. Buvik, J. Bradford, R. Hall, M. Babiker, K. Kloster and S. Sandven. 2010. **Remote Sensing for the Oil in Ice Joint Industry Program 2007-2009**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 33, Halifax NS, Canada.

Dickins, D.F. and J. Bradford. 2008. **Detection of oil on and under ice: Phase III evaluation of airborne radar system capabilities in selected Arctic spill scenarios.** Report prepared by DF Dickins Associates and Boise State University for the U.S. Minerals Management Service, Herndon VA, USA.

Dickins, D., L. Liberty, W. Hirst, J. Bradford, V. Jones, L. Zabilansky, G. Gibson, and J. Lane. 2005. **New and innovative equipment and technologies for the remote sensing and surveillance of oil in and under ice**. In: *Proceedings 28th Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. Environment Canada, Ottawa, Canada.

Fingas, M. and C.E. Brown. 2011**. Oil Spill Remote Sensing: A Review**. In *Oil Spill Science and Technology*, M. Fingas (Ed.), Gulf Professional Publishing, Burlington MA, USA. pp. 111-158.

Goodman R. 2008. **Oil under ice detection: what is the state-of-the-art?** In: *Oil Spill Response: A Global Perspective*. W.F. Davidson, K. Lee and A. Cogswell, Eds., Springer Netherlands, pp. 7-19, 2008.

Hirvi, J.P., R. Hakala and J. Rytkonen. 1987. **Study of crude oil behaviour in sub-Arctic brackish water**. Report by the Finnish National Board of Waters and the Environment and the Technical Research Centre of Finland, Helsinki.

Hodgins, D.O., S.S. Salvador, S.E. Tinis and D. Nazarenko. 1996. **Radarsat SAR for oil spill response**. *Spill Science and Technology Bulletin*, Vol. 3, No. 4, London, pp. 241-246.

Johansen, O. 1989. **Oil spill in ice simulation model development.** In: *Proceedings POAC 89: Port and Ocean Engineering Under Arctic Condition*s. Lulea, Sweden.

Khelifa, A. 2011. **Modeling Oil Spills in Ice Current Knowledge and Update on Ongoing Operational Research at ESTS**. Presented at the SINTEF Oil Spill Workshop, Houston, TX, USA, 8 February 2011.

Looström, B. 1983. **Swedish Remote Sensing Systems for Oil Spill Surveillance at Sea**. *Oil and Petrochemical Pollution* (1983) pp. 235 – 241.

Lunel, T., L. Davies, S. Shimwell, V. Byfield, S. Boxall and C. Gurney. 1997. **Review of aerial/satellite remote sensing carried out at the Sea Empress incident**. In: *Proceedings Third International Airborne Remote Sensing Conference*, Copenhagen, pp. 1-731 to 1-732.

Nedwed, T., L. Srnka and H. Thomann. 2008. **Remote detection of oil spilled under ice and snow using nuclear magnetic resonance**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 31, Vol. 2, pp. 693-702. Environment Canada, Ottawa, Canada.

Sørstrøm, S.E., P.J. Brandvik, I. Buist, P. Daling, D. Dickins, L-G Faksness, S. Potter, J.F. Rasmussen and I. Singsaas. 2010. **Joint industry program on oil spill contingency for Arctic and ice-covered waters: SUMMARY REPORT**. Accessed 8/22/11 at http://www.sintef.no/Projectweb/JIP-Oil-In-Ice/Publications/.

Spaulding, M., T. Isaji, K. Jayuko, E. Anderson, C. Turner and D. Mendelsohn. 1989. **An oil spill model system for Arctic waters**. In: *Proceedings 1989 International Oil Spill Conference*, pp. 517-523. American Petroleum Institute, Washington, DC, USA.

SSC. 2011. **MSS 6000 Airborne Maritime Surveillance System.** Accessed 8/22/11 at http://www.sscspace.com.

Venkatesh, S., H. El-Tahan, G. Comfort and R. Abdelnour. 1990. **Modelling the behaviour of oil spills in ice infested waters**. In: *Atmosphere-Ocean*, Vol. 28, No. 3, pp. 303-329.

Wadhams, P., J.P. Wilkinson and S.D. McPhail. 2006. **A new view of the underside of Arctic sea ice**. *Geophys. Res. Lett*., 33, L04501.

Section 3

Response Options: In-situ Burning

The use of in-situ burning (ISB), also referred to as controlled burning, as a spill response technique is not new, having been researched and employed in one form or another at a variety of oil spills since the late 1960s. There are two main technological components for in-situ burning: fire-resistant booms and igniters. Both have been the subject of extensive research, development, and testing over the past 30 years. In recent years there has also been extensive testing of chemical herding agents in conjunction with in-situ burning.

ISB is especially suited when oil is spilled in an environment with the presence of ice; much of the early research and development on ISB use was for spills on and under solid sea ice. More recently, the research has addressed burning spills in pack ice of various ice concentrations. In general, the technique has proven to be very effective for thick oil spills in high ice concentrations and has been used successfully to remove oil resulting from pipeline, storage tank, and ship accidents in ice-covered waters in Alaska, Canada, and Scandinavia.

The presence of ice reduces the spreading of oil, and the reduced wave activity within an ice field tends to reduce the weathering effects that make ignition of oil more difficult. As a result, the window of opportunity for burning is generally much greater for spills in ice than for spills in open water.

Despite the strong incentives for considering ISB as a primary countermeasure method, there remains some resistance to the approach. There are two major concerns: first, the fear of causing secondary fires that threaten human life, property and natural resources; and, second, the potential environmental and human-health effects of the by-products of burning, primarily the smoke.

This section provides a description of the basic processes involved in ISB, a summary of the main developments relating to its use in open water and in ice-affected waters, and a summary of the environmental trade-offs and decision-making factors involved in its use.

The Basics of In-Situ Burning

In order to burn spilled oil, three elements must be present: fuel, oxygen, and a source of ignition. The oil must be heated to a temperature at which sufficient hydrocarbons are vaporized to support combustion in the air above the slick. This means that the ignition source has to provide some heat to the slick before it will ignite. Once a small area of the slick is burning, heat from the flames will radiate back to the slick, making the process self-sustaining.

The key oil slick parameter that determines whether or not the oil will burn is slick thickness. If the oil is thick enough, it acts as insulation from the colder underlying water and keeps the upper surface of the burning slick at a sufficiently high temperature to maintain vaporization and combustion, and by reducing heat loss to the underlying water. As the slick thins, the heat flux from the flame cannot compete with heat transfer to the underlying water causing the temperature of the upper surface of the slick to drop below its **FIRE POINT**, at which time the burning stops.

There has been extensive experimentation on crude oil and fuel oils with a variety of igniters and in a range of environmental conditions to determine the minimum ignitable thickness. **Figure 8** shows an image from a tank test on ignitability limits. This is about 1mm for fresh crude oils, 2 to 5mm for weathered, unemulsified crude oil and diesel fuel, and about 10mm for heavy fuel oils (Buist et al., 1996; and 1998; Bech et al., 1992; and 1993).

*The **Fire Point** of a fuel is the temperature at which it will continue to burn for at least 5 seconds after ignition by an open flame. At the **FLASH POINT**, a substance will ignite briefly, but vapor might not be produced at a rate to sustain the fire. Most tables of material properties will only list material flash points, but in general the fire points can be assumed to be about 10ºC higher than the flash points (from: en.Wikipedia.org).*

Figure 8: Tank testing to determine ignitability limits (SL Ross Environmental Research Limited)

Aside from oil type, other factors that can affect the ignitability of oil slicks on water include: wind speed, emulsification of the oil, and igniter strength. The maximum wind speed for successful ignition of large burns has been determined to be 10 to 12m/s (20 to 25 knots) (Bech et al., 1993). For weathered crude that has formed a stable water-in-oil emulsion, the upper limit for successful ignition is about 25% water, although some crudes form meta-stable emulsions that can be easily ignited at much higher water contents (Guenette et al., 1995; Guenette and Sveum, 1995; Guenette and Wighus, 1996).

The rate at which ISB consumes oil is generally reported in units of thickness per unit time. The removal rate for in-situ oil fires is a function of fire size (or diameter), slick thickness, oil type, and ambient environmental conditions. For most large (> 3m diameter) fires of unemulsified crude oil on water, the “rule-of-thumb” is that the burning rate is 3.5mm/min. Automotive diesel and jet fuel fires on water burn at a slightly higher rate of about 4.0mm/min (Babrauskas, 1988).

These basic processes of ISB are well understood and are based on laboratory and field experiments dating back to the 1970s. More recent research has focused on some of the finer points of ISB as a response tool, such as the ignition and burning of emulsions, and the ignition and burning of oiled snow and oil in various forms of ice.

In the 1990s, the research on burning emulsions was a focal point, after the second attempted burn of crude oil from the *Exxon Valdez* reportedly failed due to the high emulsion water content (Allen, 1991). Research programs were carried out in Alaska, and jointly in Canada and Norway to investigate the burning of emulsified oil slicks on water and amongst ice in various environmental conditions, including waves. Also in the early 1990s, a field research study on burning diesel and crude oil in snow was performed in Norway and found that snow/oil mixtures with as little as 3 to 4% oil could be ignited using a promoter and burned with efficiencies of 90% or greater even two weeks after being spilled (Sveum and Bech, 1991).

In the early 2000s research looked at the effects of slush and **FRAZIL ICE** on the ignition and burning processes. Burning is still possible under these conditions, but it was found that the rate was about one-quarter to one-half the rate on open water and the overall efficiency was somewhat less (Buist et al., 2003).

__Frazil Ice__ is a collection of loose, randomly oriented needle-shaped ice crystals in water. It resembles slush and has the appearance of being slightly oily when seen on the surface of water. It sporadically forms in open, turbulent, super cooled water, which means that it usually forms in rivers, lakes and oceans, on clear nights when the weather is colder, and air temperature reaches –6°C or lower. Frazil ice is the first stage in the formation of sea ice. (from: www.Wikipedia.org).

Recent work, as part of the SINTEF JIP research program, has investigated the ignitability of various oils as a function of their initial composition and degree of weathering. One of the key conclusions of this work was that oil spilled in ice remains ignitable and burnable for a much greater period of time than in open water. This is due to the combined effects of reduced spreading, reduced weathering, and reduced emulsification when ice is present and due to the generally colder temperatures (Sørstrøm et al., 2010).

In-Situ Burning of Oil on Open Water

ISB can remove oil from the water surface very effectively and at very high rates. The use of towed fire containment boom to capture, thicken, and isolate a portion of a spill in open water or in low ice concentrations, followed by ignition, is far less complex than the operations involved in mechanical recovery, transfer, storage, treatment, and disposal.

The potential effectiveness of ISB has long been recognized, and there have been several well-known tanker spills where much of the oil had been consumed in an unintentional fire related to the accident. However, the intentional ignition of oil slicks on open water has only been seriously considered since the 1980s when researchers developed the first generation of fire-resistant oil containment boom. ISB using such boom has been conducted at four open water spills in North America in the 1990s: a major offshore tanker spill, a burning blowout in an inshore environment, and a pipeline spill into a river. Most recently, the Macondo well blowout in the Gulf of Mexico in 2010 saw the large-scale use of fire-resistant boom to burn a significant portion of the oil on an ongoing basis. Nearly 400 burns were conducted over a three-month period with an estimated 220,000 bbl to 310,000 bbl of oil eliminated from the marine environment (Mabile, 2010).

The present generation of fire-resistant boom has evolved significantly since initial designs of the 1970s and 1980s, and there are several commercially available products that have been subjected to standardized testing to verify their suitability and durability. The development of fire-resistant boom and standardized test methodologies to prove their effectiveness are discussed later in this chapter.

In-Situ Burning of Oil in Broken Ice

ISB has been considered a primary Arctic spill response countermeasure ever since the start of offshore drilling in the Canadian 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 of landfast ice with only minimal residue volumes remaining for manual recovery. This area of research culminated in 1980 with a full-scale field research program on the fate and cleanup of a simulated subsea oil well blowout under landfast sea ice (Dickins and Buist, 1981).

Research in oil spill cleanup in pack, or broken, ice also began in the 1970s and has been rekindled in recent years with the possibility of renewed exploration in frontier areas. With the known effectiveness of ISB in open water and certain ice situations, this has been a priority area for research and development. Work has been performed by researchers in Alaska, Canada, and Norway on a laboratory scale, mid-scale in test basins, and in full-scale field experiments. Work at mid-scale was aided greatly in the 1990s by the development of the Oil and Hazardous Materials Simulated Environmental Test Tank

(OHMSETT) in Leonardo, NJ, USA as a winter-time test facility, with the ability to artificially chill water if necessary, and the use of manufactured sea ice.

The consensus of the research to date on spill response in broken ice conditions is that ISB is a suitable response technique, but the effectiveness will vary greatly with the initial spill conditions, and specifically the slick thickness. For spills that occur in static ice fields of relatively dense ice, the oil will be contained to a great extent and the slick thicknesses required for effective burning will be maintained. On the other hand, oil spilled in lesser concentrations of ice will tend to spread and thin over time, making burning ineffective unless some form of containment can be employed.

Looking at three broad ranges of ice concentration:

- In open water to approximately 30% ice cover, the oil’s spread and movement will not be greatly affected by the presence of the ice, and open water ISB techniques may be possible. This could involve the collection of slicks in areas with the least ice coverage with fire boom operated by tow vessels, and their subsequent ignition.
- In 30% to 70% ice cover, the ice will reduce the spreading and movement of the slick, but not to the extent that it is completely containing the oil. The deployment and operation of boom in this ice concentration would be difficult.
- In 70% to 90%+ ice cover, the closely packed floes will effectively contain the oil; if slicks are initially thick enough, they will remain that way and can be burned effectively.

The ability to effectively burn oil in high concentrations of ice has been proven in lab and field studies over the past 30 years. Recent research has addressed the low and moderate containment requirement needed to achieve the necessary slick thickness to support combustion.

In order to burn oil in low ice concentrations, it is necessary to collect and contain sufficient oil to achieve the necessary slick thickness. Two types of fire-resistant boom were tested during Barents Sea experimental spills in 2008 and 2009 to evaluate their capabilities in ice (Potter and Buist, 2010) (**Figure 9**). These experiments were conducted as part of the SINTEF JIP project. In the first year, testing was done without oil to confirm the deployment procedures using a vessel-of-opportunity (i.e., an icebreaking vessel not specifically designed for oil spill operations) and to determine effective procedures for maneuvering the boom to capture oil floating among ice floes. This was done to prove the operational feasibility of the technique prior to gaining approval for an experiment with oil in 2009. Both boom used in the Norwegian trials have undergone extensive tank testing to prove their fire-resistance, and both were used in the Macondo incident in 2010 to perform successful open-water ISB.

Figure 9: In-situ burning within drift ice using fire-resistant boom (SINTEF)

ISB of oil spilled in pack ice during break-up will likely be easier than in the same ice concentration during freeze-up. In fall, the sea is constantly freezing, which generates significant amounts of slush ice which can severely hamper containment and thickening of slicks (naturally, or with boom) for burning; and logistics become increasingly difficult with the onset of winter. During break-up, there is much less slush and **BRASH ICE** present, the ice floes are deteriorating and melting, daylight is approaching 24 hours per day, and the temperatures are warming.

Brash Ice *is defined as accumulations of floating ice made up of fragments not more than 2 m across; the wreckage of other forms of ice. Brash is common between colliding floes or in regions where pressure ridges have collapsed.*

In-Situ Burning of Oil on Solid Ice

Oil may be found on the ice surface as a result of being spilled there directly, or because of migrating through the ice during spring (from oil trapped beneath or within the sheet following a subsea release during the winter). ISB is the countermeasure of choice to remove oil pools on ice in these situations. There is a high degree of knowledge on the ignition and burning of oil on melt pools as a result of experiments with this technique in the Canadian Beaufort Sea in the 1970s and 1980s (**Figure 10**). For large areas with many melt pools, helicopters deploying igniters would be used to ignite individual pools of oil. For smaller areas, manual ignition techniques could be employed. Work is currently underway to develop advanced aerial ignition techniques involving fixed-wing aircraft with much greater payload/range capabilities for remote operations in the Arctic.

Figure 10: ISB of oil in melt pools. (Dome Petroleum)

Wind will generally blow oil on melt pools to the downwind ice edge, where it will be herded to thicknesses of many millimetres. Individual melt pool burn efficiencies might exceed 90 to 95%. The overall operational efficiency of ISB techniques in removing oil from the ice surface found during field tests range from 30 to 90%, with an average in the rage of 60 to 70%; the efficiency will depend upon the circumstances of the spill (e.g., melt pool size distribution vs. igniter deployment accuracy, film thickness, degree of emulsification, timing of appearance vs. break-up, etc.,) (Dickins and Buist, 1981). For areas of fast ice where the oil may surface early in the spring, it could be possible to manually flush and/or recover remaining burn residue prior to final break-up of the ice sheet.

In-Situ Burning of Oil in Snow

Oil that is spilled on the ice surface and mixed with snow can be successfully burned in piles even in mid-winter Arctic conditions. 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. At the same time, oiled snow with up to 70% snow by weight can be burned in-situ. For higher snow content mixtures (i.e., lower oil content), promoters, such as diesel fuel or fresh crude, can be used to initiate combustion. For more dilute mixtures of oil in snow, the technique of ploughing oiled snow into piles where the oil may be allowed to concentrate will allow successful ignition and burning. For this technique, the oiled snow is scraped into a volcano-shaped pile, with a depression in the middle. An igniter is placed in the center of the pile. The heat from the flames melts the surrounding inside walls of the conical pile, releasing the oil from the snow, which runs down into the center and feeds the fire. This technique can generate considerable amounts of melt water at the base of the pile, which needs to be managed.

Igniters

A variety of methods are available to ignite an oil slick, including devices designed or modified specifically for ISB as well as simple, ad-hoc methods. There are two essential components to successfully igniting oil on water: heating the oil to its fire point, so that sufficient vapors are produced to support continuous combustion; and providing an ignition source to start burning.

For light refined products the flash point may be close to the ambient temperature and little if any pre-heating will be required to enable ignition. For other oil products, and those that have weathered and/or emulsified, the flash point will be much greater than the ambient temperature and substantial pre-heating will be required before the oil will ignite.

The Heli-torch was originally developed as a tool for burning forest slash (waste trimmings, branches, etc. from logging operations) and for setting backfires during forest-fire control operations. It was adapted for use in ISB in the mid-1980s and found to be an effective system for igniting spilled oil. The Heli-torch has been tested extensively, used in a number of field trials, and refined considerably over the years (NRT, 1995). The Heli-torch emits a stream of gelled fuel that is ignited as it leaves the device. The burning fuel falls as a stream that breaks into individual globules before hitting the slick. The burning globules produce a flame that lasts for several minutes, heating the slick and then igniting its vapors. Gasoline is the fuel typically used, but research and testing has shown that alternatives such as diesel, crude oil, or mixtures of the three fuels produce a greater heat flux, and should be considered for highly weathered oils and emulsions that may be difficult to ignite (Guenette and Sveum, 1995).

A variety of handheld igniters have been developed for use as devices to be thrown by hand from a vessel or helicopter. These igniters have used a variety of fuels, including solid propellants, gelled kerosene cubes, reactive chemical compounds, and combinations of these. Burn temperatures for these devices range from 650°C to 2,500°C and burn times range from 30 seconds to 10 minutes. Most hand-held igniters have delay fuses that provide sufficient time to throw the igniter and to allow it and the slick to stabilize prior to ignition (Guenette and Thornborough, 1997; Moffatt and Hankins, 1997).

For small, contained spills, simple ad-hoc techniques can be used to ignite the oil. For example, propane- or butane-fired weed burners have been used to ignite oil on land, ice, and water. As weed-burners or torches tend to blow the oil away from the flames, these techniques would only be applicable to thick contained slicks. Rags or sorbent pads soaked in fuel have also been successfully used to ignite small spills. Diesel is more effective than gasoline as a fuel to soak sorbents or rags because it burns more slowly and hence supplies more pre-heating to the oil.

Gelled fuel can also be used without the Heli-torch as an ad-hoc igniter. This was the method used for the test burn during the *Exxon Valdez* spill in 1989. Gasoline and gelling agent were mixed by hand in a plastic bag, and then the bag was ignited and allowed to drift into the slick contained within a fire-resistant containment boom. In the Macondo spill in 2010, approximately 400 burns were ignited using gelled fuel contained in plastic bottles with a flare attached.

Fire-resistant Containment Booms

In Arctic waters with low ice concentrations containment booms could be used in a same fashion as in open water. Following the successful test burn at the *Exxon Valdez* spill, considerable effort went into refining fire boom technology and developing new fire resistant and fireproof boom designs for improved durability and handling. Several key technology advancements were made, including water-cooled booms that employ water pumped through a porous outer fabric layer to protect the underlying floatation and membrane components, and a smaller, lighter weight stainless steel fireproof boom that was designed to be used as a fireproof pocket in a 'U-shaped' configuration with arms of conventional and/or fire resistant boom.

