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Beaufort Sea Oil Spills State of Knowledge Review and Identification of Key Issues

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Beaufort Sea Oil Spills State of Knowledge Review and Identification of Key Issues

by

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Introduction

During exploration activities by Imperial Oil Limited, Dome Petroleum Limited, Gulf Canada Resources Limited and Panarctic Oils Limited in the 1960s through to the 1980s, significant oil and gas potential in the Canadian Arctic was identified. With the exception of one tanker of oil from an extended flow test from Gulf's Amauligak discovery in the Beaufort Sea and a few years of seasonal tanker shipments of oil from Panarctic's Bent Horn operation on Cameron Island, these discoveries were not developed and oil and gas activity in the Canadian north stagnated. The issuance of new offshore exploration leases in recent years and changing market conditions have resulted in greater interest and increased activity in oil and gas in the Canadian Arctic.

Increased exploration activity will bring with it an increase in the risks associated with accidental spills from the operations. The study described in this report was commissioned by the Environmental Studies Research Funds (ESRF) with the following objectives:

- Review the current state of knowledge of oil spills in Arctic waters;
- Identify the key issues associated with them;
- Provide a current reference document for use by industry, regulators and the public; and
- Prepare a geographic database of coastal resources, vulnerabilities and sensitivities that may influence the choice of oil spill containment and recovery methods.

The main component of the study was a comprehensive literature review on the subject. A useful starting point for the review was the Beaufort Sea Steering Committee (BSSC, 1991) reports and particularly Volume 2, Worst Case Scenario. This report documents the approach and state of the art in oil spill response circa 1990, when oil exploration activities were winding down. This information was then updated through a literature review using the following main sources:

- Online database search services of the Canada Institute for Scientific and Technical Information (CISTI);
- The in-house libraries of the study team, which include the following: 1991 Beaufort Sea Steering Committee (BSSC) reports; Environmental Atlas for Beaufort Sea Oil Spill Response; Beaufort Region Environmental Assessment Monitoring Program (BREAM); Beaufort Sea Hydrocarbon Development Environmental Impact Statement; and proceedings of all Arctic Marine Oilspill Program (AMOP) Technical Seminars and International Oil Spill Conferences (IOSC), as well as other significant workshops and conferences; and
- Environment Canada's Emergencies Science and Technology Section (ESTS) library.

As a culmination to this study, a workshop was held in October 2009 and attended by representatives of government and oil companies that may be involved in Beaufort Sea exploration and development. At the workshop, members of the study team presented the draft findings of the study. This was followed by a discussion of a number of key issues of concern regarding planning and response to spills in the Beaufort Sea.

The following report presents the findings of the study, with separate chapters on each of the main categories of countermeasures. Appendix A lists the key issues addressed in the discussion portion of the workshop and summarizes points raised by attendees.

Introduction

Lors des activités d’exploration effectuées par Imperial Oil Limited, Dome Petroleum Limited, Gulf Canada Resources Limited et Panarctic Oils Limited dans les années 1960 jusqu’à 1980, une quantité considérable de gaz et de pétrole a été identifiée. À l’exception d’une citerne de pétrole provenant d’un essai de débit prolongé à la suite de la découverte du gisement Amauligak dans la mer de Beaufort et de quelques années de livraisons saisonnières de citernes de pétrole de l’exploitation Bent Horn de Panarctic sur l’île Cameron, les découvertes n’ont pas été développées et l’activité de gaz et de pétrole dans le Nord canadien a stagné. La délivrance de nouveaux baux pour l’exploration en mer dans les dernières années et le changement des conditions du marché ont eu comme conséquence un intérêt accru et une augmentation de l’activité liée aux gaz et au pétrole dans l’Arctique canadien.

L’augmentation des activités d’exploration apportera aussi une hausse des risques liés aux déversements accidentels causés par les opérations. L’étude décrite dans ce rapport a été exécutée par le Fonds pour l’étude de l’environnement (FEE), dont les objectifs étaient les suivants :

- Revoir l’état des connaissances actuelles des déversements de pétrole dans les eaux arctiques;
- Cerner les enjeux importants reliés;
- Fournir un document de référence actuel à l’usage de l’industrie, des organismes de réglementation et du public; et
- Préparer une base de données géographiques des ressources côtières, des vulnérabilités et des sensibilités qui influencent le choix des méthodes de confinement et de récupération des déversements de pétrole.