Figure 11: In-situ burning using fire-resistant boom (SINTEF)

As a direct result of the fire boom development efforts, fire boom test protocols were developed, and eventually adopted by the American Society for Testing and Materials (ASTM F2152 - *Standard Guide for In-situ Burning of Spilled Oil: Fire-Resistant Boom*) (ASTM, 2011). Recent use of several fire-resistant booms at the Macondo incident has validated the test procedures in terms of the relative durability of several different boom products (**Figure 11**). With the many opportunities to burn oil at sea during the Macondo incident, manufacturers have gathered important information and made significant improvements in their products (e.g., higher cooling water flow rates in water-cooled booms, and more heat-resistant materials in non-cooled fire booms).

A number of fire booms have been tested at the OHMSETT facility and have been found to have similar containment limits as conventional boom. Due to the weight of materials used for fire-resistance, the weight per unit length is generally much higher and the buoyancy-to-weight (b/w) ratio is much lower than for most conventional booms. As a result they are generally not applicable for high sea states, but this should not be an issue when used in open drift ice conditions as the ice tends to dampen waves.

Herding Agents Used to Facilitate In-Situ Burning

The key to effective ISB is thick oil slicks. Close pack ice can enable ISB by keeping slicks thick, but in open drift ice conditions, oil spills can rapidly spread to become too thin to ignite. Fire boom can collect and keep slicks thick in relatively open water; however, increasing ice concentration makes using boom more challenging. A multi-year joint industry project was initiated in 2004 to study oil-herding chemicals as an alternative to boom for thickening slicks under these conditions to facilitate ISB. **Figure 12** is an image taken during a successful field test of oil-herding chemicals during the SINTEF JIP project (2009).

Figure 12: In-situ burning using herding agents for containment (SINTEF)

Small-scale laboratory experiments were completed in 2004 and 2005 to examine the concept of using herding agents to thicken oil slicks among open drift ice for the purpose of ISB. Encouraging results prompted further mid-scale testing at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), the OHMSETT facility, and the Fire Training Grounds in Prudhoe Bay, AK (Buist and Morrison, 2005; Buist et al., 2006; 2007; and 2008).

The herder formulation used in these experiments proved effective in significantly contracting oil slicks in cold water and in brash and slush ice concentrations of up to 70% ice coverage. Herded slicks were ignited, and burned equally well in both brash and slush ice conditions at air temperatures as low as –17°C. The burn efficiencies measured for the herded slicks were similar to the theoretical maximums achievable for equivalent-sized, mechanically contained slicks on open water. As a final test of the concept, herders were successfully field tested at a large scale in 2008 as part of a Joint Industry Program on Oil Spill Contingency for Arctic and Ice-Covered Waters organized by SINTEF in the Barents Sea. Burn efficiencies of 90+% were achieved in two test burns using herders to thicken and contain oil among ice (Buist and Potter, 2010).

Research is presently ongoing to develop more effective herder formulations and on developing herder application technology.

Health and Environmental Effects of In-Situ Burning

__Burn Residue__ is the unburned oil remaining on the water surface when the fire extinguishes.

Studies of the emissions from ISB have shown fairly consistent results. About 85 to 95% of the burned oil becomes carbon dioxide and water, 5 to 15% of the oil is not burned efficiently and is converted to particulates, mostly soot, and the rest, 1-3%, is comprised of nitrogen dioxide, sulfur dioxide, carbon monoxide, polynuclear aromatic hydrocarbons (PAH), ketones, aldehydes, and other combustion by-products. The **BURN RESIDUE** from a typical, efficient (>85%) ISB of crude oil 10 mm to 20 mm thick is a semisolid, tar-like layer. For thicker slicks, typical of what might be expected in a towed fire boom (about 150 mm to 300 mm), the residue can be a solid (**Figure 13**).

Figure 13: In-situ burning residue. (NIST)

In the 1990s there was a concerted research effort to determine the potential environmental effects of in-situ burning. Environment Canada's Emergencies Science and Technology Section (ESTS) and the US National Institute for Science and Technology's (NIST) Building and Fire Research Laboratory spearheaded the two main programs. Both organizations collected and analyzed data from each other's research fires.

The two programs looked at various aspects of smoke emissions and soot production. The Environment Canada program involved a series of crude oil and diesel fires on water over a large range of fire sizes, culminating with the 1994 Newfoundland Offshore Burn Experiment (NOBE) (Fingas et al., 1994. The NIST program focused on small and mid-scale fires (in Mobile, AL and Prudhoe Bay, AK) of various types of crude oil and refined products (McGrattan et al., 1994; 1995). The work of both teams greatly advanced the understanding of what was in the smoke from an in-situ oil fire on water and how to predict its downwind impacts on the environment, and resulted in the development of computer models that are used to predict downwind concentrations of smoke emissions (discussed in **Section 7 - Selection of Response Strategies**).

Research in the 1990s also examined the burn residue. Studies showed that the residue from burns of crude oil had very little or no acute toxicity to key indicator species in salt water and freshwater (Daykin et al., 1994; Blenkinsopp et al., 1997). This is attributable to the act of burning the oil – an effective burn removes the lightest, most toxic components of crude oil. Further research looked at benthic species, which incurred very low levels of toxic effects when exposed to burn residue in seawater (Daykin et al., 1994; Blenkinsopp et al., 1997).

Other studies looked at the potential for residues to sink, and in some cases this may occur depending on the initial density of the oil and the effectiveness of the burn (highly effective burns are more likely to produce high-density residues). Sunken burn residues can affect benthos that are otherwise removed from impacts by a spill at the surface of the water. This occurred, for example, during the *Haven* spill in Italy in 1991, which involved an unintentional fire, and during the *Honam Jade* spill in South Korea in 1983 (Martinelli et al., 1995; Moller, 1992). In both cases the residue affected bottom resources in a relatively small localized area and interrupted fishing activities. It is important to note that residues as a result of a burn are not only likely to be localized, they will likely consist of scattered chunks rather than as a continuous mat covering a broad area.

The potential impacts of sunken burn residue and the time/resources needed to collect the residue before it sinks must be weighed carefully to determine the smallest overall environmental impact. In some cases it may be better to use the available resources for continued burn operations (eliminating large quantities of oil) than to commit such resources to the collection of a relatively small quantity of low-toxicity burn residue.

The production of smoke during an ISB, and the concentrations of smoke particles at ground or sea level are usually of most concern to the public as they can persist for several miles downwind of a burn. From a human health perspective, the focus is on those particles that are small enough to be inhaled into the lungs, i.e., those smaller than 2.5 microns in diameter. These are referred to as PM-2.5s (PM stands for "particulate matter").

Particulate concentrations in the plume are greatest at the burn site, but they decline with increasing distance from the site, primarily through dilution, dispersion, and fallout, but also through washing out by rain and snow. Concentrations of PM-2.5 in a smoke plume are not easy to predict accurately because they are a function of many factors including: soot yield; fire size; burn efficiency; distance downwind from the burn; terrain features; and atmospheric conditions (e.g., wind speed).

The default approach adopted in the US ensures smoke concentrations do not exceed the National Ambient Air Quality Standards (NAAQS) at downwind, populated areas by undertaking real-time monitoring of the plume. If this monitoring is not possible, the US also allows for smoke plume trajectory models, with a safety factor applied, to be used to determine safe distances. For responses in US federal waters, use of ISB requires approval by the appropriate US Regional Response Team. For responses within state waters (3 nm offshore and inland ; with some variations for particular states), the adjoining coastal state’s air quality agency is responsible for authorizing ISB in conjunction with the unified command established for the response (interested parties are directed to contact the US Coast Guard for further details). Both NIST and the National Oceanic and Atmospheric Administration (NOAA) have developed models to predict downwind smoke concentrations. These are sophisticated tools that require detailed spill and meteorological inputs and should be run by experts only.

As an interim planning measure, general examples can be used as guides. NIST has developed a simple technique for roughly estimating the maximum distance downwind over flat or complex terrain for the concentration of soot in plumes from ISBs to dilute and disperse below a given concentration (Walton and Jason, 1998). If required, more precise forecasts can be made at the time of an incident using readily available models and incident specific conditions. The distance beyond which the soot concentration falls below a given level depends mainly on the terrain height and the mixing layer depth relative to the elevation of the burn site, with wind speed being the next most important factor. The approximate distances downwind over land for the ground-level PM-2.5 concentrations from 500 and 1,000 barrels per hour (bbl/hr.) fires are in the range of 5 to 10 kilometres (3 to 6 miles). Such “exclusion zones” would not likely prevent ISB operations in Arctic due to the relatively low population densities in these areas. The PM-2.5 concentration exclusion zones also can be easily maintained for offshore burns.

Smoke plumes are also of concern because they obstruct visibility and may pose a safety hazard to operators of ships, aircraft, and motor vehicles in the immediate vicinity and downwind of the fire. (It should be noted, however, that during the Macondo incident, smoke plumes from ISB operations did not significantly impair visibility for ships or aircraft, even with multiple burns occurring in close proximity.) Light scattering primarily causes a visibility reduction from the smaller smoke particles, in the 0.3 to 0.6 micron size range. Modelling can also give estimates on these effects, but it is unlikely that serious visibility effects will be caused at ground level if the appropriate separation distances for PM-2.5 are maintained.

The smoke plume may also cause limited spatial and temporal aesthetic impacts. Even though the concentrations of particulate in the smoke plume are well below levels of concern, they can still be detected by the human nose and may cause concern among the public.

Summary Points

- ISB is a proven response technique that can rapidly eliminate oil with efficiencies as high as 98%.
- There is a good knowledge base on burning fundamentals (the limits for ignition, burning rates, effects of slick thickness and emulsions) based on 30+ years of research, much of it specifically related to Arctic conditions.
- The presence of ice may increase the window-of-opportunity for the effective use of ISB by reducing the spreading, weathering, and emulsification of oil. Predictive tools are available to aid responders in determining the ignitability of various oils based on their initial composition and likely degree of weathering.
- There is also a good knowledge base on the environmental effects of burning. This information can assist in pre-spill planning and in decision-making at the time of a response.
- In very open drift ice conditions (30% and less), the oil's spread and movement will not be greatly affected by the presence of the ice, and open water in-situ burning techniques will be possible in many cases. This would generally involve the collection of slicks with fire boom operated by tow vessels, and their subsequent ignition.
- In medium ice concentrations (30% to 70%), the ice will reduce the spreading and movement of the slick, but will not completely contain the oil. Operation of booms in this ice concentration would be difficult, if not impossible. Instead, herding agents may be used to contract slicks and thicken them sufficiently for burning. [**Please note**: the reader is directed to refer to applicable law and regulation of the country of interest for information

on the status of licensing and approval for emergency response use of herding agents.]

- In close pack conditions (70% and greater), the ice floes will help contain the oil; slicks that are initially thick enough may remain that way and be burned effectively.
- Recent technology developments include better fire-resistant boom and the use of herding agents in conjunction with burning. Multiple means of ignition exist and additional improved methods are being developed. One method under development is a fixed-wing, high-speed delivery system for gelled fuel thereby improving payload/range constraints normally associated with helicopter operations.
- ISB (with the use of fire-resistant boom) played a significant role in the response to the Macondo blowout in the Gulf of Mexico. The burning operations highlighted some of the key advantages of burning by safely and effectively eliminating large quantities of oil with minimal personnel and equipment resources. Overall, burning made effective and efficient use of available logistical resources to rapidly reduce the environmental threat of oil on the water surface before that oil could reach sensitive nearshore and shoreline environments.
- In-situ burning is a very important tool for oil spill response under Arctic conditions and research has shown it can be successfully used under a range of ice concentrations.

Further Reading

Alaska Regional Response Team (ARRT). 2008. **In-situ burning guidelines for Alaska**: Revision 1. Appendix ii, Annex F, in *The Alaska Federal/State Preparedness Plan for*

Response to Oil and Hazardous Substance Discharges/Releases.

Allen, A.A. 1990. **Contained controlled burning of spilled oil during the Exxon Valdez oil spill**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 13, pp. 305-313. Environment Canada, Ottawa, Canada.

Allen, A.A. 1991. **Controlled burning of crude oil on water following the grounding of the *Exxon Valdez***. In: *Proceedings 1991 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA.

Allen, A.A. and R.J. Ferek. 1993. **Advantages and disadvantages of burning spilled oil**. In: *Proceedings 1993 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA.

Babrauskas, V. 1988. **Burning rates**. *The SFPE Handbook of Fire Protection Engineering*. Published by the National Fire Protection Association, Quincy, MA, USA. pp. 2.1 to 2.15.

Bech, C., P. Sveum and I.A. Buist. 1992. **In-situ burning of emulsions: the effects of varying water content and degree of evaporation**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 15, pp. 547-559. Environment Canada, Ottawa, Canada.

Bech, C., P. Sveum and I.A. Buist. 1993. **The effect of wind, ice and waves on the in-situ burning of emulsions and aged oils**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 16, Vol. 2, pp. 735-748. Environment Canada, Ottawa, Canada.

Blenkinsopp, S.A., G.A. Sergy, K.G. Doe, G.D. Wohlgeschaffen, K. Li and M.F. Fingas. 1997. **Evaluation of the toxicity of the weathered crude oil used at the Newfoundland offshore burn experiment (NOBE) and the resultant burn residue**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 20a: 677-684. Environment Canada, Ottawa Canada.

Buist, I. 2007a. **In-situ burning for oil spills in ice-covered waters**. In: *Proceedings International Oil & Ice*

Workshop 2007. Minerals Management Service. Herndon, VA, USA.

Buist, I. 2007b. **Using herding surfactants to thicken oil slicks in pack ice for in-situ burning**. In: *Proceedings International Oil & Ice Workshop 2007*. Minerals Management Service. Herndon, VA, USA.

Buist, I. and J. Morrison. 2005. **Research on using oil herding surfactants to thicken oil slicks in pack ice for in-situ burning**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 28, Vol. 1, pp. 349-375. Environment Canada, Ottawa, Canada.

Buist, I. and S. Potter. 2010. **Barents Sea field test of herder to thicken oil for in-situ burning**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. Environment Canada. Ottawa, Canada.

Buist, I., D. Dickins, L. Majors, K. Linderman, J. Mullin and C. Owens. 2003a. **Tests to determine the limits to in-situ burning in brash and frazil ice**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 26, Vol. 2, pp. 629-648. Environment Canada, Ottawa, Canada.

Buist, I.A., J. McCourt, K. Karunakaran, C. Gierer, D. Comins, N.W. Glover and B. McKenzie. 1996. **In-situ burning of Alaskan oils and emulsions: preliminary results of laboratory tests with and without waves**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 19, Vol. 2, pp. 1033-1061. Environment Canada, Ottawa, Canada.

Buist, I.A., J. McCourt, J.V. Mullin, N.W. Glover, C. Hutton and J. McHale. 1998. **Mid-scale tests of in-situ burning in a new wave tank at Prudhoe Bay, Alaska**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 21, Vol. 2, pp. 599-622. Environment Canada, Ottawa, Canada.

Buist, I., T. Nedwed and J. Mullin. 2008. **Herding agents thicken oil spills in drift ice to facilitate in-situ burning: a new trick for an old dog**. In: *Proceedings 2008 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA.

Buist, I., S. Potter, T. Nedwed and J. Mullin. 2007. **Field research on using oil herding surfactants to thicken oil slicks in pack ice for in-situ burning**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No 30, Vol. 1, pp. 403-425. Environment Canada, Ottawa, Canada.

Buist, I., S. Potter, L. Zabilansky, P. Meyer and J. Mullin. 2006. **Mid-scale test tank research on using oil herding surfactants to thicken oil slicks in pack ice: An update**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 29, Vol. 2, pp. 691-709. Environment Canada, Ottawa, Canada.

Buist, I.A., S.L. Ross, B.K. Trudel, E. Taylor, T.G. Campbell, P.A. Westphal, M.R. Myers, G.S. Ronzio, A.A. Allen and A.B. Nordvik. (1994a). **The science, technology and effects of controlled burning of oil spills at sea**. Technical Report Series 94-013, Marine Spill Response Corporation, Washington, DC, USA.

Daykin, M., G. Sergy, D. Aurand, G. Shigenaka, Z. Wang and A. Tang. 1994. **Aquatic toxicity resulting from in-situ burning of oil-on-water**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 17b:1165-1193. Environment Canada, Ottawa, Canada.

Dickins, D.F. and I.A. Buist. 1981. **Oil and Gas Under Sea Ice Study: Vols. 1&2**. Prepared by Dome Petroleum Ltd. for COOSRA, Report CV-1, Calgary, AB, Canada (also published in *Proceedings 1981 Oil Spill Conference,* Atlanta GA, USA).

Fingas, M.F., F. Ackerman, K. Li, P.G. Lambert, Z. Wang, M.C. Bissonnette, P.R. Campagna, P. Boileau, N.D. Laroche, P. Jokuty, R.D. Nelson, R.D. Turpin, M.J. Trespalacios, G. Halley, J.M.R. Bélanger, J.R.J. Paré, N. Vanderkooy, E.J. Tennyson, D.V. Aurand and R.R. Hiltabrand. 1994. **The Newfoundland offshore burn experiment (NOBE) - Preliminary results of emissions measurement** In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 17b:1099-1164. Environment Canada, Ottawa, Canada.

Fingas, M.F. and M. Punt. 2000. **In-situ burning: a cleanup technique for oil spills on water**. Environment Canada Special Publication, Ottawa, Ontario, Canada. 214 pp.

Guénette, C.C. and P. Sveum. 1995. **Emulsion breaking igniters: recent developments in oil spill igniter concepts**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 18, Vol. 2, pp. 1011-1025. Environment Canada, Ottawa, Canada.

Guénette, C.C. and J. Thornborough. 1997. **An assessment of two offshore igniter concepts**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 20b:795-808. Environment Canada, Ottawa, Canada.

Guénette, C.C.; P. Sveum; C.M. Bech and I.A. Buist. 1995. **Studies of in-situ burning of emulsions in Norway**. In: *Proceedings 1995 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA.

Guénette, C.C. and R. Wighus. 1996. **In-situ burning of crude oil and emulsions in broken ice**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 19, Vol. 2, pp. 895-906. Environment Canada, Ottawa, Canada.

Mabile, N. 2010. **Fire boom performance evaluation: controlled burning during the Deepwater Horizon spill**. Report to BP America. Houston, TX, USA.

Martinelli, M., A. Luise, E. Tromellini, T. Sauer, J. Neff and G. Douglas. 1995. **The M/C *Haven* oil spill: Environmental assessment of exposure pathways and resource injury**. In: *Proceedings 1995 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA.

McGrattan, K.B., H.R. Baum and R.G. Rehm. 1994. **Smoke plume trajectory from in-situ burning of crude oil in Alaska**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 17, Vol. 1, pp. 725-733. Environment Canada, Ottawa, Canada.

McGrattan, K.B., W.D. Walton, A.D. Putorti, W.H. Twilley, J. McElroy and D.D. Evans. 1995. **Smoke plume trajectory from in-situ burning of crude oil in Alaska - Field experiments**. In: *Proceedings Arctic and Marine*

Oilspill Program (AMOP) Technical Seminar. No. 18, Vol. 2, pp. 901-913. Environment Canada, Ottawa, Canada.

Moffatt, C. and P. Hankins. 1997. **Results of experiments with flare type igniters on diesel fuel and crude oil emulsions**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 20b:1197-1213. Environment Canada, Ottawa, Canada.

Moller, T.H. 1992. **Recent experience of oil sinking**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No 15:11-14. Environment Canada, Ottawa, Canada.

National Institute of Science and Technology (NIST). 2003. SP 995: **In Situ Burning of Oil Spills: A Resource Collection**. Minerals Management Service and National Institute of Standards and Technology, March 2003. W.A. Walton, Ed. and J.V. Mullin, Project Manager.

National Response Team (NRT) Science and Technology Committee. 1995. **Igniters and ignition technology for *In Situ* Burning of oil.** NRT Fact Sheet. Washington, DC, USA. 5 pgs.

Potter, S. and I. Buist. 2010. **In situ Burning in Arctic and Ice-Covered Waters: Tests of Fire-Resistant Boom in Low Concentrations of Drift Ice** In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. Environment Canada. Ottawa, Canada.

Sørstrøm, S.E., P.J. Brandvik, I. Buist, P. Daling, D. Dickins, L-G. Faksness, S. Potter, J.F. Rasmussen and I. Singsaas. 2010. **Joint industry program on oil spill contingency for Arctic and ice-covered waters: Summary Report**. SINTEF report A14181. SINTEF. Trondheim, Norway. www.sintef.no/Projectweb/JIP-Oil-In-Ice/Publications/

Sveum, P. and C. Bech. 1991. **Burning of oil in snow: experiments and implementation in a Norsk Hydro drilling contingency plan**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 14, pp. 399-410. Environment Canada, Ottawa, Canada.

Walton, W.D., and N.H. Jason (Eds.). 1998. **In Situ Burning of Oil Spills Workshop Proceedings**. NIST Special Publication. See: Http://fire.nist.gov/bfrlpubs/fire99/PD/f99015.pdf.

Section 4

Response Options: Physical and Chemical Dispersion of Oil

Following an oil spill, some of the oil will disperse naturally into the water column. The extent to which this occurs depends on the type of oil spilled and the available mixing energy. Natural dispersion takes place when the mixing energy provided by the waves and wind is sufficient to overcome surface tension at the oil/water interface and break the oil slick into droplets of variable sizes. Generally, larger oil droplets will rapidly resurface and then coalesce to form back into an oil slick, while smaller droplets will remain suspended in the water column where they will be diluted by turbulence and subsurface currents and eventually biodegrade.

Chemical and physical dispersants are designed to enhance natural dispersion by reducing the surface tension at the oil/water interface, making it easier for waves to create small oil droplets. **Figure 14** illustrates the process of dispersant application and dispersion.

The use of dispersants to help mitigate the effects of spills in open water has been proven in numerous field experiments and in the response to many spills. Dispersants are commonly used as a first line of response in some parts of the world, while in others it is regarded as an alternative strategy after containment and recovery. Compared with the use of boom and skimmers, dispersant use offers a primary advantage in the overall treatment rates that can be achieved. Much broader areas of an oil slick can be treated by dispersant application than could generally be encountered by containment and recovery systems. Furthermore, dispersants are efficient in high sea states, when other response techniques experience significantly reduced efficiency or become unsafe to implement.

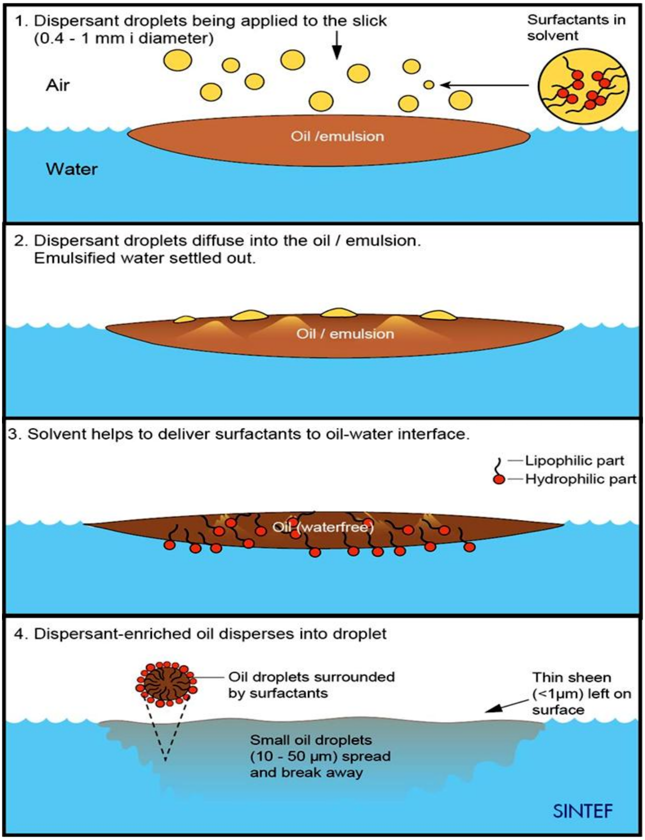


Figure 14: Dispersants enhance natural dispersion, dilution, and microbiologic degradation (Source: SINTEF)

Research and test programs over the past 20 years have looked at addressing important concerns regarding potential dispersant use in Arctic conditions, specifically their likely effectiveness in cold air and water temperatures, in the presence of ice, and in brackish water due to melting ice and river outflows. This research has shown that the critical parameters for effective dispersant use in a response include the performance of the dispersant, the oils dispersibility, the application of the dispersant, and the availability of sufficient energy for the dispersion process (Sørstrøm et al., 2010). The following describes some of the more significant research on these parameters, and together show that dispersant use has the potential to be a very effective countermeasure in a number of Arctic situations.

What are Dispersants?

Chemical dispersants are a mixture of surfactant chemicals similar in properties and effects to many common dish soaps. When applied to an oil slick, dispersants diffuse into the oil and work by lowering the surface tension of the oil. In the presence of wave energy, the lowered surface tension causes the oil to break into smaller droplets compared with untreated oil. Dispersants have been specially formulated for this task and are most effective when applied before oils have weathered to become too viscous. Because released oil changes its properties with time due to weathering processes, dispersant use has a distinct ‘window of opportunity’ when it is most effective. Once oil becomes too viscous or too emulsified, dispersants would have reduced efficiency. The “window of opportunity” can vary significantly depending on both the properties of the oil and the conditions of the spill.

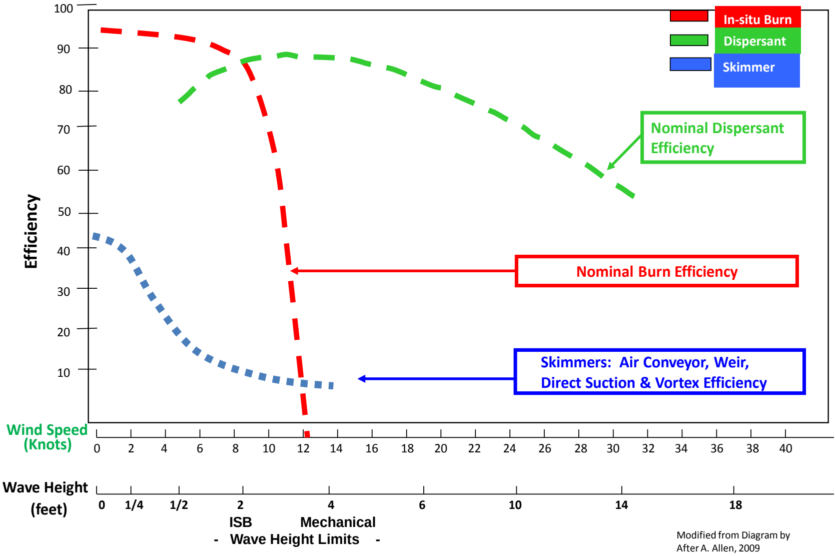
Toxicity testing is used to confirm that dispersants have an acceptably low toxicity. Many countries publish lists of dispersants that have passed standardized toxicity testing and that are approved for use. For example, Corexit 9500, among the more widely available dispersants and used in the Macondo incident, is comprised of various chemicals with common household applications (**Table 2**). In some countries, including the US, dispersant toxicity is measured in the laboratory but not used as an approval criterion. Laboratory and field studies have shown that toxicity concerns should be focused on potential environmental effects of dispersed oil, rather than on dispersants themselves.

Table 2: Other uses of Corexit 9500 ingredients	
Corexit 9500 Ingredients	**Common Day-to-Day Use Examples**
Span 80 (surfactant)	Skin cream, body wash, emulsifier in juice
Tween 80 (surfactant)	Baby bath, mouth wash, face lotion, emulsifier in food
Tween 85 (surfactant)	Body/face lotion, tanning lotions
Aerosol OT (surfactant)	Wetting agent in cosmetic products, gelatin, beverages
Glycol butyl ether (solvent)	Household cleaning products
Petroleum distillate (solvent)	Air freshener, cleaner
From Nalco website: http://www.nalco.com/applications/4297.htm	

Modern dispersants are much less toxic than dispersed oil. In fact, Environment Canada found that modern dispersants are less toxic than common household cleaners. The environmental trade-offs of dispersant use must weigh exposures of organisms in the water column to dispersed oil against potential impacts of that same oil remaining on the surface and/or stranding on shorelines (IPIECA, 2001).

Why Use Dispersants?

Dispersants don't simply remove oil from the water surface and mix it into the water column; they facilitate removal of oil from the environment by enhancing opportunities for the natural biodegradation process. Furthermore, dispersants have an advantage over other response options because they can treat large areas very rapidly and be applied over a broader range of ocean conditions than other response strategies, even during high seas when other response techniques have reduced efficiency (**Figure 15**).



Modified from Diagram by After A. Allen, 2009

Figure 15. Estimated response system efficiencies vs. wind speed and wave height for light-to medium weight fresh crude oils (Modified from A. Allen, 2009).

Dispersants convert surface slicks into tiny droplets (< 100 micrometres in diameter) that mix into the water column and rapidly dilute. Waves and other sources of mixing energy distribute dispersed oil droplets in the water column where oil undergoes natural biodegradation. The benefit of creating smaller droplets is twofold: first, the droplets are less likely to re-surface and will tend to remain suspended in the water column; and second, the droplets are in a form that is more easily degraded by micro-organisms that occur naturally in the water. These droplets have several hundred times larger surface area that bacteria can colonize than a surface slick. In simple terms, the effective use of chemical dispersants can fragment spilled oil into a form that can be more easily degraded by naturally-occurring micro-organisms in the environment.

The principal goal of dispersants use is to remove oil from the sea surface and prevent oil from entering near-shore bays and estuaries, or stranding on shorelines, thereby protecting coastal habitats and the species that inhabit them. In most offshore environments, species and resources on the water surface (birds, marine mammals), in nearshore areas, and on shorelines are considered more vulnerable to the effects of oil as compared with the resources that might be contacted by dispersed oil.

However, dispersing oil into the water column does present a trade-off. Mitigating damage to the shoreline and to organisms that may encounter surface slicks means exposing the water column temporarily to elevated concentrations of dispersed oil. Many studies have demonstrated that such trade-off may be acceptable considering overall net environmental benefit to the ecosystem. A joint industry program at the Aberdeen University Research and Industrial Services (AURIS, 1994) found that habitat recovery time for oiled rocky shores can take 3 years, salt marshes can take 5 years, and mangroves can take 80 years, whereas the recolonization by organisms that have planktonic life stage is far more rapid, with phytoplankton recovering in weeks and zooplankton recovering in months. However dispersants should not be used close to sensitive sub-surface resources such as coral reef and known spawning beds, and should be used with caution in **SHALLOW WATERS**. In situations where sensitive resources could be impacted, dispersant use should be evaluated on a case-by-case basis.

__Shallow Water__ has been defined in US Regional Response Team guidance documents as waters within 3 km of shore or possessing a depth of 10m or less. Guidance documents used by other jurisdictions may make distinctions for pre-approval or approval of application of chemical dispersants based on depth of water or proximity to shore, and readers are directed to consult applicable regulatory authorities.

Questions surrounding the benefits and potential risks of using dispersants, have led to substantial research to understand and compare the effects of undispersed and dispersed oil. The general use of dispersants in temperate waters is a subject unto itself, and is well summarized in a document entitled *Oil Spill Dispersants* produced by the Norwegian independent research organization SINTEF (see

Further Reading below). The publication includes the principles of dispersant use, limitations on their effectiveness, how to make dispersant-use decisions, and several case studies of natural dispersion and chemical-aided dispersion.

Another key report is the National Research Council's (NRC, 2005) publication *Oil Spill Dispersants Efficacy and Effects* developed by a committee of appointed scientists and responders who took emphasis on risk-based decision making and framed their assessment on recommendations around the questions that planners and responders are faced with when deciding whether or not to use dispersants.

Use of Dispersants in Arctic Environments

This section addresses the use of chemical dispersants in Arctic environments, focusing on the key issue of effectiveness and highlighting some of the key research programs that have examined different aspects of dispersant use in the Arctic, such as performance in cold temperatures, brackish water, and in the presence of ice.

Dispersant Effectiveness in Cold Water

There is a general misconception that cold temperatures inhibit dispersant effectiveness; however a substantial amount of testing and research exists to prove the effectiveness of dispersants in cold water. This has been a recent concern for contingency planners in southern Alaska and off Canada's East coast where there are near-freezing water temperatures for parts of the year and where there has been interest in including dispersants as a response tool.

The main concern is the effect of temperature on the oil's viscosity: oil becomes more viscous in cold temperatures, and there are viscosity limits for effective dispersion. The viscosity limits for effective dispersion have been the subject of extensive research in laboratory-scale experiments starting in the 1980s, and more recently, in large-scale experiments between 2003 and 2008 at the US

National Oil Spill Response Test Facility (OHMSETT) (www.Ohmsett.com) (**Figure 16**). The common finding in these experiments has been that dispersants remain effective for most unemulsified oils at freezing and near-freezing temperatures, as long as the oil viscosity does not exceed 20,000 cP and the pour point of the oil is lower than the ambient water temperature (Belore, 2003; and 2008; Mullin, 2004; 2007; Mullin et al., 2008). In fact, SINTEF has shown that oils with pour points up to 10°C above ambient can still disperse (Nedwed et al., 2006; Brandvik, et al. 1995; and Daling et al., 1990). At temperatures 10°C below the oil's pour point, the oil will not readily flow, will resist the inclusion of dispersants applied to the oil, and will not break into the small droplets required for effective long-term dispersion.

Figure 16: Effective dispersion in OHMSETT (SL Ross Environmental Research Limited)

A report from Clark et al., (2009) presents additional results from past research on cold condition dispersant effectiveness testing. Some of the key findings from the international researchers identified in this report are summarized below:

- Farmwald and Nelson (1982) concluded that low air temperature should not govern the decision to use dispersants after conducting tests using cold air (4°C to -40°C) over 1°C water and determining that dispersant effectiveness was not impaired.
- Byford et al., (1983) suggested that higher oil viscosities due to cold temperatures might reduce oil re-coalescence of dispersed oil drops and the higher density of the oil reduces buoyancy; both factors resulting in better dispersion with cold temperatures. Cold temperatures did not significantly reduce dispersant effectiveness in these tests.
- Brandvik et al. (1992) achieved 10% to 90% DE in small-scale tests at 0°C for a range of dispersants on various weathered oil and water-in-oil emulsions.
- Mackay (1995) completed cold-water (4°C) dispersant effectiveness tests in both a bench scale apparatus (EXDET test) and in the ESSO Resources Canada outdoor test basin using Alaska North Slope (ANS)

Crude oil and Corexit 9527. The bench scale results showed a slight decrease (from 90% to 80%) in effectiveness as the temperature increased from 4°C to 15°C, suggesting that the cold conditions slightly improved the dispersant performance. The tests completed in the outdoor basin resulted in measured dispersant effectiveness values between 80% and 97% for weathered ANS crude oil subjected to breaking waves immediately after the application of dispersant.

- Several dispersant effectiveness test programs were completed at OHMSETT in cold water (-1°C to +10°C) on Alaskan and east coast Canadian crude oils (Belore, 2003; and 2008; Mullin, 2004; and 2007; Mullin et al., 2008). Corexit 9500 and 9527 dispersants were found to be very effective on all of the oils tested in these large outdoor test tank experiments (**Figure 17**).

Figure 17: Tank testing in ice with dispersants. This picture is the Aker Arctic ice test basin and is relevant to the Spring et al. 2006 and Nedwed et al. 2007 work with icebreakers described below

(SL Ross Environmental Research Limited)

Finally, current research is aimed at modifying dispersant formulations to increase their effectiveness on viscous oils. In particular, the development of a new ‘gelled’ dispersant has shown promise in increasing the time that the active ingredient in the dispersant remains in contact with the oil, which can allow it to be more effective (Nedwed et al., 2008, Nedwed, 2007).

Dispersant Effectiveness in The Presence of Ice

As noted in ***Section 1: Oil-in-Ice Behaviour***, the presence of ice can be beneficial to some spill response countermeasures. In waters partially covered with ice, wave energy is greatly reduced, and this in turn retards the natural evaporation and emulsification of spilled oil, which can be a big advantage for spill response. This was documented in the SINTEF (2009) JIP lab experiments and subsequent field trials, where it was found that there was a much greater window-of-opportunity for dispersant use for spills among ice than for spills in open water (Sørstrøm et al., 2010). Conversely, the reduced wave activity can be a disadvantage for dispersant operations because a certain amount of wave energy is needed to permanently mix oil into the water column after dispersant application.

For many years, the prevailing view was that ice concentrations greater than 30 to 50% would significantly dampen the wave field and curtail the effective use of dispersants. Test tank experiments in the 1990s and 2000s began to change this view when it was found that, although the overall wave energy was indeed reduced, there was enhanced localized energy created by the mechanical grinding and pumping actions as ice pieces rise and fall and interact. Tests in large wave basins showed that this localized energy was, in many situations, sufficient to disperse chemically treated oil (Brown and Goodman, 1996; Owens and Belore, 2004; Nedwed 2007).

More recent tests in 2009 in the laboratory and subsequently in the Barents Sea explored this concept further. Tests were done in the lab with ice concentrations ranging up to 90%, and looked at both aspects of the effects of ice: the reduced weathering and emulsification and the effect on mixing energies for dispersion. The tests showed that there was an expanded window-of-opportunity for dispersant use as the ice concentration was increased, but at ice concentrations in the range of 90% and greater, there was insufficient mixing energy to disperse the treated oil (Sørstrøm et al., 2010). A subsequent test in a full-scale field experiment confirmed this, but effective dispersion did occur when supplemental mixing energy was applied using the ship's bow thrusters and from propeller wash from small boats. Other researchers have found similar results, using the turbulence from a ship's propeller or from fire monitors (Spring et al., 2006; Nedwed et al., 2007; Nedwed, 2007) (**Figure 18**).

Figure 18: Using boats to supply extra mixing energy (SINTEF)

The advent of azimuthal-drive icebreakers makes the concept of ship-induced turbulence quite feasible. These vessels can provide very good mixing energy over a broad area, and can do so in a targeted manner (**Figure 19**). This is important because in dense ice situations and in complete

Figure 19: Ship induced turbulence for mixing energy (SINTEF)

ice cover, the mixing energy must be sufficient to create very small droplets to ensure that the droplets remain suspended and diffuse throughout the water column under the limited natural turbulence present under the ice cover: otherwise the oil would simply rise back to the underside of the ice after the ship moved on.

The research to date has included tests in small-scale and at close to full-scale in a ship-maneuvering basin, and has shown that the technique is likely to be very effective, with the droplets generated remaining suspended in a quiescent tank for several weeks (Spring et al., 2006; Nedwed et al., 2007; Nedwed, 2007). The scaled ice-basin test also found that prop wash from a large ice breaker is likely to immediately disperse the oil to depths of 15 to 20m below the surface. This results in a more dilute and therefore immediately less toxic solution with smaller oil droplets and a more stable dispersion. To gain further knowledge, additional research could include measuring the amount of turbulence present under ice, the size of the oil drops required for permanent dispersal under the ice, and the drop sizes generated by this process for different oil types.

Brackish Water Influence

Brackish water (i.e., water with less than the typical salinity of seawater) could be a concern for effectiveness of dispersants in nearshore areas that are influenced by river outflows and in ice fields that are melting, due to the effect of melt water. It has been well documented that traditional marine dispersant products are most effective in water with salinity between 25 and 40 parts per thousand (ppt) (SL Ross, 2010). The effectiveness of most dispersants declines with salinities that are higher or lower than this range. However, some freshwater formulations have been developed and many have proved to be more effective in brackish and fresh waters than conventional dispersants (Belk et al., 1989; Brandvik et al., 1992; Byford et al., 1983; George-Ares et al., 2001; Lehtinen and Vesala, 1984; Lewis and Daling, 2007). This could be an important issue from a contingency planning perspective: to assess and stockpile dispersant products that are specifically suited to the salinity conditions that occur in the areas of interest.

Application Equipment

To treat surface spills, dispersants are sprayed onto an oil slick using a variety of devices from boats, helicopters, and fixed-wing aircraft. One of the problems with most application equipment, and particularly those used with aircraft, is precisely targeting the oil slick and not wasting dispersant. This is a particular problem with fixed-wing aircraft: although they are excellent for providing coverage over broad areas and giving a benefit of high encounter rates relative to boat based application, they are less adept at hitting discrete slicks as might be found in an ice-affected environment.

A recent innovation developed in Norway and tested in the SINTEF JIP experiments in 2009 addresses this problem. The device is an articulated spray arm, similar to those used for aircraft de-icing operations. The arm provides up to several metres reach from the side of the application ship, and the series of nozzles on the arm provide accurate delivery of the dispersant to the target areas (**Figure 20**). The device was tested in laboratory experiments, and then used successfully in the 2009 tests in dense pack ice in the Barents Sea (Sørstrøm et al., 2010).

Figure 20: 2009 SINTEF JIP FEX testing the articulated spray arm (SINTEF)

Toxicity

Modern dispersant formulations are composed of low toxicity, biodegradable surfactants (CDC, 2010a; NRC, 2005) dissolved in nonaromatic hydrocarbon or water-miscible solvents. Ingredients used in Corexit 9500, for example, have many alternative household uses, as shown in **Table 2** (Nalco, 2010). Environment Canada found that commonly used dish soap was 25 times more toxic to rainbow trout than a common dispersant (**Table 3**; Fingas et al., 1995). In its 2005 report on dispersants, the NRC stated

Table 3.
Environment Canada comparison of aquatic toxicity of household cleaners to modern dispersants (Fingas et al., 1995)*.

Product	Rainbow Trout 96 hour LC_{50} (ppm)
Palmolive dish soap	13
Sunlight dish soap	13
Mr. Clean cleaner	30
Citrikleen XPC cleaner	34
Enersperse 700 dispersant	50
Lestoil cleaner	51
Corexit 9527	108
BP 1100 WD	120
Oil Spill Eater bioremediation product	135
Corexit 9500	354
BP 1100X AB dispersant	2900

*Note that lower LC_{50} defines greater toxicity

that the potential acute toxicity of chemically dispersed oil is primarily associated with the oil and dissolved oil constituents and not with the current generation of dispersants (NRC, 2005).

The key determinants of toxicity for a given species are concentrations and time of exposure. The available data suggest that maximum dispersed oil concentrations after a spill are less than 50 mg/L immediately after dispersion and that dispersed oil concentrations dilute rapidly, dropping to 1 to 2 mg/L in less than 2 hours (Cormack and Nichols, 1977; McAuliffe et al., 1980; Daling and Indrebo, 1996).

Trudel et al. (2009) showed that concentrations of dispersed oil after successful dispersion are generally less than 100 mg/L, even in closed wave tanks.