Le principal élément de l’étude était une analyse documentaire détaillée sur le sujet. Les rapports de Beaufort Sea Steering Committee (BSSC, 1991), et particulièrement le Volume 2, *Worst Case Scenario*, servirent de point de départ très utile. Ce rapport documente l’approche et la technologie de pointe pour l’intervention en cas de déversement de pétrole vers 1990, alors que les activités d’exploration tiraient à leur fin. Ces renseignements étaient ensuite actualisés grâce à une analyse documentaire effectuée en utilisant les principales sources suivantes :

- Services de recherche des bases de données en ligne de l’Institut canadien de l’information scientifique et technique (ICIST);
- Les bibliothèques internes du groupe d’étude, dont : les rapports du Comité directeur de la mer de Beaufort (CDMB) de 1991; *Environmental Atlas for Beaufort Sea Oil Spill Response*; *Beaufort Region Environmental Assessment Monitoring Program* (BREAM); *Beaufort Sea Hydrocarbon Development Environmental Impact Statement*; et les comptes rendus de tous

- Bibliothèque de la Section de la science et de la technologie des urgences d’Environnement Canada.

Le point culminant de cette étude est un atelier tenu en octobre 2009 auquel des représentants du gouvernement et d’entreprises pétrolières, qui ont été impliqués dans l’exploration et le développement de la mer de Beaufort, ont pris part. À l’atelier, les membres du groupe d’étude ont présenté l’ébauche des conclusions de l’étude. Une discussion portant sur plusieurs enjeux importants liés à la planification et à l’intervention lors de déversements dans la mer de Beaufort a eu lieu par la suite.

Le rapport suivant présente les conclusions de l’étude, en chapitres indépendants portant sur chacune des principales catégories des mesures de prévention. L’annexe A dresse la liste des enjeux importants abordés dans la section « discussion » de l’atelier et résume les points soulevés par les participants.

Oil Spill Behaviour and Modelling in Ice Conditions

This section documents improvements in the state of the art for oil spill behaviour and modelling in ice over the last twenty years. First, a brief summary is given of oil spill behaviour and modelling as it existed in the early 1990s. Then, the research and development efforts to improve the understanding of oil behaviour and improve computer modelling over the subsequent two decades are described.

State of the Art in the Early 1990s

In the early 1990s, the majority of the knowledge of oil spill behaviour in Beaufort Sea ice conditions focused on oil spills under or on landfast sea ice (including oil in snow and oil in leads). The emphasis was to answer questions regarding the fate of oil released from Beaufort Sea exploration well blowouts lasting through a winter (see DF Dickins and Fleet Technology, 1992, and Fingas and Hollebone, 2002, for excellent reviews of the key studies). Only a few laboratory or test tank experiments and one experimental spill of oil in pack ice had taken place at the time (SL Ross and DF Dickins, 1987).

The understanding of the behaviour of oil and gas emanating from a subsea blowout was quite advanced in the early 1990s, again because of various research programs in the 1970s and 1980s in support of exploration drilling in the Beaufort.

Although routine analysis of the physical and chemical properties of crude oils to determine their spill-related properties was not common at the time, several key Beaufort Sea crude oils had been so analysed, and the results were used in submissions to the EIRB in the early 1990s.

The state of the art in oil spill modelling at the time was also reasonably advanced for predicting the spread, advection and weathering of surface slicks on open water (Jayko et al., 1991); however, the same could not be said for modelling spills in ice. A simple model did exist to predict the distribution of oil on or under landfast first-year sea ice or multi-year ice, but this model did not predict the motion of the oiled ice (Wotherspoon and Swiss, 1985). Modelling of the release of oil and gas from a subsea blowout and the subsequent surface slick was also in its infancy in the early 1990s. At the time, there was no model for deep-well blowouts with the attendant issue of gas hydrate formation and its effect on underwater plume dynamics.

Research and Development Relative to Oil Spill Behaviour and Modelling in Ice Since 1990

R&D efforts relevant to Beaufort Sea oil spill response in the past 20 years have focused on two areas of spill behaviour and modelling:
1. Spilled oil fate and behaviour in ice conditions
2. Computer modelling improvements

Spilled oil fate and behaviour in ice

Several detailed technical reviews of the subject over the past 20 years are available (Fingas, 1992; Dickins, 1994; Dickins and Buist, 1999; Buist and Dickins, 2000; Fingas and Hollebone, 2002; Brandvik, 2007). The focus of oil spill behaviour in ice research over the past 20 years has been on spills in drift and pack ice conditions (also sometimes called broken ice).

In 1993, following a series of test tank experiments, an experimental spill involving 26 m^3 of North Sea crude took place in the Barents Sea marginal ice zone off the coast of Norway (Singsaas et al., 1994; Reed and Aamo, 1994; Jensen, 1994). It was concluded that the high concentrations of pack ice (90% initially, declining to 75% at the end of the experiment) during the field experiment kept the oil thick and immobile for an extended period of time (days) which, in combination with cold temperatures and the damping of wave action by the ice, significantly slowed oil weathering processes (evaporation, natural dispersion and emulsification). Brandvik (2004) presents a comparison between the results obtained from the experimental spill in pack ice with a similar experimental spill in open water.

Other tank tests of oil spreading under and in broken ice features have been reported by the following: Sayed and Ng (1993), who experimented with small (3 litre) slicks of Amauligak, Hibernia and Norman Wells crude in various brash ice concentrations; Weerasuriya and Yapa (1993) who experimented with spreading of oil under ice floes in a small tank; Yapa and Belaskas (1993), who experimented with spreading of oil under and over simulated broken ice fields in a small tank; and Gjosten and Loset (2004) who measured spreading rates of IFO-30 and Marine Diesel in various concentrations of slush ice in different mixing energies. All of these research programs confirmed that the presence of broken ice significantly slowed oil spreading.

A series of meso-scale weathering experiments with Statfjord crude in broken ice (0%, 30% and 90% coverage) were carried out on Svalbard in an outdoor circulating wave flume cut in the ice (Brandvik and Faskness, 2009). The results showed that the weathering of spilled oil was dependent on the ice coverage and wave damping by the ice. The greater oil thicknesses in highest ice coverage reduced evaporation, and the wave damping at the highest ice coverage reduced emulsification. There was a small decrease in evaporation in 30% ice cover, compared to 0%, but little difference in emulsification or viscosity increase. The oil weathered in the 90% ice concentration was both ignitable and chemically dispersible at the end of the 60-hour tests, whereas the oil weathered for the same time in the lower ice concentrations was not. Another series of experiments on Svalbard involved studying the dissolution over four months of water-soluble components from six different crude oils encapsulated near the surface in sea ice from February to June (Faskness and Brandvik, 2005). It was concluded that the water-soluble components would diffuse down through the ice sheet to the bottom of the sheet (110 cm thick), but that concentrations at the bottom would be low (6 ppb).

A series of experimental spills of diesel and petrol on ice floes in the Russian Arctic (Serova, 1992; Ivanov et al., 2005) showed that light distilled fuels evaporate to completion rapidly on the surface of ice floes in the spring and summer and that photo-oxidation is a more significant process in the 24-hour daylight than in more temperate climates. Series of experiments on oil spilled under ice floes typical of the Sea of Okhotsk were undertaken in the late 1990s and early 2000s (Ohtsuka et al., 1999; Ohtsuka et al., 2001). The results showed that oil will progressively fill under-ice cavities on the bottom of the ice floes and that compressed gas (air) released under the floe will displace the oil. Only a small amount (less than 1%) of the oil will permeate up to the surface of a 7-cm to 10-cm thick floe. In a separate series of experiments, the evaporation rate of Iranian crude on water was found to be almost the same at 0°C as it was at room temperature. A series of spreading tests for oils spilled under smooth freshwater ice was carried out in Finland (Rytkonen et al., 1998) in order to determine equilibrium thicknesses. The oils spread under smooth ice at a rate dependent on their viscosity to an equilibrium thickness of 7 mm to 14 mm, which did not appear to be a function of viscosity.

In a study of the stability of oil-in-water emulsions (commonly known as dispersions), it was shown that the dispersions separated 3.5 times more slowly at near-freezing temperatures (1°C) than at 15°C (Stochmal and Gurgul,1992).