For most species that have been tested, dispersed-oil acute toxicity thresholds are on the order of 1 mg/L based on laboratory tests that expose test organisms in closed 1-L containers for periods of 2 to 4 days. Water column concentrations above toxicity thresholds in an actual spill are limited to the top few metres and are limited in time because of rapid dilution. A simple calculation illustrates how rapidly dispersed oil dilutes. A low-viscosity oil is expected to have an average thickness on the sea surface of 0.1 mm (adapted from Lehr et al., 1984). Applying dispersant to a slick in 1m waves is expected to cause nearly immediate mixing of dispersed oil into the top 1 m of the water column. This results in immediate dilution by a factor of 10,000 to give an average hydrocarbon concentration of 100 mg/L. Trudel et al. (2009) studied dispersion of several Alaskan crude oil samples in a wave tank confirming the immediate dilution. They sampled the clearly observed dispersed oil plume right after dispersion and found concentrations that ranged from 5 mg/L to a maximum of 147 mg/L oil. For these tests, the dispersion effectiveness ranged from a low of 85% (the only test of ten reported that had <90% effectiveness) to 100%. Dispersed oil plumes continue to dilute with time, and dispersed oil at sea is estimated to become very dilute in less than a day (Cormack and Nichols, 1977; French McCay and Payne, 2001; French McCay et al., 2006; IPIECA, 2001; McAuliffe et al., 1980).

Dispersed oil may potentially cause environmental impacts but these are limited to the organisms in the immediate vicinity of quickly dissipating dispersed oil plume. These impacts are generally limited to non-mobile organisms that have reproductive schemes that can readily recover from large losses.

Dispersants themselves rapidly dilute in the open ocean even in the absence of dispersed oil. The NRC (1989) report stated that small-scale field tests have indicated that the concentration of dispersant in water falls to less than 1 mg/L within hours. These low concentrations are generally below estimated toxicity threshold concentrations derived from “constant” exposure experiments (NRC, 1989).

With the exception of the use of an engine room degreaser as a dispersant during the 1967 Torrey Canyon spill in the United Kingdom, catastrophic losses of mature fish populations from dispersant use have never been reported. Monitoring following the 1996 *Sea Empress* oil spill incident in the United Kingdom demonstrated that the use of dispersants resulted in an environmental benefit compared to other potential response strategies (Lunel et al., 1997). Surveys conducted after the 2010 Macondo incident, where dispersants were used in the Gulf of Mexico, indicate that significant losses of juvenile fish and larvae did not occur. Scientists from the University of North Carolina’s Institute of Marine Science used a five-year data set within the oil-affected region and conducted surveys of juvenile fish in sea grass beds along the coasts of Mississippi, Alabama, and Florida two months after flow was stopped from the Macondo well. The fish species they surveyed would have been floating as larva in the Gulf of Mexico during the oil spill. They found that overall, species by species catch rates were high in 2010 after the spill relative to the previous four years (Fodrie and Heck, 2011).

Dispersant toxicity research has been conducted recently on specific Arctic species of concern. It was found that Arctic species that were tested have similar or greater tolerance to representative concentrations of dispersed oil, and that the dispersants’ acute toxicity only occurs at concentrations that are much greater than any proposed use of dispersant product (McFarlin et al., 2011).

Degradation of Dispersed Oil in Arctic Environments

Dispersed oil readily biodegrades in the marine environment partly due to the increased surface area resulting from the production of small oil droplets (Lessard and Demarco, 2000). Dispersion and dilution in the open water allows the natural levels of biologically available oxygen, nitrogen and phosphorus to support efficient biodegradation and maintain a viable community of oil degrading bacteria (Swannell and Daniel, 1999; Hazen et al., 2010). Laboratory studies have shown that oil degrading microbes colonize dispersed oil droplets within a few days (MacNaughton et al., 2003). Furthermore, recent arctic specific research has shown that biodegradation and mineralization occurred in fresh and 20% weathered ANS crude at both 2°C and -1°C with indigenous Arctic microorganisms and that the addition of Corexit 9500 enhanced the degradation (McFarlin et al., 2011). The composition of some dispersants enhances the biodegradation because they serve as an initial food source for bacterial growth (Varadaraj et al., 1995).

The EPA conducted a study on dispersed oil biodegradation using concentrations approaching expected field concentrations (Venosa and Holder, 2007). They studied the biodegradation of dispersed ANS crude oil at two temperatures and two concentration ranges: nominally 833 mg/L and 83 mg/L. They found rapid biodegradation at 20ºC (greater than 80% of the alkanes consumed in 30 days) and only slightly reduced biodegradation rates at 5ºC (greater than 80% of the alkanes consumed in 40 days).

Studies of the Macondo incident are providing evidence of crude oil biodegradation in the Gulf of Mexico. Hazen et al. (2010) collected deep water samples during the incident, analyzed the microbial communities, and conducted lab biodegradation studies. They found that a variety of oil degrading populations existed in the subsea plume and that the microbial communities rapidly adapted to and consumed the dispersed oil. Their findings indicate that rapid biodegradation of oil occurs in the deep-sea and that oil degrading bacteria have an important role in removing hydrocarbons from the Gulf.

The studies conducted by Venosa and Holder (2007), Hazen et al. (2010) and McFarlin (2011) provide evidence that biodegradation of dispersed oil readily occurs at temperatures approaching those expected in Arctic waters.

Guidance Documents

In order to facilitate quick decision-making during a spill; regulatory agencies in many parts of the world have established systems for expediting decisions regarding dispersant use. This may include establishing dispersant pre-approval zones or conditions, or developing tools to assist in the decision process.

Many countries have guidance documents for dispersant use. They generally specify the conditions under which dispersant use is or is not acceptable, and list the products that have been approved for use. The International Maritime Organization (IMO) publishes the *IMO/UNEP Guidelines on Oil Spill Dispersant Application including Environmental Considerations*. It provides a good framework for evaluating the use of dispersants in general and for particular situations. CEDRE, the Center of Documentation, Research and Experimentation on Accidental Water Pollution developed a dispersants airborne and shipborne treatment response manual called *Using dispersant to treat oil slicks at sea*.

Use of Oil-Mineral Aggregates (OMA)

Many research studies have shown that physically dispersed oil droplets aggregate readily with suspended particulate matter (SPM), such as clay minerals or organic matter to form oil-SPM aggregates (OSA), also called OMA. It is important to distinguish the use of OMA from sinking agents: rather than cause the oil droplets to sink, OMA will cause the oil to be suspended in the water, in much the same manner as chemical dispersants (Khelifa, 2005; Khelifa et al., 2005; Clouthier et al., 2005). Terminologies such as oil-clay flocculation, oil-SPM interactions, and oil-fines interactions have been used to describe this natural process. The simplest form of OMA consists of an oil droplet coated with micrometre-sized solid mineral particles that prevent the droplets from sticking to each other and reforming a slick.

When OMA forms, the dense mineral fines (2.5 to 3.5 times denser than most oils) adhering to the oil droplets will reduce the overall buoyancy of the droplets, retarding their rise to the surface, promoting their dispersion throughout the water column at low concentrations, and ultimately enhancing their biodegradation by natural bacteria. Preventing the surfacing of the droplets under the adjacent ice would be a significant environmental benefit as OMA formation enhances natural cleanup of oiled shorelines and biodegradation of spilled oil.

In recent years, the Canadian Coast Guard and Department of Fisheries and Oceans Canada have been researching the concept of adding mineral fines to oil spills in ice, then subjecting the treated slick to the prop wash from icebreakers in order to promote dispersion of the spills and enhance their biodegradation. Positive lab and basin tests of the concept led to a field test in 2008 (Lee et al., 2011).

The field test was designed to evaluate the concept of using an icebreaker's propeller to create OMA. Several experimental spills of about 200 litres of fuel oil were carried out in the St. Lawrence River near Matane, Québec. Chalk fines were mixed with seawater and sprayed onto the spilled oil while the propeller of an icebreaker was used to mix the slurry with the oil and disperse the mixture. Visual observations confirmed that the oil was physically dispersed into the water column and that it did not resurface. Resurfacing was observed in the tests that did not receive treatment (**Figure 21**). The researchers used

Figure 21: Photos taken during field tests of OMA-treated oil in ice after enhancing the dispersion with propeller wash of an ice breaker (SINTEF)

microscopes to verify that the oil had formed OMAs, and they collected water samples to conduct biodegradation studies in the lab. Results from the laboratory study showed that more than 56% of the total petroleum hydrocarbons (TPH) had been degraded after 56 days incubation at 0.5°C (Lee et al., 2009).

Additional laboratory, test tank and fieldwork have been conducted to further advance this potential countermeasure in ice conditions (Lee et al., 2011). The research supports the use of this technology as an oil spill response tool.

Summary Points

- There is a good knowledge base on the use of dispersants in temperate conditions based on 30+ years of research and usage in spill response. There is also a significant amount of research on dispersants in Arctic conditions. Laboratory, test tank, and field testing indicate that dispersants can be an effective response technology at cold temperatures, in the presence of ice, and even in the influence of brackish water.
- There is also a good knowledge base on the environmental effects of dispersant-use, and good decision-making tools have been developed to assist in pre-spill planning and in decision-making at the time of a response.
- Research has also addressed questions on the ultimate degradation of dispersed oil in Artic environments finding that oil does biodegrade in temperatures found in the Arctic.
- In open drift ice conditions (30 to 90% ice coverage), wave energy may be sufficient to allow dispersion of oil that has had dispersants applied to the slick.
- In more dense ice conditions, additional mixing energy is likely required, and research has found that the use of propeller wash from ice-breaking vessels is effective is ice environments..

- Recent technology developments include improvements to dispersant formulations and more targeted application equipment for use from ice-breaking vessels that can also provide the targeted mixing energy needed for dispersants use in ice.
- Dispersant use has been a controversial technique and remains somewhat restricted in some jurisdictions. The successful use of dispersants during the Macondo spill to reduce the environmental threat of oil on the water surface, and the ongoing studies related to the ultimate fate of the oil will add to our understanding of benefits of dispersant use.
- Arctic conditions could result in the extended window of opportunity for dispersant use. When used with appropriate environmental considerations in mind it has the potential to become a prominent Arctic response technique.

Further Reading

Aberdeen University Research and Industrial Services (AURIS). 1994. **Scientific criteria to optimize oil spill clean-up operations and efforts**. Report by AURIS Environmental, Aberdeen, Scotland. 56 pp. plus appendices.

Belk, J.L., D.J. Elliott and L.M. Flaherty. 1989. **The comparative effectiveness of dispersants in fresh and low salinity waters**. In: *Proceedings 1989 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA.

Belore, R. 2008. **Effectiveness of chemical dispersants on Alaskan oils in cold water**. In: *Proceedings Northern Oil and Gas Research Forum*. MMS Alaska. Anchorage, AK, USA.

Belore, R. 2003. **Large wave tank dispersant effectiveness testing in cold water**. In: *Proceedings 2003*

*International Oil Spill Conferenc*e. American Petroleum Institute. Washington, DC, USA.

Belore, R.C., K. Trudel, J.V. Mullin and A. Guarino. 2009. **Large-scale cold water dispersant effectiveness experiments with Alaskan crude oils and Corexit 9500 and 9527 dispersants**. *Marine Pollution Bulletin*, 58, pp. 118–128.

Brandvik, P.J., M.Q. Moldestad and P.S. Daling. 1992. **Laboratory testing of dispersants under Arctic conditions**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar* No. 15, pp. 123-134. Environment Canada, Ottawa, Canada.

Brown, H.M. and R.H. Goodman. 1996. **The use of dispersants in broken ice**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar* No. 19, Vol. 1, pp. 453-460. Environment Canada, Ottawa, Canada.

Byford, D.C., P.J. Green, and A. Lewis. 1983. **Factors influencing the performance and selection of low-temperature dispersants**. In: *Proceedings of the Arctic Marine Oilspill Program (AMOP) Technical Seminar*, pp. 140-150. Environment Canada, Ottawa, Canada.

CDC (2010a) website http://emergency.cdc.gov/gulfoilspill2010/dispersants_hcp_info.asp.

CEDRE. Using dispersants to treat oil slicks at sea. Available: http://www.cedre.fr/en/publication/dispersant/dispersant.php.

Clark., J., T. Coolbaugh, R. Belore, J. Mullin, R. Lessard, and A. Findlay. 2009. **Assessing the dispersibility of heavy and viscous oils**. In: *Proceedings of Interspill 2009*. Marseille, France, May 12 to 14, 2009. 10 pp.

Cloutier, D, S. Gharbi and B. Michel. 2005. **On the oil-mineral aggregation process: a promising response technology in ice-infested waters**. In: *Proceedings 2005 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA.

Cormack, D. and J.A. Nichols. 1977. **The Concentrations of Oil in Sea Water Resulting from Natural and Chemically Induced Dispersion of Oil Slicks**. In: *Proceedings*

1977 International Oil Spill Conference. American Petroleum Institute. Washington, DC, USA.

Daling, P.S. and G. Indrebo. 1996. **Recent improvements in optimizing use of dispersants as a cost-effective oil spill countermeasure technique**. In: *International Conference on Health, Safety & Environment*, New Orleans, LA, USA. 9-12 June 1996.

Derewicz, M. 2011. **After the spill the fish are all right?, endeavors, research and creativity**, The University of North Carolina at Chapel Hill, NC, USA. Spring 2011.

EPA. 2011. EPA Response to BP Spill in the Gulf of Mexico: Dispersants Website http://www.epa.gov/bpspill/dispersants.html.

Farmwald, J.W. and W.G. Nelson. 1982. **Dispersion characteristics and flammability of oil under low ambient temperature conditions**. In: *Proceedings of the Fifth Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*. Environment Canada, Ottawa, Ontario, Canada.

Fingas, M.F., D.A. Kyle, N. Laroche, B. Fieldhouse, G. Sergy and G. Stoodley. 1995. **The effectiveness of oil spill-treating agents**. In: *The Use of Chemicals in Oil Spill Response*, ASTM STP1252, P. Lane, Ed. American Society of Testing and Materials, Philadelphia, PA, USA. pp. 286-298.

Fodrie F.J. and K.L. Heck, Jr. 2011. **Response of coastal fishes to the Gulf of Mexico oil disaster**. *PLoS ONE* 6(7): e21609. doi:10.1371/journal.pone.0021609. Available on line from: http://www.plosone.org/article/info:doi/10.1371/journal.pone.0021609 .

French McCay, D.P. and J.R. Payne. 2001. **Model of oil fate and water concentrations with and without application of dispersants**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. Environment Canada, Ottawa, Canada. pp. 611-645.

French McCay, D.P., J.J. Rowe, W. Nordhausen and J.R. Payne. 2006. **Modeling potential impacts of effective dispersant use on aquatic biota**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical*

Seminar. Environment Canada, Ottawa, Canada, pp. 855-878.

George-Ares, A., R.R. Lessard, K.W. Becker, G.P. Canevari and R.J. Fiocco, 2001. **Modification of the dispersant Corexit 9500 for use in freshwater**. In: *Proceedings 2001 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA.

Hazen, T.C., E.A. Dubinsky, T.Z. DeSantis, G.L. Andersen, Y.M. Piceno, N. Singh, J.K. Jansson, A. Probst, S.E. Borglin, J.L. Fortney, W.T. Stringfellow, M. Bill, M.S. Conrad, L.M. Tom, K.L. Chavarria, T.R. Alusi, R. Lamendella, D.C. Joyner, C. Spier, J. Baelum, M. Auer, M.L. Zemla, R. Chakraborty, E.L. Sonnenthal, P. D'haeseleer, H-Y.N. Holman, S. Osman, Z. Lu, J.D. Van Nostrand, Y. Deng, J. Zhou and O.U. Mason. 2010. **Deep-sea oil plume enriches indigenous oil-degrading bacteria**. *Sciencexpress*, August 24, 2010, DOI: 10.1126/science.1195979.

IMO/UNEP 1995. **Guidelines on oil spill dispersant application including environmental consideration**. International Maritime Organization.

International Petroleum Industry Environmental Conservation Association (IPIECA). 2001. **Dispersants and their role in oil spill response, 2nd Edition**. *IPIECA Report Series Volume Five*. London, UK. 36 pp.

Khelifa, A. 2005. **Validation de la formation d'agrégats pétrole-argile dans une eau saumâtre et froide**. Technical Report No. FJMP3-05RTI submitted to the Canadian Coast Guard, 28 pp.

Khelifa, A., L. Ajijolaiya, P. MacPherson, K. Lee, P. Hill, S. Gharbi and M. Blouin. 2005. **Validation of OMA formation in cold brackish and sea waters**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 28, Vol. 1, pp. 527-538. Environment Canada, Ottawa, Canada.

Lee, K., Z. Li, B. Robinson, P. Kepkay, M. Blouin, and B. Doyon. 2011. **Field trials of in-situ oil spill countermeasures in ice-infested waters**. In: *Proceedings of the 2011 International Oil Spill Conference*. Portland, OR, USA. #2011-160.

Lee, K. Z. Li, B. Robinson, P. Kepkay, X. Ma, S. Cobanli, T. King, M. Blouin and B. Doyon. 2009. **In-situ remediation of oil spills in ice-infected waters: oil dispersion by enhancing formation of oil-mineral aggregates**. In: *Proceedings of Interspill 2009*. Marseille, France, May 12 to 14, 2009.

Lehr, W.J., H.M. Cekirge, R.J. Fraga and M.S. Belen. 1984. **Empirical studies of the spreading of oil spills**. *Oil & Petrochemical Pollution*, Graham & Trotman, Ltd. Vol. 2 No. 1.

Lehtinen, C.A. and A.M. Vesala. 1984. **Oil spill chemical dispersants**. **Research, experience and recommendations**. *Effectiveness of oil spill dispersants at low salinities and low water temperatures*. ASTM Special Technical Publication STP840. pp. 107-121.

Lessard, R. and G. Demarco. 2000. **The significance of oil spill dispersants**, *Spill Science & Technology Bulletin*, Volume 6, Issue 1, February 2000, pp. 59-68.

Lewis, A. and P.S. Daling. 2007. **Oil in ice: A review of studies of oil spill dispersant effectiveness in Arctic conditions** (JIP Project 4, Act. 4.11). Report No. 11: SINTEF A 16086 Report Publication. 22 pp.

Lewis, A. and SINTEF. 2001. **Oil Spill Dispersants.** SINTEF publication. Trondheim, Norway. http://documents.plant.wur.nl/imares/dispersants/08sintef.pdf).

Lunel, T., J. Rusin, N. Bailey, C. Halliwell and L. Davies. (1997). **The net environmental benefit of a successful dispersant operation at the *Sea Empress* incident**. In: *Proceedings of the 1997 Interspill Oil Spill Conference*. United Kingdom.

Mackay. 1995. **Effectiveness of chemical dispersants under breaking wave conditions: the use of chemicals in oil spill response**. ASTM STP 1252. Peter Lane (Ed.), American Society for Testing and Materials, West Conshohocken, PA, USA.

MacNaughton, S.J., R. Swannell, F. Daniel and L. Bristow. 2003. **Biodegradation of dispersed forties crude and Alaskan North Slope oils in microcosms under**

simulated marine conditions. *Spill Science & Technology Bulletin*, 8, 179.

McAuliffe, C.D., J.C. Johnson, S.H. Greene, G.P. Canevari and T.D. Searl. 1980. **Dispersion and weathering of chemically treated crude oils on the ocean**. *Environmental Science and Technology*, 14:1509.

McFarlin, K. M., R.A. Perkins, W.W. Gardner, J.D. Word, and J.Q. Word. 2011. **Toxicity of physically and chemically dispersed oil to selected Arctic Species**. In: *Proceedings of the 2011 International Oil Spill Conference*. Portland, OR, USA. #2011-149.

Mullin, J. 2004. **Dispersant effectiveness experiments conducted on Alaskan and Canadian crude oils in very cold water**. In: *Proceedings of Interspill 2004*. United Kingdom.

Mullin, J. 2007. **Cold water dispersant effectiveness experiments conducted at OHMSETT with Alaskan crude oils and Corexit 9500 and 9527 dispersants**. In: *Proceedings International Oil & Ice Workshop 2007*. Minerals Management Service. Herndon, VA, USA.

Mullin, J., R. Belore and K. Trudel. 2008. **Cold water dispersant effectiveness experiments conducted at OHMSETT with Alaskan crude oils using Corexit 9500 and 9527 dispersants**. In: *Proceedings of the 2008 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA.

Nalco (2010). **COREXIT Ingredients**. Available online at http://www.nalco.com/applications/4297.htm.

National Research Council (NRC). 1989. *Using Oil Dispersant on the Sea*. The National Academy Press, Washington, DC, USA. 335 pp.

National Research Council (NRC). 2005. *Oil Spill Dispersants: Efficacy and Effects*. The National Academy Press, Washington, DC, USA.

Nedwed, T. 2007. **ExxonMobil research on remotely applied response options for spills in dynamic ice**. In: *Proceedings International Oil & Ice Workshop 2007*. Minerals Management Service. Herndon, VA, USA.

Nedwed, T., W. Spring, R. Belore and D. Blanchet. 2007. **Basin-scale testing of ASD icebreaker enhanced chemical dispersion of oil spills**. *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 30, Vol. 1, pp. 151-160. Environment Canada, Ottawa, Canada.

Nedwed, T., G.P. Canevari, J.R. Clark and R. Belore. 2008. **New dispersant delivered as a gel**. In: *Proceedings of the 2008 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA.

Owens, C. and R. Belore. 2004. **Dispersant effectiveness testing in cold water and brash ice**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar* No. 27, Vol. 2, pp. 819-841. Environment Canada, Ottawa, Canada.

Sørstrøm, S.E., P.J. Brandvik, I. Buist, P. Daling, D. Dickins, L-G. Faksness, S. Potter, J.F. Rasmussen and I. Singsaas. 2010. **Joint industry program on oil spill contingency for Arctic and ice-covered waters: Summary report**. SINTEF report A14181. SINTEF. Trondheim, Norway. www.sintef.no/Projectweb/JIP-Oil-In-Ice/Publications/.

SL Ross Environmental Research (SL Ross). 2010. **Literature review of chemical oil spill dispersants and herders in fresh and brackish waters**. Prepared for the US Dept. of the Interior, Minerals Management Service, Herndon, VA, USA. 60 pp.

Spring, W., T. Nedwed and R. Belore. 2006. **Icebreaker enhanced chemical dispersion of oil spills**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar* No. 29b, pp. 711-727. Environment Canada, Ottawa, Canada.

Swannell, R.P.J. and F. Daniel. 1999. **Effect of dispersants on oil biodegradation under simulated marine conditions**. #212, In: *Proceedings of the 1999 InterSpill 1999*. United Kingdom.

Trudel, K., R. Belore, M. VanHaverbeke and J. Mullin. 2009. **Updating the U.S. SMART dispersant efficacy monitoring protocol**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. Environment Canada, Ottawa, Canada, pp. 397-410.

Varadaraj, R., M.L. Robbins, J. Bock, S. Pace and D. MacDonald. (1995). **Dispersion and biodegradation of oil spills on water**. In: *Proceedings of the 1995 International Oil Spill Conference*. American Petroleum Institute, Washington, DC, USA.

Venosa, A.D. and E.L. Holder. 2007. **Biodegradability of dispersed crude oil at two different temperatures**. *Marine Pollution Bull*., 54:545-553.

This Page Intentionally Left Blank.

Section 5

Response Options: Containment and Recovery

The term "containment and recovery" is generally used to describe those actions taken to remove oil from the surface of water, whether by containing the oil with boom, and/or recovering it with a skimming device or sorbent material, followed by storing the recovered oil on board the skimming vessel or associated barge, and then disposing or recycling the recovered liquids and oil-contaminated material. A principal reason for the commonly expressed preference for this technique is that when it is successful, it removes the spilled oil from the environment. Containment and recovery is well suited to spill response in harbors and other protected waters where conditions are most favorable to the basic physical challenge of removing one liquid from the surface of another, and where equipment and supplies to accomplish containment and recovery are often available and quickly deployable. It is and will continue to be the most widely used response option because most spills are small and occur near shore. The suitability of this method for many Arctic marine response scenarios, particularly large offshore spills, could be more problematic.

__Encounter Rate__ refers to the amount of oil which comes into contact with a recovery device (skimmer, sorbents) over a given period of time.

The key for this response option to be effective and efficient is **ENCOUNTER RATE**. It is important to understand that encounter rate is negatively impacted through oil rapidly spreading on the water's surface under the effects of gravity, surface tension, current movement, and wind. Spilled oil will quickly spread out over the water surface to a thickness of about one millimetre. As a reference point, visible oil sheen is only 0.003mm thick, and a cup of spilled oil can create a visible sheen over an area the size of a football field. Additionally, it does not take long for wind to further reduce the encounter rate by moving spilled oil into fragmented fingers or windrows of oil on the surface. As oil rapidly spreads and reduces in layer thickness and breaks into patches or **WINDROWS**, the encounter rate and recovery efficiency of skimming equipment in particular is significantly reduced. Historically, mechanical recovery has only been able to recover a fraction of oil spilled into the open ocean. Thus, if mechanical recovery is the only response option used for offshore spills, most of the oil will remain in the environment in a form that has the potential to increase environmental damage and slow recovery. Oil spill responders, planners, and decision-makers need to understand these limitations to develop robust response strategies.

*A **Windrow** refers to when an oil slick on water spreads, and becomes thinner, it is more susceptible to being broken up by wave, wind, and current movement, forming into smaller patches and narrow, multiple bands or streaks that are oriented in the direction of the wind or current; this begin to form with wind speeds of approximately six knots or more. (Source: NOAA, 2007 – Open Water Oil Identification Job Aid for Aerial Observation.)*

In planning for response to potential spills in the Arctic, two very different situations must be considered: open water conditions and varying degrees of ice cover. Most Arctic regions have minimal ice or are ice-free for at least some portion of the year and traditional containment and recovery operations can be conducted using booms and skimmers; this is described briefly below. However, the focus of this section is on techniques and equipment that would be used to recover oil that might be spilled in and amongst pack ice, which has led to the development of a number of specialized skimmers for this situation. Finally, planning for response to potential spills in the Arctic should take into account the fact that during much of the open water period when containment and recovery methods are feasible, extended daylight hours will assist responders in their efforts to track a spill, to observe the efficacy of response efforts and to make such operational adjustments as appropriate and necessary.

Containment in Open Water

Oil spilled on open water will quickly spread to form a thin slick. As a result, some form of containment is generally required to concentrate oil and thicken it for effective recovery. A typical configuration for oil containment and recovery in open water consists of a segment boom drawn between two vessels and a skimmer for recovery and pumping of the recovered oil back to tanks onboard the mother vessel. In recent years systems operated from a single vessel have been developed. This is typically done with booms connected to arms alongside of a vessel creating a pocket to concentrate oil for recovery. In either case, a skimmer would be positioned in the pocket of the boom where the oil would be concentrated for effective recovery (**Figure 22**).

Figure 22: Skimmer positioned in boom apex (SINTEF)

With containment boom, there are a multitude of good products available. For offshore applications, the most commonly used boom are air-inflatable and generally reel-mounted, which together provide a product that is relatively compact that can be deployed relatively quickly. Many offshore boom products are made with abrasion-resistant, high-strength materials, which will allow use in waters where occasional ice intrusions occur, and which will avoid embrittlement in cold water, cold temperature operating conditions. Containment boom used in arctic conditions should be made of materials suitable for cold weather applications.

The length of open water containment boom usually deployed in an open-water tow is typically limited to 460m (1,500 ft.). Beyond 460m, controlling the tow vessel(s) becomes difficult and increased vessel size and horsepower become necessary. When using boom lengths of 460m, the actual opening or swath width to encounter oil is limited to 90 to 150m.

The speed of advance of boom systems is a limiting factor in encounter rate. Many conventional containment boom fail to contain oil at speeds greater than about 1 knot. This is a result of oil entraining from the front of the slick and flowing past the underside of the boom, and is a function of fluid dynamics rather than boom performance. In recent years there have been a number of innovative designs capable of containing oil at speeds greater than 1 knot, for example, the Vikoma Fasflo and the NOFI Current

Buster^{TM}. Both systems modify the flow of water at the entrance to the containment area to create a more quiescent zone for skimming. As part of the USCG Fast-Water research program, these and several other fast-water devices were tested at OHMSETT in currents of up to 5 knots. The tests showed that efficient containment and recovery could be achieved in currents of over 3 knots in calm water, and in 2-knot currents with a harbour chop wave condition (USCG, 2001). Systems such as these could be of use in open waters and in waters with low ice concentrations: with a greater encounter speed, a reasonable encounter rate could be achieved with a shorter length of boom. This would be advantageous from two perspectives: first, it could be more easily managed by vessels-of-opportunity, and second, it would be more easily manoeuvred in the presence of occasional ice floes.

Another recent innovation is the use of boom vanes, which provide superior positioning of containment boom while using fewer boats (Hansen, 2000). A boom vane uses a series of vertical plates within its structure, all of which is submerged in operation, to develop a hydrodynamic force that will pull the end of the boom into the current. By precisely establishing the length of towline with respect to the length of boom and the speed of the tow, a boom vane will position the leading end of a boom at a fixed position relative to the towing vessel or to the shore.

To maximize encounter rates, a number of advancements have been made for better management of response resources so that they can be directed to the heaviest concentrations of oil. As such, developments have occurred in a number of forms:

- Ship radar-based systems;
- Infrared cameras/sensors;
- Aerial observation systems; and
- Ensuring rapid down-linking of aerial observations or oil plots to vessels on scene and improving

communication arrangements to ensure that surface vessels can be directed to oil concentrations.

Skimming Systems for Recovery in Open Water

***Oleophilic** refers to a product (in this case skimming system) that has a strong affinity for oils rather than water.*

There are currently four main types of skimmers that have been used to recover oil at sea: **OLEOPHILIC**, weir, vacuum, and mechanical. Although the principles behind skimming systems have not changed considerably over the past thirty years or more, better design and engineering have led to notable improvements in recovery efficiency. Each of the systems has their advantages and disadvantages.

Oleophilic systems

Oleophilic systems rely on the property of oil adhering to a drum, belt, brush, disc or mop type arrangement. The oil is then scraped off into a chamber from where it is pumped to storage. These devices are efficient and it is common for them to have a high recovered oil-to-water ratio. The oil types most suited are the light to medium viscosity oils but very high viscosity oils could be handled using the brush type fittings.

Weir skimmers

These systems rely on oil passing over a weir arrangement which is used to separate the oil and water phases. In many applications these units are less efficient than oleophilic skimmers and often recover significant amounts of free water together with oil, requiring more storage capacity for recovered liquids than is usually the case for oleophilic systems. The range in the size of weir skimmers varies tremendously. Larger systems take in substantial quantities of oily water mix and then use high powered pumps to transfer the mixture into large capacity storage tanks where settling and separation can take place. One of the benefits of weir skimmers is their ability to handle both light and heavier products. The heavy products may require the introduction of water with the recovered product to assist in pumping the material into storage.

Vacuum skimmers

These units rely on the use of vacuum or air movement technology to lift oil from the surface of the sea or the shore. Vacuum systems are versatile and able to be used on a variety of oil types (generally excluding heavy oil) although refined volatile products must be avoided for safety reasons. The advantage of vacuum systems is that generally they include an integral storage container and, if mobile, may be used to transport oil to final storage. A disadvantage is that they can be inefficient by recovering more water than oil.

Mechanical skimmers

These systems rely on the physical collection of oil from the surface and include devices from conveyor belts to actual grab buckets. These types of skimmers are more suited to very viscous oils.

Storage and Decanting

An important and limiting factor in effective containment and recovery operations is the availability of recovered oil storage on the skimming vessel. The size of storage, in comparison to the recovery capability of some of the recovery systems, is a critical factor. Weir skimmers as noted previously are prone to high levels of water pick-up which rapidly fills storage barges or tanks to capacity with large quantities of water. “Decanting operations” or the act of pumping water gathered with the recovered oil from temporary storage into the apex of the collection system for re-treatment through the recovery process is critical to extending the operating capability of the system (**please note**: certain jurisdictions require agency authorization and or the issuance of permits before decanting can take place).

The nature of the recovered product is also an important factor as heavy oils may prove difficult to handle, particularly in a cold temperature operating environment. Specialized pumps may be required and storage tanks may require heating coils to permit the recovered product to be removed.

Mechanical Recovery in Ice

As discussed above, boom will generally be required for spills in open water to contain and concentrate oil for recovery. A conventional booming strategy will be most effective in open water and ice concentrations up to 10%, but could also be used with some effectiveness in concentrations up to 20 to 30% especially with active ice management as ice concentrations exceed 70%. Single vessel recovery skimming systems with short sections of boom attached to the sweep arms could maneuver between large ice floes and operate in higher ice concentrations than conventional boom. As ice concentrations increase beyond 70% the ice provides more of a barrier against oil spreading, and in dense ice, will completely prevent oil from spreading and thinning out. This natural containment can be an advantage for response teams because the oil will tend to occupy a smaller area and will remain in thick pockets that are more easily recovered than thin, widespread slicks. Furthermore, the presence of ice also modifies the wind-induced wave action at sea because short waves are damped by the presence of ice. In the absence of breaking waves, oil between ice floes will not weather as fast as it would do in open water where emulsified and weathered oil can have significantly higher viscosity.

Any mechanical recovery system working in ice covered waters needs to be able to deflect the ice in order to gain access to the oil to effectively remove it (referred to as ice processing). It is also necessary to deal with low temperatures, and the skimmers should therefore be protected and/or heated to avoid freezing. In Arctic experiments and field trials to date it has proved to be difficult achieve recovery rates through mechanical means that begin to approach removal rates achievable through burning or dispersant use. For spills near shore in relatively smooth, fast ice, there are mechanical strategies involving trenching, skimming in sumps, and trucking to shore that could prove effective.

Summary Points

- Mechanical recovery of oil spills in ice-covered waters is possible and the methods should be part of the “toolbox” required for response to oil spills in ice.
- Mechanical recovery in the open water season can be more effective in the Arctic than in temperate regions because of the long periods of daylight.
- Concentrated ice (> 70%) can reduce the rate of oil spreading in the absence of boom and thereby reducing spill area and allowing mechanical recovery operations if the oil can be accessed by skimming equipment.
- The effects of cold temperatures must be taken into account in planning and carrying out containment and recovery operations.
- Low encounter rates and the challenge of accessing oil in concentrated ice will limit effective mechanical recovery to small spills.

Further Reading

Hansen, K. 2000. **Boom vane field tests.** Report prepared for United States Coast Guard, Marine Safety and Environmental Protection (G-M) and Systems (G-S). Washington, DC, USA.

Lampela, K. 2007. **Baltic approach to oil spill recovery in ice: case studies and recent development in Baltic Sea**

states. In: *Proceedings International Oil & Ice Workshop 2007*. Minerals Management Service. Herndon, VA, USA.

Mullin, J.V., H.V. Jensen and W. Cox. 2003. **MORICE: new technology for effective oil recovery in ice**. In: *Proceedings 2003 International Oil Spill Conference*. American Petroleum Institute. **Washington, DC, USA.**

NOAA. 2007. **Open water oil identification job aid for aerial observation; New Standardized Oil Slick Appearance and Structure Nomenclature and Code**. UPDATED November 2007. NOAA Office of Response & Restoration, Emergency Response Division. Seattle, WA, USA. 50 pp. Available from http://www.response.restoration.noaa.gov/.

Solsberg, L.B. and M. McGrath. 1992. **Mechanical recovery of oil in ice**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 15, pp. 427-437. Environment Canada, Ottawa, Canada.

Sørstrøm, S.E., P.J. Brandvik, I. Buist, P. Daling, D. Dickins, L-G. Faksness, S. Potter, J.F. Rasmussen and I. Singsaas. 2010. **Joint industry program on oil spill contingency for Arctic and ice-covered waters**. Summary Report. SINTEF Report no. A14181, Trondheim, Norway.

U.S. Coast Guard Research and Development Center. 2001. **Evaluation of four oil spill recovery devices in fast water conditions at OHMSETT**. U.S. Department of Transportation, USCG. Washington, DC, USA.

This Page Intentionally Left Blank.

Section 6

Response Options: Shoreline Protection and Cleanup

Introduction

Research and experience over the past 40 years provide planners and responders with a good understanding of the fate and behaviour of oil in Arctic and cold climate environments.

There are many guidance documents developed to assist decision-makers, operations planners and cleanup workers in responding to oil spills in the Arctic. Two examples are the Alaska Clean Seas (ACS) *Technical Manual for Spill Response* (ACS, 2010) and the Arctic Council's Emergency Prevention, Preparedness and Response (EPPR) working group's *Field Guide for Oil Spill Response in Arctic Waters* (EPPR, 1998).

The primary feature of cold climate shorelines is the presence of ice and snow for some part of the year. Shore-zone ice and snow can occur in a number of forms in latitudes as far south as 40ºN. Excluding inland seas, as much as an estimated 45% of the world's approximately 850,000km of ocean coastlines can have snow or ice for some part of the year.

Character of Cold-Climate Shorelines

Shoreline Types

To a large extent, the shoreline types of cold-climate regions are similar to those of ice-free and snow-free environments. Our knowledge and understanding of shore zone materials and coastal landforms from warmer coastal environments is applicable to cold climates in most respects, with the addition of ice and snow and the presence of tundra, glaciers and ice sheets. Nevertheless, some specific shore types are unique to Arctic and cold-climate regions, among which:

- Ice cliffs of "tidewater" glaciers and ice sheets;
- Ice-rich tundra cliffs with exposed permafrost (**Figure 23**);
- Inundated low-lying tundra (**Figure 24**);
- Boulder barricades, formed by ice rafting on intertidal platforms;
- Sediment ridges created by ice push or ice pressure; and
- Ridges and scarred shores on coasts with fine-grained sediments (sands, silts and clays) in low wave-energy environments.

Figure 23: Tundra cliff shorelines are an erosional feature composed of a tundra mat that usually overlies peat and exposed ground ice (E. H. Owens)

Figure 24: Low-lying inundated tundra (Canadian Beaufort Sea, E. H. Owens)

Our knowledge and understanding of shore-zone processes in warmer climates is also applicable to cold-climate environments with the modifications necessary to account for the role and effects of ice. Typically, ice begins to form onshore before nearshore ice and persists after the nearshore ice has broken or melted. The shore-ice season is therefore longer than the nearshore or offshore ice season. In high latitudes, the ice-free period may be only a few days or weeks so that wave and tidal processes that are typical of warmer environments are limited and very little energy is available to rework shore-zone sediments or stranded oil. Arctic or cold climate shorelines are not necessarily low wave-energy environments, but the length of the open-water season may be shortened due to the presence of ice.

Behaviour of Oil in the Shore Zone

The behaviour of oil in cold climates depends on the source of the oil, the oil characteristics, and the presence and character of ice and/or snow. Spills onto shore ice or snow result from oil either being washed ashore when the adjacent waters are ice free, under-ice oil reaching shore and emerging in tidal cracks, or from land-based spills that flow down slope to the shore.

Studies of oil on Arctic shorelines go back to a 1976 biodegradation experiment in Svalbard that demonstrated accelerated weathering by the addition of a commercial fertilizer (Sendstad, 1980; Sendstad et al., 1984). As there have been few oil spills on Arctic or high latitude coasts, the large-scale BIOS (Baffin Island Oil Spill, Canada) experiment between 1980 and 1983, and the Svalbard Field Trials of 1997 and 2006, Norway (**Figure 25**) provide valuable information (see ***Appendix B: Experimental Spill Studies*** for further details on these experiments). In terms of oil fate and behaviour, these two research studies demonstrate that the same physical and chemical changes occur on cold climate beaches and oil naturally weathers and degrades, albeit more slowly when compared to warmer environments.

Figure 25: Shoreline treatment experiment (Svalbard, E. H. Owens)

Oil and Ice in the Shore Zone

When ice is present in the shore zone it will tend to protect the shoreline from approaching oil. Ice is impermeable so that oil deposited on the surface remains there unless there are cracks in the ice, the ice conditions are floes grounded on the shore, or during the formation of shore fast ice. The ways in which the presence of ice modifies oil behaviour include:

- Oil that flows into cracks or leads may be carried or trapped under the floating ice if the holding capacity of the lead is exceeded.
- Oil may be mixed among grounded floes, coating the floes and shoreline as the individual ice floes

are refloated and moved with the tides or by wave action.

- Oil can become incorporated within existing shore-fast ice or covered by newly formed ice by the freezing of wave splash, spray, or swash.
- The penetration of oil deposited on a beach that is ice free may be limited by the presence of subsurface ice (temporarily frozen groundwater or permafrost).

Oil and Snow in the Shore Zone

The behaviour of oil in snow is known largely from field and laboratory experiments (Bech and Sveum, 1991; Carstens and Sendstad, 1979; Johnson et al., 1980; Mackay et al., 1975). The absorptive or holding capacity of snow varies with oil type and snow characteristics as shown in the following graph (**Figure 26**), (also shown as **Figure 1** in ***Section 1 - Fate and Behaviour of Oil in Arctic Conditions***).

Fresh snow typically has a low density and a high porosity and is a relatively effective sorbent for spilled oil so that light and medium oil may easily penetrate. This reduces surface spreading but this is offset by the increase of oil in the subsurface snow. The volume of Arctic diesel that can be sorbed by fresh, granular snow is on the order of 20%, after the snow-ice mixture has melted. The effect of snow to restrict both horizontal and vertical spreading leads to a much higher percentage oil content.

Evaporation is the single most important weathering process for oil trapped in snow and, although rates are slower, oil on ice in cold environments will eventually (even though covered by snow) evaporate to approximately the same degree as it would if spilled on the water in summer. Test data show that oil covered by snow continues

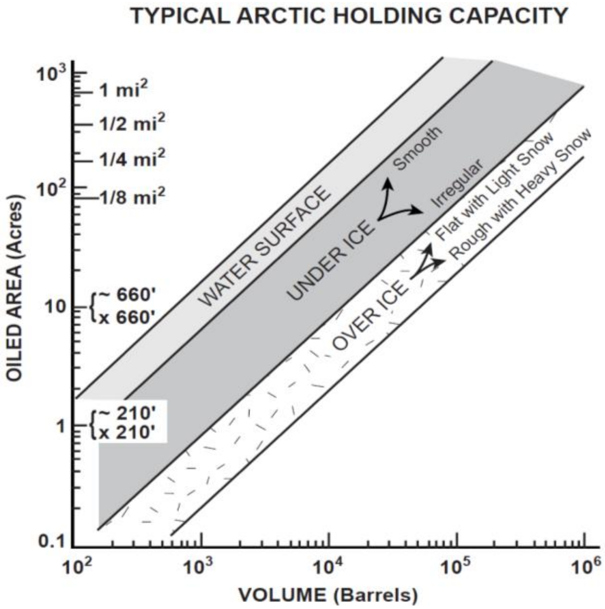


Figure 26: Oil holding capacity for Arctic ice/snow (from ACS Tech. Manual, Vol.1)

to evaporate, albeit at a lower rate than oil directly exposed to air (Buist and Dickins, 2000).