In August 2004, an autonomous underwater vehicle (AUV) took multi-beam, three-dimensional sonar measurements of the underside of a first-year landfast ice sheet that was 1.3 m thick (Wilkinson et al., 2007). Using an older method of calculating (which assumes that all of the available void spaces will fill completely with oil), the under-ice oil-holding capacity of the sheet was estimated to have a mean pooling capacity of 30,000 m^3/km^2. Using a model that assumes that oil will progressively fill (by gravity-driven flow) only those void spaces that have flow pathways connecting them gave a result of 2,000 m^3/km^2, an order of magnitude lower. The mean pooling capacity model predicts that 50% of the ice sheet area would contain oil, while the gravity-driven flow predicts 6%.

From 2004 to 2008, a three-year experimental program was carried out to generate empirical data and spill process algorithms in order to improve oil spill in ice behaviour models (Buist et al., 2008 and 2009). The research program focused on completing a large number of small-scale experiments with four Alaskan crude oils. The emphasis was on spill processes for oil spilled on or under landfast sea ice in the Beaufort Sea.

The experiments were conducted at the following three facilities:
1. An outdoor test facility near Ottawa constructed using insulated, intermediate bulk container (IBC) shipping containers as the test tanks, each containing 1 m^3 of salt water;
2. An indoor, 11-m^3 wind/wave tank in Ottawa; and
3. The 10,000-m^3 Ohmsett Facility in New Jersey outfitted with large-capacity industrial water chillers to ensure freezing water temperatures.

As a result of six series of small-scale experiments, the best algorithms were selected to predict the following:
- Equilibrium thickness of oil on quiescent cold water
- Spreading of oil on cold water
- Equilibrium oil thickness on ice
- Oil spreading on ice
- Oil spread in snow
- Stripping velocity for small oil forms under ice
- Evaporation on ice, under snow and among drift ice

It was not possible to develop algorithms for emulsification processes in drift ice or for the rate of appearance of oil on the surface of melting ice in the spring.

In many of the small-scale experiments (primarily the spreading and evaporation test series), particularly at colder test temperatures, one or more of the crude oils had a pour point above the ambient temperature. The results of these tests often do not correlate with the results of the experiments with the other crude oils and the results were not used in the algorithm selection process. This is because oils whose pour point exceeds ambient temperature have unusual physical characteristics. As these oils cool, wax particles begin to precipitate from solution in the bulk oil and eventually, in the absence of external mixing energy, form a polymer-like matrix in the oil that renders it a gel-like semi-solid. This has two major effects from the perspective of the tests:

1. The oils develop a resistance to the initiation of flow (termed a yield stress) and become non-Newtonian fluids; typically they exhibit pseudoplastic rheology, i.e., shear thinning, and become thixotropic. i.e., their viscosity is time-dependent. These changes greatly reduce, or prevent, spreading of the oil on water, on ice and through snow. At present, there is no way to model this; however, in most situations the gelled oil simply does not spread at all.
2. The onset of the internal wax matrix greatly restricts diffusive movement of the volatile molecules through the slick to the air/oil surface that changes the way in which the oil evaporates. This reduced evaporation can be effectively modelled by using an internal resistance to mass transfer.

Gjosteen (2004) developed a mathematical model to predict the spreading of oils with Newtonian viscosity over water and slush ice, and found good agreement with the lab data of Sayed and Loset (1993). The model was reportedly coupled to a discrete-element ice model.

Computer modelling improvements

In 1990, the Atmospheric Environment Service of Environment Canada undertook a study of oil spreading in broken ice (Venkatesh et al., 1990). They developed empirical methodologies for computing the spread of oil based on the equilibrium thickness of oil on cold water and in slush ice. They reported good agreement with the field test data available at the time. The model was further refined to account for the observed spreading rate dependency on oil viscosity, net surface tension and slush ice particle size (El-Tahan and Venkatesh, 1994).

A model was developed in Finland (the Atmospheric Environment Service of Environment Canada also participated) to predict the movement, fate and weathering of oil spills in Baltic Sea ice conditions (Hirvi et al., 1992). The known movements of the oil from the *Antonio Gramsci* spill in 1987 were used to test the model. It was concluded that the model could calculate the general patterns of oil transport and spreading, but that the lack of ice data limited the accuracy of the simulations. The small-scale interactions of oil and ice were not described by the model (the resolution employed was a four-kilometre grid).

The experimental data generated by Weerasuriya and Yapa (1993) and Yapa and Belaskas (1993) were used to develop a numerical model of oil spreading in broken ice (Yapa and Weerasuriya, 1997).