The actual rate of evaporation is a complex function of a number of variables including snow diffusivity (related to the degree of packing), oil properties, air temperature, wind speed, and the thickness of the oiled layer.

Detection and Delineation of Oil in Ice and Snow on the Shore

Surveys to locate and document the presence of oil on the shore typically follow a systematic procedure that may involve an initial ground or air survey followed by detailed ground surveys to locate and define the extent of the affected area. The Shoreline Cleanup Assessment Technique (SCAT) is commonly used as a tool to detect and delineate oil on the shore and has been adapted for use in cold climates and on shorelines with ice and/or snow (Owens and Sergy, 2004). This technique is based on a systematic survey design and the use of standard terms and definitions to create an information base for the response team to decide which shorelines should be cleaned and how cleanup end points can be achieved without incurring environmental damage. In particular, a set of standard terms define the basic categories of shore zone ice and snow conditions.

Oil on the surface of a shoreline or on ice and snow is easily detectable and delineation is straightforward. The detection and delineation of oil on the shore becomes significantly more difficult when oil penetrates beach sediments, is incorporated within or covered by ice or snow. In these circumstances some or none of the oil may be visible and digging, probing or other techniques are required to delineate the subsurface locations(s) and distribution.

Typically, the search for subsurface oil involves a grid or other geometric pattern based on either working outwards from a source or from an observed surface oil patch. Digging pits and trenches is time consuming, especially in ice, and portable ice drills are more efficient. Dogs have been used for many years to detect subsurface oil pipeline leaks and recent field trials have demonstrated that they can successfully and rapidly detect even small amounts of subsurface oil in snow (Sørstrøm, et al., 2010).

Shoreline Protection

The Alaska Clean Seas (ACS) organization has published a regularly revised technical manual which provides a comprehensive and practical guide for inland and shoreline protection.

Protection Priorities

The establishment of response strategies and protection priorities involves evaluation of relative risk for those resources in a potential spill path. Many Arctic regions have well defined high-use habitats, such as deltas, wetlands, bird rookeries, and mammal haul outs, which can be easily identified and mapped. Pre-spill planning may extend to the development of first response protection strategies, for example, at inlets or river mouths.

Setting response priorities involves communication with regional and local communities to identify subsistence and cultural sites that are important to their life style, as well as areas of economic and recreational value.

Protection Strategies

The primary response strategy in all oil spills is to recover or eliminate oil on water as close to the source as possible. To that purpose, depending on the origin of the spill, (e.g., onshore, river, nearshore or offshore) operations involving berms, trenches, dams, shore booms, offshore booms will be used for containment, diversion, deflection and exclusion, as described in ACS Technical Manual, Volume 1 - *Tactics Descriptions*. The coastal zone is one of the more productive ecosystems. As such, the fallback response strategy when source or near-source control is not possible is to prevent oil reaching the shore or to minimize the effects of spilled oil on shore.

Response timing is very different after shoreline and nearshore ice has formed and through the winter as few shoreline resources are at risk. By comparison, a spill towards the end of the winter leaves only a short “summer season” window of opportunity to remove oil in the shore zone before the growing season begins.

Shoreline Cleanup

Shoreline treatment manuals have been prepared for the Arctic and cold climate shorelines that summarize accumulated experience to provide guidance for decision makers and planners. The EPPR *Field Guide for Oil Spill Response in Arctic Waters* (1998) is one such example.

The Cleanup Decision Process

The first steps in the cleanup decision process involve the development of agreed cleanup priorities, strategies, the monitoring and inspection process and the end points so that everyone has the same goals and expectations. However, the decision process is rarely straightforward and must balance environmental concerns, the needs of local communities, operational practicality, and safety (Baker, 1997). Frequently, trade-offs are necessary. For example, tundra shorelines are sensitive to trampling and vehicle traffic during the summer but oil removal or treatment may be considered critical to protect wildlife. The process of Net Environmental Benefit Analysis (NEBA) is particularly important in Arctic environments where recovery would be expected to be slower and where vegetated tundra or wetland shorelines are highly susceptible to disturbance by human or vehicle traffic.

Shoreline Treatment Options

Treatment or cleanup tactics are determined to a large degree by the type and amount of oil and by the shoreline type. **Table 4** is an example of a matrix of preferred tactics developed for different oil types on inundated low-lying tundra.

To a large extent, the same strategies and tactics typically used in warmer environments apply equally to Arctic and cold-climate shorelines so that experiences gained and lessons learned can be applied in most situations. The primary differences relate to the presence of specific shoreline types, in particular, ice and inundated tundra, and operational, safety, and logistics issues associated with remote areas and cold working environments.

Table 4:
Summary of tactics for inundated low-lying tundra

Oil on the surface	Volatile	Light	Medium	Heavy	Solid
Natural recovery	🟢	🟢	🟢		
Flooding	🟢	🟢	🟢		
Low-pressure ambient washing	🟢	🟢	🟢		
Manual removal		○	○	○	
Vacuums		🟢	🟢	🟢	
Vegetation cutting		○	○	○	○
Passive sorbents		○	○	○	

🟢 Preferred option
○ Possibly applicable for small amounts of oil

In addition, winter or cold conditions can significantly alter the physical characteristics of the shore zone with respect to oil behaviour. The selection of cleanup options depends on the character of the shore zone thus response strategies and tactics must be modified when ice and/or snow are present; for example, a shore with permeable coarse sediments in warm months can be replaced by a frozen, impermeable substrate in cold conditions.

The recovery of oiled snow and ice can create a large volume of waste that contain only small amounts of oil and one option to minimize the waste stream is to melt and decant the ice or snow on site.

The individual tactics treat or clean shorelines can be grouped into three basic shoreline response strategies: natural recovery without intervention, physical removal of oiled materials, and in-situ treatment of the stranded oil.

Natural Recovery

Allowing shorelines to recover naturally is often the least damaging alternative for treating light and moderate oiling, particularly where access is limited or difficult, as is often the case for many Arctic shorelines. This strategy may be appropriate where:

- To treat or clean stranded oil may cause more (unacceptable) damage than leaving the environment to recovery naturally;
- Response techniques would not be able to accelerate natural recovery; or
- Safety considerations could place response personnel in danger either from the oil (itself) or from environmental conditions (weather, access, hazards, etc.).

Physical Removal

Physical removal involves the recovery and disposal of stranded oil. There are a range of tactical options to remove oil that basically involve either flushing or washing and recovery or manual or mechanical removal.

Flooding and washing move oil either onto the adjacent water where it can be contained by booms and collected by skimmers, or towards a collection area, such as a lined sump or trench, where it can be removed by a vacuum system or skimmer. This strategy is slow and labor intensive but generates only liquid wastes. Manual removal includes collecting oil using shovels and rakes, cutting oiled vegetation, and deploying and recovering passive sorbents. Manual removal is slow and labor intensive, but generates less waste than mechanical removal. Mechanical removal techniques essentially use equipment designed for earth-moving or construction projects, although a few commercial devices have been fabricated specifically for shoreline cleanup applications. Although cleanup rates are less labor intensive and are much faster than manual removal (which may be factors in remote areas), as much as ten times more waste is generated by mechanical removal, which in itself may be a logistics issue.

In-Situ Treatment

These options involve treatment that is conducted on-site and minimizes the generation or recovery of oiled waste materials that then must be transported and disposed. In-situ treatment is particularly suited for remote areas where logistics are a major factor in operational practicality and feasibility. The range of tactics includes:

- Mechanical mixing of oiled sediments (also known as tilling, land farming, or aeration) can involve agitation either in the absence of water ("dry" mixing) above the water line, or underwater ("wet" mixing). The intent is to expose more oil to weathering or to create a sediment-oil mixture that reduces the potential for wildlife impacts.
- Sediment relocation (also known as berm relocation or surf washing) differs from mixing, although the sediments are thoroughly mixed as the oiled sediments are purposely moved from one location to another with higher wave energy levels.
- Burning of oiled logs or organic debris is commonly used as these contain very small amounts of oil.
- Chemical or biological tactics that involve the addition of agents to facilitate removal of the oil from the shore zone, or accelerate natural in-situ oil removal, degradation and weathering processes. Only bioremediation and the application of shoreline cleaning agents are true in-situ stand-alone techniques, as the other tactics require an

additional removal component. Chemical and biological agents are regulated by government agencies and require appropriate approvals and compliance.

- Bioremediation is a practical option although biodegradation rates may be slowed in cold climates by temperature and limited nutrient availability. Nutrient addition, however, is an option.

Summary Points

- Research and experience over the past 40 years provide planners and responders with a good understanding of the fate and behaviour of oil in Arctic and cold climate environments.
- Tools and guidelines are in place to assist decision-makers, operations planners and cleanup workers, such as the ACS (2010) *Technical Manual for Spill Response* and the EPPR *Field Guide for Oil Spill Response in Arctic Waters* (1998).
- Much of the knowledge and understanding of shore zone materials and coastal landforms, as well as the fate and behaviour of oil in the shore zone, derived from warmer coastal environments is applicable to cold climates in many respects, provided that the additional effects and constraints of ice and snow and the presence of tundra, glaciers and ice sheets are taken into account.

- Shortened growing seasons are the period of higher sensitivity and vulnerability.
- Ice is impermeable so that oil remains on the surface of shore fast ice unless new ice is forming.

- Oil can infiltrate and be absorbed by fresh, granular snow so that little may remain on the surface.
- Landfast ice prevents offshore spilled oil from reaching the shore.
- Setting protection priorities as part of pre-planning in high risk areas typically involves communication at the regional and local levels and an understanding of a range of subsistence, cultural, and economic issues.
- It must be understood that cleaning an oiled shore may do more harm than good. There are always trade-offs in decision-making whether or not to clean, how to clean, and how much to do.
- It is crucial that decision-makers agree on the cleanup strategy, the end points and the inspection ("sign off") process so that everyone has the same objectives and expectations. These should be developed and agreed upon as soon as possible as these goals and objectives are critical to planning for the cleanup operation.
- Washing or manual removal cleanup are labor intensive. Mechanical removal is much quicker but generates more waste for transport and disposal, whereas in-situ treatment tactics minimize the waste stream, an important operational factor in remote areas. The other important operational factors are safety and logistics issues associated with operations in remote and difficult areas such as inundated tundra, and cold working environments.

Further Reading

Alaska Clean Seas (ACS). 2010**. Alaska Clean Seas Technical Manual** (3 volumes), Revision 9, Prudhoe Bay, Alaska, USA, 99734-0022.

Baker, J.M. 1997. **Differences in risk perception: how clean is clean**? Issue Paper prepared for the *International Oil Spill Conference*, American Petroleum Institute, Washington, DC, USA, Tech Report IOSC-006, 52 pp.

Bech, C. and P. Sveum. 1991. **Spreading of oil in snow**. In: *Proceedings of the 14th Arctic and Marine Oilspill Programme (AMOP) Technical Seminar*, Environment Canada, Ottawa, Ontario, Canada, pp. 57-71.

Buist, I. and D.F. Dickins 2000. **Oil fate and behavior in ice.** In: Proceedings of the International Oil and Ice Workshop, Anchorage, organized by Alaska Clean Seas, Prudhoe Bay, Alaska (on disk only).

Carstens, T. and E. Sendstad. 1979. **Oil spill on the shore of an ice-covered fjord in Spitsbergen**. In: *Proceedings POAC 79, 5th Int. Conf. on Port and Ocean Engineering under Arctic Conditions*, pp. 1227-1242.

EPPR. 1998. **Field guide for oil spill response in Arctic Waters**. Environment Canada, Yellowknife, Northwest Territory, Canada, 348 pp.

Johnson, L.A., E.B. Sparrow, T.F. Jenkins, C.M. Collins, C.V. Davenport and T.T. McFadden. 1980. **The fate and effect of crude oil spilled on subarctic permafrost terrain in Interior Alaska**. US Environmental Protection Agency, Office of R&D, Corvallis, OR, USA. Rept. 600/3-80-040.

Mackay, D., P.J. Leinonen, J.C.K. Overall and B.R. Wood. 1975. **The behaviour of crude oil in snow**. *Arctic*, 28(1), 9-22.

Owens, E.H., D.F. Dickins and G.A. Sergy. 2005. **The behavior and documentation of oil spilled on snow- and ice-covered shorelines**. In: *Proceedings International Oil Spill Conference*, American Petroleum Institute Pub. No. I 4718B, Washington, DC, USA, pp. 513-519.

Owens, E.H. and G.A. Sergy. 2004. **The Arctic SCAT Manual – A field guide to the documentation of oiled shorelines in Arctic regions**. Environment Canada, Edmonton AB, 172 pages. (see also: 2004, *Proceedings 27th Arctic Marine Oilspill Program (AMOP) Technical Seminar*, Environment Canada, Ottawa, Ontario, Canada, pp. 703-712.

Owens, E.H. and G.A. Sergy. (2010). **A field guide to oil spill response on marine shorelines**. Environment Canada, Ottawa, Ontario, Canada.

Sendstad, E. 1980. **Accelerated biodegradation of crude oil on an Arctic shoreline**. In: *Proceedings of the 3rd Arctic and Marine Oilspill Programme (AMOP) Technical Seminar*, Environment Canada, Ottawa, Ontario, pp. 402-416.

Sendstad, E., O. Sveum, L.J. Endal, Y. Brattbakk and O. Ronning. 1984. **Studies on a seven years old seashore crude oil spill on Spitsbergen**. In: *Proceedings of the 7th Arctic and Marine Oilspill Programme (AMOP) Technical Seminar*, Environment Canada, Ottawa, Canada.

Sergy, G.A. and P.J. Blackall. 1987. **Design and Conclusions of the Baffin Island Oil Spill Project**. VOL. 40, SUPP. 1 (1987) P. 1-Q ARCTIC.

Sørstrøm, S.E., P.J. Brandvik, I. Buist, P. Daling, D. Dickins, L-G. Faksness, S. Potter, J.F. Rasmussen and I. Singsaas. 2010. **Joint industry program on oil spill contingency for Arctic and ice-covered waters**. Summary Report. SINTEF Report no. A14181, Trondheim, Norway.

This Page Intentionally Left Blank.

Section 7

Selection of Response Strategies

As described in ***Section 1 - Fate and Behaviour of Oil in Arctic Conditions***, when crude oil is spilled at sea, a number of natural processes take place which change the physical and chemical properties of the oil, called weathering. These natural processes are evaporation, water-in-oil emulsification, and oil-in-water dispersion, the release of oil components into the water column, spreading, sedimentation, oxidation and biodegradation. The relative contribution of each process varies depending on the type of oil, the duration of the spill, weather and sea conditions. Due to the changes in the oil's properties, the possibility for the use of various oil spill response countermeasures, such as mechanical recovery, dispersants and ISB, also changes. In ice-covered waters time-dependent weathering may be significantly reduced depending on ice type, ice coverage and energy conditions. This can be an advantage and contribute to the enhancement of response effectiveness for some oil spill scenarios. The selection of one or more strategies to deal with a spill in an Arctic environment will depend upon a variety of factors, including the size and type of spill, local weather and sea conditions, and the presence, concentration and characteristics of ice. Equally important to an effective response to a spill in an Arctic environment will be the efficiency of the available response options. The dynamic nature of oil spills necessitates that responders have the flexibility to utilize all response options.

While there are many variables inherent in every spill response, the approach outlined below minimizes the likelihood of oil impacting sensitive shorelines or nearshore environments while maintaining responder safety for the specific scenario of a subsea well blowout:

- The primary strategy should be to address the spill as close to the source and as far offshore as possible, and implement source control operations in the event of an ongoing discharge.
- Oil near the source of the spill should be addressed through a combination of surface application of dispersants, mechanical recovery and/or ISB, as determined to be appropriate based on environmental conditions and operations challenges, as described further in this section. Near the source, these response activities need to be coordinated closely with other spill response and source control activities.
- Beyond the immediate vicinity of the source, aerial dispersant application should be used to treat oil that escaped the near-field mechanical recovery and ISB efforts.
- Further from the wellhead both dispersant application and mechanical recovery using available vessels should be deployed to combat floating oil. Accurate targeting of oil through visual observation and remote sensing from aerial and other platforms should be a key component of the response.
- Safety considerations must be central to the development and implementation of strategies and tactics for response not only for the purpose of prevention of harm to response personnel, but also to avoid delays with the execution of response strategy(s) that can occur when someone is injured and must be assisted or rescued. Response objectives cannot be allowed to compromise safety.

Another important factor that governs all decisions on response strategies is the Net Environmental Benefit Analysis (NEBA) of a given option or choice of options and this process is described in some detail.

Applicability of Offshore Response Options for Various Ice Conditions

It is important to note that while discussion and analysis of oil spill response capability often focuses on large-scale response to a significant offshore spill, applicability of certain response techniques may differ for smaller spills or those that occur in nearshore waters.

Containment and Recovery: Conventional containment and recovery tactics will require the use of containment boom to collect and concentrate oil for recovery and are most applicable to open water conditions (i.e. characterized by low or negligible presence of ice), but could be used in light to moderate ice conditions with reduced effectiveness due to down-times associated with equipment repositioning to avoid ice. In addition, although it may be possible to recover oil already collected and contained in a boom, the current state of the art efficiency of offshore oil clean-up operations will diminish significantly at night under most scenarios.

ISB with Fire Boom: Burning using fire-resistant boom can be conducted in open water and light ice conditions and in moderate ice conditions with reduced effectiveness due to down-times associated with the necessary equipment repositioning to avoid ice. In light and moderate ice conditions, ISB is likely to be less sensitive to ice incursions than the use of skimmers.

ISB with herders can be used under moderate ice conditions (3 to 9/10$^{\text{ths}}$) when ice would hinder the use of boom but would provide some natural containment that could be augmented by herding agents.

ISB with Natural Containment: In dense ice, natural containment by the ice would allow the effective use of ISB without additional measures. This technique would also apply to burning in melt pools for oil spilled under ice, in which case the burns would be conducted the subsequent melt season.

Dispersant Use (No Additional Mixing): To the extent dispersant applications would involve the use and deployment of aircraft, this technique would be dependent upon flight conditions and visual minimums. Conventional dispersant application from aircraft or boats would be most applicable to open water, in active sea states, and light-to-moderate ice conditions, as the ice motion itself produces the turbulence necessary for dispersion.

Dispersant Use (with Artificial Mixing): In dense ice conditions, effective dispersant use may require artificial mixing energy supplied by boats or other means.

Further Note: The efficacy of each of the above techniques would depend in significant measure on the ability to carry out on-site aerial surveillance to direct response operations to the most significant portions of the spill. In conditions where the visibility is restricted to less than 1km it is impossible to direct response operations from the air and extremely difficult to find and recover oil slicks using vessels, even with state of the art remote sensing techniques. The importance of aerial spotting and direction in a successful ISB operation offshore was reinforced during the MC252 blowout response.

Another factor will be wind, temperature and sea state conditions that could lead to superstructure icing on vessels employed in offshore response. Water spray during periods of cold temperatures and higher wind speed in the offshore can result in vessel and equipment superstructure icing that can affect both operation safety and performance. For large-scale containment and recovery it has been assumed that operations will be able to function normally under light icing conditions, will be marginally effective when icing rates are moderate and will not be possible under high ice build-up. Notwithstanding, these and other factors may have the potential to limit the efficacy or use of certain response techniques; it is likewise important to recognize that under such circumstances an immediate response or response using a particular technique or techniques is not possible but that a deferred response may nevertheless be possible and effective. The feasibility and potential effectiveness of a deferred response may vary somewhat according to the specifics of a spill, as described in this report. Accordingly, such environmental factors should be considered by oil spill contingency planners, those evaluating contingency plans, and most importantly those tasked with developing and executing strategies and tactics for actual response depending on the specific spill scenarios and the environmental and operating contexts in which they may occur.

NEBA Considerations in Technique Selection

Net Environmental Benefit Analysis (NEBA) is a decision-making process used to identify spill response method(s) that offer the greatest reduction in potential environmental impacts during a particular spill. NEBA results can guide response operations by helping to select the best cleanup methods for a particular spill scenario including determining the level of intensity of the cleanup and when to stop cleaning.

NEBA is a consensus-based process in which responsible parties, regulators, and resource trustees formulate a decision on the best course of action given the specific circumstances of a spill and relative to a “natural recovery” or “no response” option – monitoring and observing a slick only. At the outset it is important to understand that once an oil spill has occurred some consequences to the receiving environment will result regardless of the response method(s) used. As such, there will be impacts to individual species and it is up to decision-makers to weigh the overall effects on an ecosystem and identify the response strategies that would lead to the best overall minimization of environmental damage. NEBA must assess the long-term effects on an ecosystem as a whole, including likely recovery rates, and not just the immediate effects of the spill and the cleanup process on individual species.

Responders have a number of cleanup methods available for response on water (recovery, dispersants, ISB, monitor only) and on shorelines (manual collection of oil, low-pressure flushing, shoreline cleaning agents, pressure-washing, etc.). Each response method has certain advantages (e.g., speed, efficiency, simplicity), and disadvantages from operational or environmental perspectives (e.g., burning produces soot and leaves residue; the low encounter rates for containment and recovery in many open water situations). The usefulness of each cleanup method in any given situation depends on factors such as: type of oil spilled, environmental resources and habitats threatened; weather and sea state conditions; and availability of logistic and operational support. NEBA takes all of these factors into account when selecting the best response strategy(s).

Conducting a NEBA involves the following main steps.

1. Prepare a list of the local oil-sensitive environmental resources at risk from the spill using:
    a. the predicted fate and trajectory of the spill; and
    b. environmental sensitivity maps showing the distribution of important human use and natural resources.

    When considering response methods like dispersants or shoreline cleaners that alter the fate of the spilled oil, it is necessary to identify additional resources at risk that might be exposed to the oil that otherwise might not be exposed if the technology were not applied.

2. Determine potential recovery rates for available response techniques and identify potential constraints that may limit the practicality of these options as well as any environmental or operational conditions that may improve the efficiency of certain techniques.

3. Establish spill protection priorities for all resources at risk based on the human use, ecological importance and protected status of each.

4. Estimate the potential impact on each priority resource that might result from the spill if no countermeasures were used based on:

    a. predictions of the fate and trajectory of the spilled oil;

    b. toxicity of the oil to the different resource groups (e.g., coastal marshes, fur-bearing mammals, waterfowl, finfish, etc.); and

    c. the spatial distribution of each priority resource in the spill area for the time of year of the spill.

    Oil fate and trajectory models are used to predict oiling of offshore areas, types and lengths of shorelines oiled, and levels of contamination of each.

5. For each type of countermeasure, estimate the degree to which environmental contamination and impact on each resource might be reduced if the countermeasure were to be deployed alone (recognizing the capabilities and environmental side-effects of each and the realities of local logistics, the potential consequences of untreated oil, and weather and safety considerations). Next consider the operational issues that may be presented by employing specific countermeasures in combination in order that potential tactical and logistical conflicts may be identified and minimized or avoided.

    For on-water countermeasures (containment, dispersants, burning), certain response organizations and governmental or research entities with Arctic experience have developed guidelines that may be referenced for estimating the efficiency of each type of countermeasure. These guidelines are based on the known capabilities of each unit (boom-skimmer combination, dispersant spray system), number of units available, mobilization time and operating condition requirements (wind, sea state, visibility, presence of ice). Similarly, for shoreline cleanup, guidelines may be referenced to ascertain:

   a. the need to clean up different shoreline types (exposed bedrock, sheltered coastal marsh) based on the type of oil spilled, level of oiling, shoreline sensitivity and potential for natural cleaning;
   b. the most appropriate cleanup methods for different shoreline types and potential impacts of each method; and
   c. the level of effort and time required to clean each.
6. Consider the reductions in spill impact that might result from the use of each countermeasure and select the countermeasure(s) that offer:
   a. the greatest protection to priority resources; and
   b. the greatest overall reduction in adverse consequences to the receiving environment.

When to Stop Cleaning or How Clean is Clean?

In addition to selecting the most appropriate response methods, it is also necessary to decide on the cleanup level of intensity and when to conclude the cleanup. Different levels of intensity are possible. For example, in some sites, oiled areas may be cleaned thoroughly, returning them to their pre-spill state; in others, some of the oil might be removed and the remainder might be allowed to degrade naturally; while in others the oiled area might be left completely alone to recovery naturally. Although the purpose of cleanup is to mitigate the spill impact, the cleanup methods themselves pose some challenge, which include environmental stresses that vary with the type of environment being cleaned, the cleanup techniques used and safety risks associated with cleanup efforts.

Decisions about the level of intensity of cleanup may be based on the potential environmental and socioeconomic impacts of the spill, the potential impact of the cleanup operations themselves and the ability of the environment to recover naturally from the effects of the spill. One set of standards suggested for cleaning endpoints is summarized in **Table 5** at the end of this section.

Summary Points

This section describes some of the most significant selection considerations in evaluating different response options.

- Environmental factors, particularly those to be encountered in the Arctic, must be considered by those developing plans (or strategies and tactics for implementing plans) for responding to oil spills in Arctic waters. When weighing the potential advantages and disadvantages from a response technique for a given situation, it is important to recognize that an immediate response or response using a particular technique(s) may not always be possible; a deferred response may be necessary and ultimately more effective.

- The presence of cold water and ice can enhance response effectiveness by limiting the spread of oil and slowing the natural weathering process. As a consequence, the window of opportunity for ISB and dispersant use in ice-covered waters can increase compared to some open water scenarios.

- Each response technique has demonstrated some merit in responding to an oil spill in an Arctic environment. Evaluating the merit of all applicable response options is considered key to a successful oil spill response operation under Arctic conditions.

- There is no one technique that is applicable to all conditions; the three main response strategies (containment and recovery, ISB, and dispersant use) have the potential to provide an effective response to the range of potential ice conditions. To select the best response technique or combination of techniques will depend on the incident-specific conditions and the ability to gauge the relative intensity of environmental impact(s) from applying the different response techniques.

For ISB, this includes the use of fire-resistant boom in open water and light ice conditions, herding agents in moderate ice conditions, and burning of oil naturally contained by ice in dense ice conditions.

For dispersant use, this includes application with no additional mixing in open water and light ice conditions, and with the use of artificial mixing in moderate and dense ice.

- NEBA is an important process and the basis for selecting the most appropriate response technique(s) for a given spill situation, and for determining the endpoint of any strategy or tactic.
- Safety considerations must be central to the development and implementation of all strategies and tactics for the response; not only for the prevention of harm to response personnel, but also to avoid the necessary delay that can occur when someone is injured and must be assisted or rescued during a response operation. Response objectives cannot be allowed to compromise safety.

Table 5:
Endpoints for cleanup and decision criteria

Intensity of Cleanup	Conditions Where Appropriate
All oil removed	• Suitable for areas where there is very high human or environmental activity, high risk from oil, and little risk from intense cleanup activity (e.g., recreational sand beaches)
Most visible oil removed; traces remain producing intermittent visible sheen	• Oiled areas may or may not be sensitive to oiling but adjacent areas are at high risk if oil moves into them • Oiled area is insensitive or moderately sensitive to cleaning
Small amounts of visible oil remain as stains, thin surface coating or thicker coating of weathered oil that is not sticky and cannot be scraped off on contact; oil poses no risk to humans or animals on contact	• Environmental resources present are sensitive to oiling • Most oil removed eliminating most risks to local resources, visible oil poses no risk to environmental or human use activities • Further cleanup may require large effort to produce limited improvement
Enough oil removed to reduce the most important risks	• Environmental resources present are sensitive to oiling • Some oil removed reducing the most severe risks; remaining oil may pose limited risks, but less than risks associated with further aggressive cleanup • There is potential for natural cleaning / recovery **Example**: low energy flushing of marshes with cold water to remove thick patches of oil; some oil remains posing some risk, but aggressive cleanup using high energy flushing or flushing with hot water would cause severe, long-term damage to the habitat
No oil removed, monitor only	• Areas where oil may pose modest to little risk to the contaminated area or surroundings; potential for natural cleaning and recovery is high; sensitivity to cleanup is high
Contamination is no worse than pre-spill background contamination	• Applicable in areas of significant background contamination, such as with tar balls, etc.

Modified from Fejes et al., 2005 & Michel and Benggio, 1999.

Further Reading

Baker, J.M, 1995. **Net Environmental Benefit Analysis for Oil Spill Response**. In: *Proceedings International Oil Spill Conference*, American Petroleum Institute, Washington, DC, USA. pp. 611-614.

Fejes, J., C. Lindgren and C. Labjork. 2005. “***How Clean is Clean?***” – **Proposed Method for Determining Endpoints and Evaluating Results of Oil Spill Cleanup Operations**. In: *Proceedings International Oil Spill Conference*, American Petroleum Institute, Washington, DC, USA. Paper No. A329; 6 pp.

Michel, J. and B. Benggio. 1999. **Guidelines for Selecting Appropriate Endpoints at Oil Spills**. In: *Proceedings 1999 International Oil Spill Conference*, API Publication No. 4686, American Petroleum Institute, Washington, DC, USA.

Appendix A:

Sea Ice Environments

This section describes the ice environments in selected Arctic regions. Ice is a dominant feature of the Arctic environment affecting spill fate and behaviour and spill response.

Sea ice in its multitude of forms (**Figure A1**) affects every aspect of spill behaviour as well as the choice and implementation of countermeasures for over nine months of the year in much of the Arctic, and up to six months of the year in many sub-Arctic areas with extensive winter ice covers: e.g. Labrador, Baltic, North Caspian, Gulf of St. Lawrence, and Sakhalin. This section introduces some general terms and common processes that define the ice cycle from freeze-up to melt.

Land-fast ice, or simply fast ice, is sea ice that has frozen along coasts ("fastened" to them) and/or in part to the sea floor. Unlike drift ice, fast ice does not move with currents and wind and tends to be most stable and extensive along shorelines with a broad shallow shelf extending offshore e.g. Alaskan North Coast, Canadian Beaufort Sea, Yamal Peninsula in the Kara Sea, and the Pechora Sea. Out to approximately 2m of water depth, a portion of the fast ice is grounded for much of the winter–the so-called bottom-fast zone.

This zone can be used in many cases to safely construct winter ice roads that can support the logistics of mechanical spill response, e.g., off Prudhoe Bay. Further offshore, the floating fast ice zone often extends out as far as 30m water depth by mid-winter and remains relatively stable at these depths for several months, albeit often highly deformed. In general, routine surface operations are not feasible in these water depths owing to the obstacles of ridging and rubble

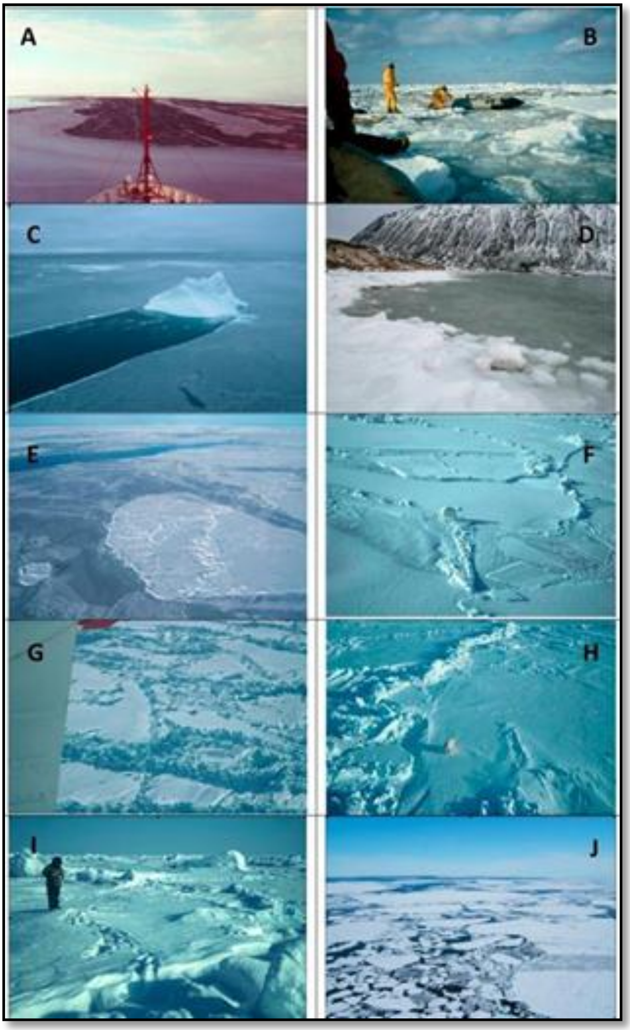


Figure A1: Depiction of various ice types

A: Grease ice at freeze-up
B: Slush and pancake ice
C: Grey ice with an iceberg wake
D: Freeze-up along the coast with an ice foot forming
E: Mix of grey, grey-white and thin first-year
F: Thin first-year ice
G: New rubble and ridging in thin first-year ice
H: Consolidated thick first-year pack ice
I: Surface of a multi-year (old) floe
J: Open drift ice 6/10 with small to big floes (20 to 2,000m)

(D. F. Dickins, except **D**, E. H. Owens) and the increasingly unpredictable nature of the ice cover with distance from shore.

Drift or pack ice makes up most of the ice cover in the Northern Hemisphere and consists of ice that floats freely on the surface of the water, as distinguished from fast ice that is attached to or contiguous with the shore. The aerial extent of pack ice present relative to visible open water is referred to as the ice concentration and expressed as tenths. When packed together in large masses over 6/10 concentration, drift ice is called pack ice as close (7-8/10) or very close (9-9+/10). While pack ice can remain static and close to unmoving for weeks at a time, these periods are not predictable and the pack can open or quickly in response to wind and current driving forces. This unpredictability generally precludes working on the ice within the seasonal pack for any extended period with response crews. Short term operations require continuous vessel and/or helicopter support together with established evacuation plans.

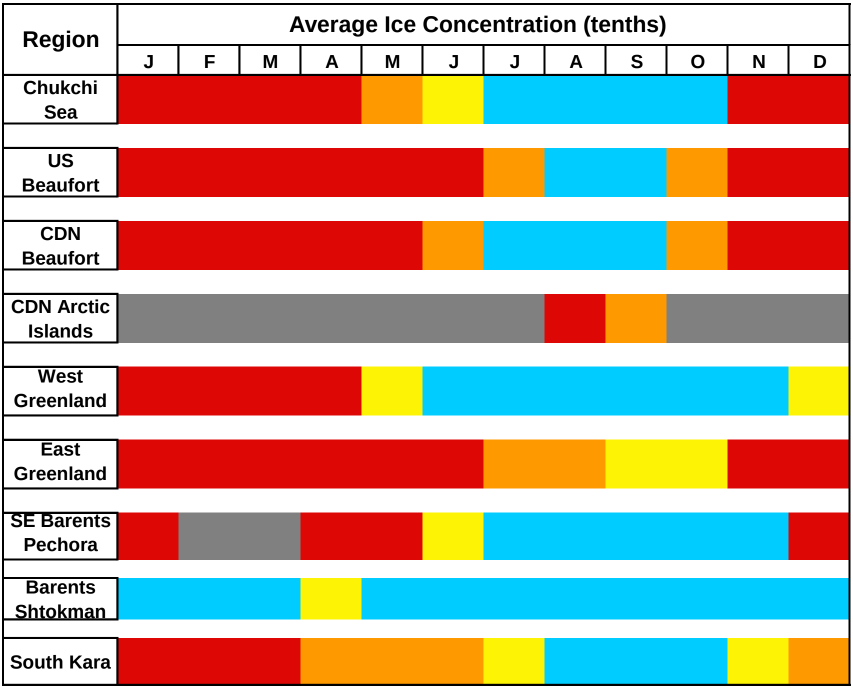
Ice coverage will largely govern whether an oil spill will tend to spread rapidly to an extent approximating an open water condition (ice concentrations up to ~3/10) or be largely contained when the majority of floes start to contact at some point on their perimeter in concentrations over 6/10. The intermediate ice condition of very open to open drift ice (1-5/10) is often raised as a “response gap” because it represents too much ice for traditional boom and skimmer systems to operate effectively, but too little ice to benefit from the natural containment realized in higher concentrations.

Fortunately, ice concentrations in this intermediate range tend to be short lived and represent a transient condition, as the pack is either opening or closing in response to wind forces. For example, based on data collected by the National Ice Center over the 20 year period from 1986 to 2006, the condition of 1-5/10 drift ice, representing perhaps the greatest challenge in terms of spill containment and recovery, existed on average for only 25 days a year along the shipping route between Point Barrow and Prudhoe Bay. New developments in the application of herding agents show great potential in being able to overcome the lack of artificial or natural containment under these conditions by creating and sustaining thick slicks without the need for boom or ice barriers (Buist et al., 2010b).

In ice concentrations of 6/10 and greater the majority of the oil will tend to move with the ice at similar rates. Oiled ice drift rates impact oil spill response in a number of ways:

1. They play an important role in affecting the film thickness of oil trapped on or under the ice from a continuous surface or subsurface release – the faster the ice moves, the thinner the oil coating;
2. They dictate how rapidly oiled ice may drift across international borders or impact another country's marine resources e.g. Russia/Norway; Russia/Japan; Canada/Denmark; Canada/US; and
3. They affect the magnitude of any offshore logistics plan needed to access oil in the ice through the winter and into the following spring. Oiled ice can travel hundreds of kilometres from the source in a matter of a few months.

Figures A2 and **A3** graphically show the seasonal ice cycle for different areas expressed in terms of concentration and thickness throughout the year.



Region	Average Ice Concentration (tenths)											
	J	F	M	A	M	J	J	A	S	O	N	D
Chukchi Sea	🟥	🟥	🟥	🟥	🟧	🟨	🟦	🟦	🟦	🟦	🟥	🟥
US Beaufort	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟦	🟦	🟧	🟥	🟥
CDN Beaufort	🟥	🟥	🟥	🟥	🟥	🟧	🟦	🟦	🟦	🟧	🟥	🟥
CDN Arctic Islands	⬛	⬛	⬛	⬛	⬛	⬛	⬛	🟥	🟧	⬛	⬛	⬛
West Greenland	🟥	🟥	🟥	🟥	🟨	🟦	🟦	🟦	🟦	🟦	🟦	🟨
East Greenland	🟥	🟥	🟥	🟥	🟥	🟥	🟧	🟧	🟨	🟨	🟥	🟥
SE Barents Pechora	🟥	⬛	⬛	🟥	🟥	🟨	🟦	🟦	🟦	🟦	🟦	🟥
Barents Shtokman	🟦	🟦	🟦	🟨	🟦	🟦	🟦	🟦	🟦	🟦	🟦	🟦
South Kara	🟥	🟥	🟥	🟧	🟧	🟧	🟨	🟦	🟦	🟦	🟨	🟧

Legend

Open water to 3/10	🟦
4 to 6/10	🟨
7 to 8/10	🟧
9 to 9+/10	🟥
Fast 10/10	⬛

Notes:

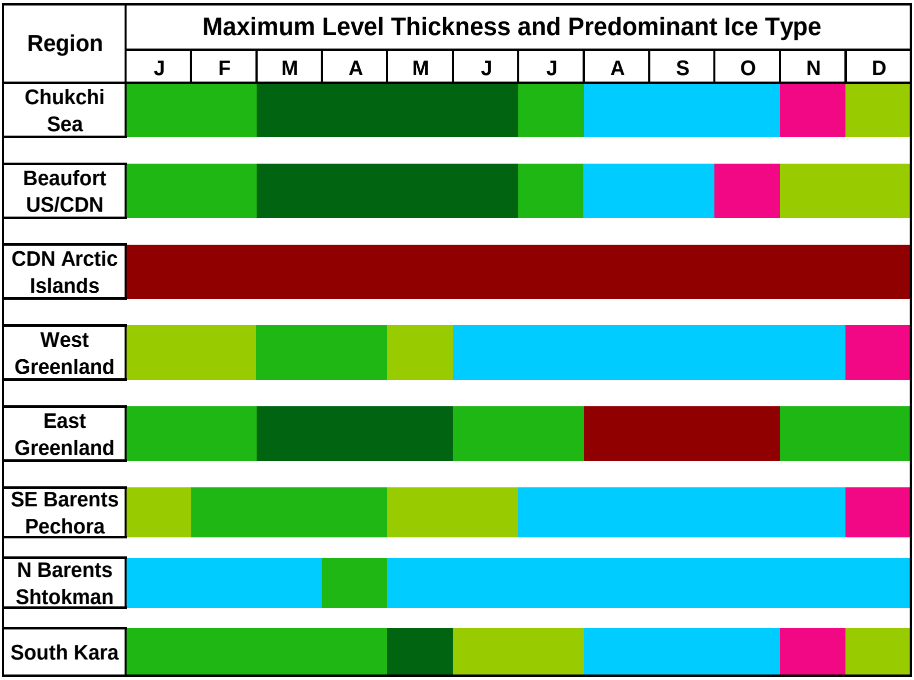
Beaufort relates to nearshore areas between approx 30 and 60 m depth

Color codes follow WMO standards for ice chart presentation

Ice occurs annually in every area except Shtokman

Source: DF Dickins Associates 2008

Figure A2.



Legend

Thickness (m)	Code	Dominant Ice Type
0	🟦	Open Water
.1 to .3	🟪	Young First-year
.3 to 0.7	🟨	Thin first-year
.7 to 1.2	🟩	Medium first-year
1.2 to 2.0	■	Thick first-year
3 to 5+	🟥	Old Ice

Note: Color codes follow WMO Standards for ice chart presentation as closely as possible

Source: DF Dickins Associates 2008

Figure A3.

Further Reading

Buist, I., S. Potter and S.E. Sørstrøm, 2010b. **Barents Sea Field Test of Herder to Thicken Oil for *In Situ* Burning**. In: *Proceedings Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 33, pp. 1085-1108. Environment Canada, Ottawa, Canada.

Canadian Ice Service – Environment Canada. 2009. **Sea Ice Symbols Fact Sheet.** Available online from: www.ec.gc.ca. 2 pages.