The oil spill trajectory model OILMAP was used to forecast trajectories of oil in pack ice for the 1993 spill in the Barents Sea marginal ice zone by SINTEF (Reed and Aamo, 1994). The model performed reasonably well early in the spill when the winds were from the ice towards the open water (off-ice) and ice concentrations were 60% to 90% by applying a 2.5% of wind speed drift factor and an Ekman veering angle of 35° to the right (in open water spill modelling these parameters are normally 3% to 3.5% and 10° to 20°). When the wind changed to on-ice, a wind factor of 1.5% and a veering angle of 60° worked best.

Belore et al. (1998) describe a model to predict the deposition of oil droplets on the surface of tundra or ice. This model is used in Alaska for spill contingency planning purposes.

Ovsienko et al. (1999) present a theoretical analysis of equations that predict the effect of viscosity on oil spreading rates on water and the spreading of oil on water around fixed circular ice floes.

Gjosten et al. (2003) and Yapa and Dasanayka (2006) in particular present excellent reviews of the state of the art in modelling the spread and movement of oil in ice. Gjosten et al. (2003) list the following three oil spill models that can include oil-in-ice predictions.

1. The Oil Spill Model for the Antarctic Sea described in Petit (1997) includes drift and spread of oil as well as weathering and under-ice storage of oil and is coupled to a sea ice formation model. The oil drift component is modelled as two separate regimes: at low concentrations of ice the oil moves independently of the ice, and at higher concentrations the oil drift is restricted as it becomes trapped in closed leads between floes. This oil drifts with the ice. There is a continuous transition between the two regimes at about 30% ice coverage. The model also applies a horizontal diffusion coefficient to the drift vector for the various spillets being modelled. This coefficient is 0 at ice covers in excess of 80% and increases linearly to its maximum, open-water value at ice coverage below 30%. Under-ice storage volume is deemed to be proportional to ice thickness. The spilled oil properties at ambient temperature and winds are calculated using standard oil property correlations (e.g., Whiticar et al., 1993) and take into account the lesser wave energy in an ice field.

2. Oil Spill Contingency and Response (OSCAR) is the commercial model for the fate and drift of an oil spill developed by SINTEF (http://www.sintef.no/static/ch/environment/oscar.htm). It includes oil fate predictions based on oil property analysis and tank testing data, 3-D modelling capability and spill response modelling, exposure models for several species at risk from oil spills, and shoreline interactions. The interaction between oil and ice is typically

described by assigning a ‘state’ to various particles of oil being modelled. Examples of the ‘states’ include oil under ice, oil on ice floes, and surface oil.

3. OILMAP^{TM} is a commercial model of the trajectory, behaviour, fate and countermeasures for oil spills at sea developed by Applied Science Associates (www.asascience.com). The model can predict the trajectories for either instantaneous or continuous spills and includes algorithms for spreading, evaporation, emulsification, natural dispersion, shoreline impacts and oil-ice interaction. The mass balance of the spill is predicted for the specific type of oil selected, based on a library of that oil’s physical and chemical properties. This model was used to predict the movement of the experimental oil slick in the marginal ice zone of the Barents Sea in 1993, described above.

Yapa and Dasanayka (2006) recommend the finite difference approach to modelling the motion of viscous oil slicks among ice floes of Gjosten (2004).

Surveillance and Monitoring

This review focuses on the demonstrated and expected potential of different sensors to detect oil and map the contaminated boundaries in a range of oil and ice scenarios. Given the limited real-life experiences in detecting actual spills in ice, assessments are forced in some cases to draw on the much broader range of experiences with spills in open water.

A number of authors have summarized the history of oil-in-ice detection research using a wide range of technologies (Dickins, 2000; Brown, 2008; Goodman, 2008). Much of this research took place over an intensive ten-year period beginning in the late 1970s, largely in response to active Arctic offshore drilling 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. Much of this work was conducted in Canada under the direction of Environment Canada and with the participation of the Canadian Centre for Remote Sensing (CCRS), Imperial Oil and the Centre for Cold Ocean Resources Engineering (C-CORE). Technologies tested included acoustics, radar, UV fluorescence, viewing trapped oil under UV light from a bare ice surface, IR (including active heating with a laser), gamma ray, microwave radiometer, resonance scattering theory (USCG), gas sniffers and impulse radar. Following the demise of the Beaufort drilling program in the late 1980s, very little new progress was made until about 2004. At that time, a series of projects sponsored by the Minerals Management Service (MMS) and the oil industry in Canada and Norway began to evaluate and test a new generation of Ground Penetrating Radar (GPR), acoustics and ethane gas detectors (Shell's LightTouch™ system)—see various reports by Dickins and Boise State University. In 2007, ExxonMobil began to explore the concept of using nuclear magnetic resonance (NMR) as a basis for future airborne detection systems. Work continues on several fronts and there is a strong interest in developing operational tools to apply in the near term.

The greatest advances in Arctic ice surveillance technology over the past 20 years are all-weather radar satellite systems with the latest generation of platforms. Those launched over the past two years are able to detect surface features down to 1 metre. The capabilities of these new satellites in assisting with Arctic spill response are not fully understood, but it is thought that there could be significant problems in reliably detecting and mapping oiled area boundaries in the presence of ice. Results forthcoming over the next year from the recently completed SINTEF Joint Industry project (JIP) may point to areas where satellites could play a key role in future Arctic surveillance. Perhaps their greatest value will be in providing highly detailed images of ice conditions near a spill site to help plan marine operations on a tactical scale, as opposed to 'seeing' the oil directly.

Challenges of Making a Positive Initial Identification

Detection and mapping oil in ice becomes an immediate concern once a spill has occurred. In some cases the actual spill location will be in doubt or even unknown.

Pipeline leaks below detectable limits may persist for months or more and generate oil trapped beneath the ice without being detected through aerial surveys. In this case, the oil may only become visible in May and June after migrating naturally to the surface. In the case of a larger rupture, it may be possible to isolate the spill location between certain shut-off valves, but the exact point of discharge could require under-ice surveys or drilling probes.

Detection of low-flow rate leaks from fittings or tanks can be extremely difficult, especially in a situation where a ship experiences substantial ice build-up on the deck, superstructure and, in some cases, the hull itself.

Detection is clearly not a critical issue in the case of a large visible spill around a vessel resulting from a major damage incident or from a fixed exploration or production platform. However, continued monitoring and tracking of the oiled ice will be required in a dynamic pack ice environment where the spill source and the oil may become quickly separated by tens of kilometres. Over time, the spill may separate into multiple parcels covering a large area and further complicating the process of long-term tracking (Vefsnmo and Johannessen, 1994).

Other situations requiring detection could include oil flowing onto an ice surface (e.g., from a drill rig on an artificial island) that may be buried under fresh snow and hidden from view, or a vessel that leaks oil beneath winter ice cover.

Brown (2008) summarizes the following challenges involved in oil-in-ice detection:

- Ice heterogeneity with a wide variety of structural forms
- Ice inclusions such as bubbles, water, salt and sediment
- Oil distribution heterogeneity: multiple layers possible and vertical migration
- Oil distribution parameters: from cohesive layers to small droplets
- Snow cover
- Lack of distinctive ice/water interface early and late in the season

The type of oil is important; for example, relatively colourless diesel spills are close to impossible to detect visually when mixed with dynamic ice.

Estimating the true area of contamination and oil volume for spills in ice during the winter is complicated by the presence of the ice cover. A large proportion of the spill can be hidden beneath floes in the case of a subsurface release, or hidden on the surface of floes beneath snow following surface deposition (e.g., from a blowout plume). Visual spotting of oil trapped in brash and slush between floes is difficult, especially under conditions of limited daylight and restricted visibility. The task becomes somewhat easier during break-up as the daylight expands and less oil is hidden or masked by slush and new ice, but discriminating between oil and natural ice discoloration is still difficult as described below.

In many Arctic areas, such as off the Mackenzie River Delta, high concentrations of suspended material are carried into the ocean where it is incorporated into the ice at freeze-up and/or deposited on the ice surface through winds and spring overflood. The result of these various interactions is the typical ‘dirty’ appearance of rotting nearshore ice in the spring leading to a high likelihood of ‘false positives’ in aerial surveillance of a potential spill area. The need to follow-up and check for false leads can strain already limited resources and waste much time and energy. The most effective way to reduce these occurrences is to employ trained observers in helicopters or fixed-wing aircraft to carry out regular low-level aerial surveillance with experienced observers.

Another important aspect of Arctic spill response is the tracking of oiled ice over the long-term, potentially for weeks to months, following the initial detection and mapping of contaminated boundaries.