NASA Arctic Theme Page http://www.arctic.noaa.gov/

National Snow and Ice Data Center "**All About Sea Ice**" http://nsidc.org/seaice/intro.html

This Page Intentionally Left Blank.

Appendix B:

Experimental Spill Studies

There have been few actual spills of significant size in Arctic conditions, so the main source of knowledge on oil behaviour and countermeasures has been drawn from experimental studies. There is a considerable breadth of such work, starting in the 1970's, and including work done in Canada, Norway, and the United States.

The following summaries highlight most of the medium to large-scale experimental crude oil spills known to have been conducted in sea ice, regardless of latitude. Also included are two significant shoreline projects involving experimental spills and long term monitoring. There may be other experiments, for example in Russia that are not included because project reports and publications are not available. This review does not include spills in open water, or terrestrial spills focused on oil spreading and absorption in snow.

Behaviour of Oil Spills in the Arctic, Chukchi Sea 1970

A series of small-scale spills (one to two barrels each) was conducted on fast ice in the Chukchi Sea by the US Coast Guard in July 1970. The surface spills (diesel and North Slope crude) quickly drained through a permeable recrystallized upper layer and collected on the melt pools. The crude oil pumped under the ice at two sites rose and collected in the under-ice depressions. The researchers concluded that the presence of ridges and hanging blocks under the ice would be able to contain fairly large oil volumes as long as currents and turbulence in the water column were low (Glaeser and Vance, 1971).

Crude Oil Behaviour on Arctic Winter Ice, Beaufort Sea, United States 1972

This project is considered one of the "classic" early experiments aimed at understanding the spreading of oil on snow and ice. Much of the work involved developing spreading theories from first principles. Three spills were made with warm North Slope Crude on sea ice. The spreading rates measured in the field generally matched the theoretical predictions and confirmed that only gravity and inertia forces need to be considered. A key observation was that there was no significant penetration into the ice surface by the warm oil. Fresh snow blowing across the oil tended to stick and migrate downward, creating a dry mixture of 80% snow by volume. A heavy snowfall directly on top of the oil compacted the upper snow/oil interface and prevented the new snow from infiltrating the already spilled oil (McMinn, 1972).

Interaction of Crude Oil with Arctic Sea Ice, Beaufort Sea, Canada 1975

This was the first large-scale investigation into all aspects of oil in ice behaviour, including spreading under ice, encapsulation, and progressive vertical migration as the ice warmed, spreading on surface melt pools in the spring and weathering. A large portion of the oil was removed by in-situ burning on the ice in June some 7 months after the initial spill. A total of 54 m^3 (11,900 gallons) of two different crudes were released in stages throughout the winter of 1974-1975 into containment skirts cut into fast ice within a confined Bay near Cape Parry on the Canadian Beaufort Sea coast. In addition to the contained spills, two additional spills were carried out 30 km offshore, where the oil was allowed to spread freely in the presence of a 10 cm/sec current and movements documented by divers and underwater camera footage. This study demonstrated conclusively that effective removal of oil spilled under ice could be achieved through in-situ burning in the spring. Mechanical removal of the residue completed the successful clean-up. The presence of the trapped oil had no significant effect on the eventual ice thickness, comparing control and oiled sites. As well the presence of oil pooled on the ice surface in the spring had only a minor local effect on the rate of ice deterioration and break-up, advancing the process by a few days to one week (Norcor, 1975).

Oil Behaviour Under Multi-year Ice, High Arctic Canada 1978

Three small-scale spills of ~3.8 bbl each (0.6m^3) of Norman Wells crude were completed at Griper Bay in the Canadian High Arctic in June 1978. An overflight later that summer showed a considerable amount of oil on the surface at two of the spill locations. A field visit in September of the following year found oil in the ice at two of the sites (up to 10%) and very little at the third side, which was bisected by a crack. No oil was found at any of the sites in the fall of 1982, four years after the spill. This is the only known field test involving oil and multi-year ice (Comfort et al., 1983).

Oil and Gas Under Sea Ice, Beaufort Sea, Canada 1979-1980

The focus of this unique project was to investigate the fate and behaviour of oil released with compressed air (Gas-to-oil ratio up to 300) to simulate a shallow water blowout in 20m of water under stable fast ice. This is the only known project of its kind that comes close to approximating the conditions that would be faced with a subsea release in the presence of gas under ice. Three spills of Prudhoe Bay crude, ~6m^3 each, were discharged over the winter of 1979-1980 in December, April and May at a nearshore site in the Canadian Beaufort Sea. Individual spill volumes ranged from 5.9 to 6.8m^3.

Oil behaviour and fate depended largely on the ratio of gas to oil and timing. Early in the season the thin ice sheet was uplifted by the gas, which vented through cracks. Finer droplets were carried further out from the discharge point as gas volumes increased. In all of the spills, the oil was encapsulated by new ice growth within a time frame of 24 to 48 hours regardless of whether there was gas present. The spills later in the winter led to larger pools of oil beneath gas pockets that filled the natural under-ice depressions. An estimated 85% of the spill volume appeared on the ice surface in the spring through ablation of the surface down to the trapped oil droplets and vertical migration of oil from larger trapped oil pools. Approximately two-thirds of the spill was removed through a series of ISB in numerous melt pools. Residue was recovered by teams on the ice prior to break-up (Dickins and Buist, 1981).

Oil Migration and Modification Processes in Solid Sea Ice, Beaufort Sea, United States 1979-1980

This paper reports on a series of 18 small-scale spills (1.5 to 18 gal. each) of fresh and emulsified Prudhoe Bay crude and diesel fuel under first-year fast ice during the early part of the winter of 1979-1980. Significant vertical migration quickly occurred when hot crude oil or diesel was injected without any opportunity for new ice to form beneath the oil. The authors noted that abnormally deep snowdrifts present at times could have led to internal ice temperatures more representative of spring than winter conditions. Emulsions injected in the Prudhoe Bay crude tests did not migrate vertically to any extent. The tests were terminated in March 1980 when the oiled ice was cut out of the parent ice and removed to shore (Nelson and Allen, 1982).

Physical Interaction and Clean-up of Crude Oil with Slush and Solid First-year Ice, Beaufort Sea, United States 1980-1981

During the winter of 1980-1981, three experimental spills involved spraying 1m^3 (6 bbl) of hot Prudhoe Bay crude onto snow to simulate a surface oil well blowout in mid-winter and spring. In the test under cold temperatures with 30cm of hard snow, the oil covered an area of close to 500 m^2 and penetrated less than 5cm into the snow surface. In the first spring test in mid-April the oil immediately saturated the snow-slush mixture to a much greater extent. When left for two weeks, the low albedo oil surface gradually subsided relative to the surrounding clean snow. Samples from the oiled snow had water contents in the range 75 to 90%, the equivalent to what would be encountered from mechanical removal of an oiled snow layer (Nelson and Allen, 1982).

The Baffin Island Oil Spill Project, Baffin Island, Canada 1980-1983

The Baffin Island Oil Spill (BIOS) Project sponsored multidisciplinary field studies between May 1980 and August 1983 in Canada's eastern Arctic on the northern end of Baffin Island. Forty-five cubic metres of a sweet medium °API gravity crude oil were released in two experimental spills designed to assess and compare the short- and long-term fate and effects of chemically dispersed oil near shore vs. a beached oil slick.

The main conclusions of the BIOS Project were: first, the results offer no compelling ecological reasons to prohibit the use of chemical dispersants on oil slicks in nearshore areas; second, the results provide no strong ecological reasons for the cleanup of stranded oil (on certain shoreline types). From these results, the authors concluded that consideration would be given to using chemical dispersants near shore where warranted to protect wildlife or their critical habitat or traditional human land-use sites (Sergy and Blackall, 1987).

Emulsions in Ice, Beaufort Sea, Canada 1982

This project involved two spills of crude oil under 1.65m thick, solid fast ice at McKinley Bay, NWT, Canada in March 1982. One hundred nine-two (192) litres of 60% oil-in-water emulsion were injected at two adjacent sites, and the same volume of fresh oil enclosed within a containment skirt was established as a control. The highly viscous emulsion formed a static irregular "lumpy" surface under the ice with no lateral spreading. In contrast the fresh oil formed a more uniform coating within the skirted area. New ice crystals started forming within the emulsion within 24 hours and all spills were encased by a thin skim of new ice beneath the oil within 48 hours.

The presence of the oil had no measurable effect on ice growth. The fresh crude started to appear in quantity on the ice surface due to natural migration processes through the sheet by mid-June while the equivalent surfacing of the emulsions did not occur for another 3 weeks. This difference was attributed to the differing oil viscosities affecting the ability of emulsions to flow up the open brine channels in the melting ice. Rather than through migration, the emulsified oil was brought to the ice surface by a combination of melting of the ice from the surface down, and melting of ice above the trapped emulsion layer through solar heating.

Eventually, the project estimated that 90% of all oil injected was released from the ice by the time break-up occurred on July 8. The emulsions were stable through the entire project duration and did not "break" (Buist et al., 1983).

Experimental Spills of Crude Oil in Pack Ice, Nova Scotia, Canada 1986

This was the first project to involve experimental spills of crude oil in dynamic pack ice. Three discharges of $1m^3$ each of Alberta sweet mixed blend crude were completed offshore of Nova Scotia, Canada in March 1986. Ice conditions ranged from open drift ice (40 to 60% coverage) to close pack (70 to 80%). The main finding was that high concentrations of slush or brash ice between floes greatly reduced and in many cases stopped the oil spreading. The oil interacted with the ice by saturating the brash ice in the water between the floes and splashing onto the edges of small ice pancakes as the ice pieces ground together. Small volumes of oil were carried under the floes by relative water motion. Oil was rarely transported to the surface of the ice.

The experimental results demonstrated that slush and brash ice are not major factors in oil spreading. The spreading of oil in pack ice can be predicted by simple modifications to standard open water equations, to account for the effect of ice concentration. Existing trajectory models such as SINTEF developed to predict spilled oil concentration areas for a spill in snow can be adopted for spreading of oil among slush and brash ice at sea.

There was no evidence of emulsification in spite of a water temperature of -1.5°C. There was some evidence of natural dispersion but the oil droplets being created were relatively large and rapidly rose to collect under the ice. Two of the three discharges in the 1986 Canadian experiment were contained in very close ice pack and were successfully burned with efficiencies ranging from 80 to 93%. There were no problems with ignition or sustaining the burn and the residue was easily recovered. The third spill occurred in 4 to 6/10 ice cover and was not naturally contained to a thickness that could sustain combustion; no attempt was made to recover the oil. It was concluded that burning appeared to be the only feasible countermeasure for spills under dynamic pack ice (Buist and Dickins, 1987).

Marginal Ice Zone Experiment, Barents Sea, Norway 1993

In 1993, following a series of test tank experiments, an experimental spill involving (163 bbl) 26m^3 of North Sea crude took place in the Barents Sea marginal ice zone off the coast of Norway. The high concentrations of pack ice kept the oil thick and immobile, which, combined with cold temperatures and limited wave action, significantly slowed the oil weathering processes. Oil spreading and slick thickness were sensitive to relatively small changes in ice concentration: the spill thickness rapidly dropped from 1cm to 1mm as the ice cover opened slightly from 80 to 70% coverage. Most of the oil remained in the slush and openings between floes. Approximately 2-5% of the total volume was smeared around the perimeter of the floes and an insignificant proportion of the spill was transported as small particles under the ice.

Attempts to use an oleophilic rope mop skimmer for recovery was hampered by the influence of the vessel opening up the ice cover and allowing the oil to spread – the same effect was noted during the Canadian experiment in 1986. No other effort was made to clean up or recover the oil (Singsaas et al., 1994; Vefsnmo and Johannessen, 1994).

The MORICE Program, Multi-government, agencies, and industry 1995 to present

The MORICE (Mechanical Oil Recovery in Ice-Infested Waters) program was initiated in 1995. Governments, research organizations, and industry from Norway, Canada, USA, Germany, and Sweden sponsored MORICE. The program aimed at developing better methods and technologies for the mechanical recovery of oil in ice. The objectives of MORICE were to identify and address the fundamental challenges related to oil recovery in ice, to assess the potential of existing oil spill clean-up equipment for use in ice, and to suggest technical solutions for oil-in-ice recovery that could be commercialized. A thorough review of past research was conducted. More than 200 references were examined and formed the basis for technical discussions undertaken by a Technical Committee that proposed about 20 concepts for possible application to mechanically recover oil in broken ice. The most promising of these ideas were identified and assessed in detail along with the main function of each device and its overall potential as concluded by the Technical Committee. A number of concepts were evaluated, with six selected for laboratory testing, and one selected for full-scale testing at the OHMSETT facility. The final selected device uses a belt to lift oiled ice pieces from the water, then cleans the ice with a pressurized water spray, and skims the oil from a central area that is protected from ice.

In-situ Clean-up of Oiled Shorelines; Svalbard Shoreline Project, Norway 1997-1998

Experimental oil spill studies were conducted on Svalbard to quantify the effectiveness of selected in-situ shoreline treatment options to accelerate natural oil removal processes on mixed-sediment (sand and pebble) shorelines. A total of 5,500 litres of oil was deposited in July and August 1997 along a 3m wide swath in the upper intertidal zone at three sites. Approximately one week after oiling, a different treatment technique was applied to each plot: sediment relocation (surf washing), mixing (tilling), bioremediation (fertilizer application), and bioremediation combined with mixing. One plot at each site was monitored for natural attenuation.

The results verified that relocation of oiled sediments significantly accelerated the rate of oil removal by more than one year. The oil mineral aggregate (OMA) formation process was active and was increased by sediment relocation. Oil biodegradation occurred both in the oiled sediments and on the fine mineral particles removed from the sediment by natural physical processes. The biodegradation of oil in sediment was significantly stimulated by simple bioremediation protocols. Mixing (by tilling) did not clearly stimulate oil loss and natural recovery.

The treatment techniques did not elevate the toxicity in the nearshore environment to unacceptable levels, nor did they result in consequential alongshore or nearshore oiling (Sergy et al., 1998).

Svalbard Experimental Spill, Norway 2006

This experiment involved a discharge of 3,400 litres of fresh Statfjord crude oil under 65cm solid fast ice in a fjord on Svalbard on March 27, 2006. The spill was contained within a skirted area of 100m^2. Average film thickness was 3.5cm but under ice depressions led to pockets of oil over 10cm deep. The primary objectives of the experiment were to create an under-ice spill as a target for ground penetrating radar and to document the weathering processes of the oil.

Oil started to migrate naturally to the surface 24 days after the spill. Most of the oil had surfaced by May 30, just over 60 days following release. The oil was burned with an efficiency estimated at 96% after lying exposed on the ice surface for over one month and having undergone 27% evaporative reduction (Dickins et al., 2008a).

Joint Industry Program on Oil Spill Contingency for Arctic and Ice-covered Waters: Oil in Ice Field Experiments, Barents Sea, Norway 2008 & 2009

As part of a large international, multi-disciplinary Joint Industry Program carried out over four years (2006 to 2009) two field projects were conducted in the Norwegian Barents Sea between 78 and 79°N, east of Svalbard, within the pack ice. Two small uncontained spills totaling only $0.8m^3$ (5 bbl) were completed in 2008 with the purpose of testing the application of oil herders to thicken an oil slick in open pack ice enough to support ISB – the result was a complete success with better than 90% removal effectiveness. This was the first time the combination of herders and burning had been tried in an Arctic field setting.

The 2009 project included three uncontained releases (0.5, 2.0 and $7.0m^3$) into close pack ice (over 80%) to document oil weathering and fate as well as to assess dispersant effectiveness on two spills that were contained within towed boom. Study findings indicated that: burning of thick oil films trapped between floes in pack ice is highly effective (confirming earlier work in Canada and elsewhere); that dispersants are potentially useful to deal with a spill in pack ice as long as sufficient mixing energy is available, and that fire resistant boom can be used in light ice cover to both recover and burn oil at high efficiencies in very low ice concentrations that would otherwise not be ignitable. Measurements of the weathering of oil and the ignitability verified in both lab- and meso-scale studies were used to develop predictive models of the window-of-opportunity for ISB (Sørstrøm et al., 2010).

Summary of Key Experimental Spills

Table 1-A:
Summary of Field Experiments in Arctic Conditions

Field experiment	Location	Year
Behaviour of oil spills in the Arctic	Chukchi Sea, Arctic	1970
Crude oil behaviour on Arctic winter ice	Beaufort Sea, USA	1972
Interaction of crude oil with Arctic sea ice	Beaufort Sea, CAN	1975
Oil behaviour under multi-year ice	High Arctic, CAN	1978
Oil and gas under sea ice	Beaufort Sea, CAN	1979, 1980
Oil migration and modification processes in solid sea ice	Beaufort Sea, USA	1979, 1980
Physical interaction and cleanup of crude oil with slush and solid first-year ice	Beaufort Sea, USA	1980. 1981
The Baffin Island oil spill project	Baffin Island, CAN	1980, 1983
Emulsions in ice	Beaufort Sea, CAN	1982
Experimental spills of crude oil in pack ice	Nova Scotia, CAN	1986
Marginal ice zone experiment	Barents Sea, NOR	1993
In-situ cleanup of oiled shorelines; Svalbard shoreline project	Svalbard, NOR	1997
Svalbard experimental spill 2006	Svalbard, NOR	2006
Joint Industry Program on oil spill contingency for Arctic and ice-covered waters: oil in ice field experiments 2008 and 2009	Barents Sea, NOR	2008, 2009

Further Reading

Buist, I.A., S. Potter and D. Dickins. 1983. **Fate and behavior of water-in-oil emulsions in ice**. In: *Proceedings of the 6th Arctic and Marine Oilspill Program (AMOP) Technical Seminar,* pp. 263-279. Environment Canada, Ottawa, Ontario, Canada.

Buist, I. and D. Dickins. 1987. **Experimental spills of crude oil in pack ice**. In: *Proceedings 1987 International Oil Spill Conference*. American Petroleum Institute. Washington, DC, USA. pp. 373-381.

Comfort, G. T. Roots, L. Chabot, and F. Abbott. 1983. **Oil behaviour under multi-year ice at Griper Bay, NWT**. In: *Proceedings of the 6th Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. Environment Canada, Ottawa, Ontario, Canada.

Dickins, D., P.J. Brandvik, J. Bradford, L.-G. Faksness, L. Liberty, and R. Daniloff. 2008a. **Svalbard 2006 experimental oil spill under ice: remote sensing, oil weathering under Arctic conditions and assessment of oil removal by in-situ burning**. In: *Proceedings 2008 International Oil Spill Conference*, Savannah, Georgia, USA.

Dickins, D.F. and I.A. Buist. 1981. **Oil and Gas Under Sea Ice Study: Vols. I&2**. Prepared by Dome Petroleum Ltd. for COOSRA, Report CV-1, Calgary, AB, Canada (also published In: *Proceedings 1981 Oil Spill Conference*, Atlanta, GA, USA).

Glaeser, J.L. and G. Vance, 1971. **A study of the behavior of oil spills in the Arctic**. Report Number 714/08/A/001, 002. US Coast Guard, Washington, DC, USA. 53 pp.

McMinn, T.J. 1972. **Crude oil behavior on Arctic winter ice: Final Report**. U.S. Coast Guard, Office of Research & Development. 56 pp.

Nelson, W.G. and A.A. Allen, 1982. **The physical interaction and cleanup of crude oil with slush and solid first year ice**. In: *Proceedings of the 5th Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. pp. 37-59. Environment Canada, Ottawa, Ontario, Canada.

Norcor. 1975. **The Interaction of Crude Oil with Arctic Sea Ice. Beaufort Sea Project Technical Report No. 27**, Canadian Department of Environment, Victoria, British Columbia, Canada.

Sergy, S.A., C.C. Guénette, E.H. Owens, R.C. Prince and K. Lee. 1998. **The Svalbard shoreline oilspill field trials.** In: *Proceedings of the Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 21, Vol. 2, pp. 873-889. Environment Canada, Ottawa, Ontario, Canada.

Singsaas, I., P.J. Brandvik, P.S. Daling, M. Reed and A. Lewis. 1994. **Fate and behaviour of oils spilled in the presence of ice - A comparison of the results from recent laboratory, meso-scale flume and field tests.** In: *Proceedings of the Arctic and Marine Oilspill Program (AMOP) Technical Seminar*. No. 17, Vol. 1, pp. 355-370. Environment Canada, Ottawa, Ontario, Canada.

Sergy, G.A. and P.J. Blackall. 1987. **Design and Conclusions of the Baffin Island Oil Spill Project.** VOL. 40, SUPP. 1 (1987) P. 1-Q ARCTIC

Sorstrom, S.E., P.-J. Brandvik, I. Buist, P. Daling, D. Dickins, L.-G. Faksness, S. Potter, J.F. Rasmussen and I. Singsaas. 2010. **Joint Industry Program on Oil Spill Contingency for Arctic and Ice-covered Waters: Summary Report**. Oil in Ice JIP Report No. 32, SINTEF, Trondheim, Norway.

Vefsnmo, S. and B.O. Johannessen. 1994. **Experimental Oil Spill in the Barents Sea - Drift and Spread of Oil in Broken Ice.** In: *Proceedings of the 17th Arctic and Marine Oil Spill Program (AMOP) Technical Seminar*. Environment Canada. Ottawa, Ontario, Canada.