Airborne and Spaceborne Remote Sensing

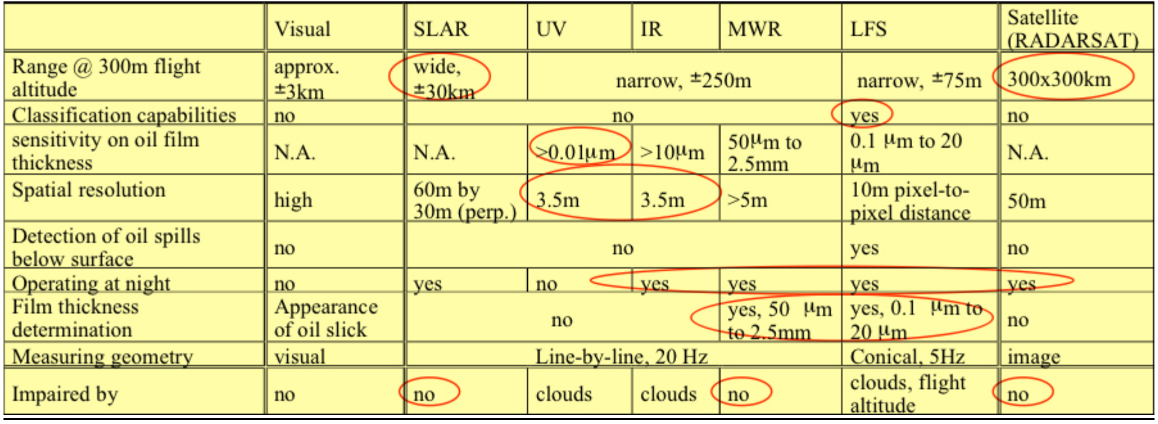
Airborne Systems

Multispectral airborne remote sensing supplemented by visual observations remains the most effective method for identifying and mapping the presence of oil on water. However, very little is known about the capabilities of these sophisticated airborne systems in ice-covered environments. Isolated examples where aerial documentation of experimental spills was obtained include conventional vertical photography off the Canadian East Coast in 1986 (SL Ross and DF Dickins, 1987) and helicopter-mounted IR cameras off Svalbard in 1993 (Singsaas et al., 1994). There is no published record of any of the current generation of pollution surveillance aircraft developed over the past decade having responded to a spill in ice. The new Swedish Dash 8 Q300 made a high-level pass over the 2009 SINTEF JIP spill site in the Norwegian Barents Sea, but the results were not publicly available at the time of writing.

The main oil spill co-operative for the Prudhoe Bay field, Alaska Clean Seas (ACS), has emergency access to a Twin Otter equipped with low-light-level forward-looking video, infrared sensors and standard visual photographic equipment linked to the onboard GPS. Most nations operate aircraft equipped with a range of sensors specifically optimized for pollution surveillance over open water (Canada, most coastal states in Europe, Iceland, Japan, etc). Canada is the only country to initiate regular pollution surveillance flights over its Arctic area. Other countries such as Denmark and Russia carry out Arctic missions that focus more on fisheries infractions and sovereignty issues and have a secondary oil spill mandate.

Bashek (2007) hypothesized on the likely performance of a mix of airborne sensors in an ice environment based on what is known about their capabilities in open water (see Table 1). This table compares the various sensors (using the German Dornier 228 as an example) in terms of their resolution, surface footprint (scan width), sensitivity to weather conditions, limiting film thickness, etc. A Laser Fluorosensor is fitted on one of the two German aircraft, making it the only fully operational surveillance aircraft known to use this sensor in the world (not counting the Environment Canada DC-3 operated in a quasi-operational/research mode).

Table 1: Airborne and Space Sensor Comparison for Spills on Water (after Baschek 2007)



	Visual	SLAR	UV	IR	MWR	LFS	Satellite (RADARSAT)
Range @ 300m flight altitude	approx. ±3km	wide, ±30km	narrow, ±250m			narrow, ±75m	300x300km
Classification capabilities	no	no				yes	no
sensitivity on oil film thickness	N.A.	N.A.	>0.01μm	>10μm	50μm to 2.5mm	0.1 μm to 20 μm	N.A.
Spatial resolution	high	60m by 30m (perp.)	3.5m	3.5m	>5m	10m pixel-to-pixel distance	50m
Detection of oil spills below surface	no	no				yes	no
Operating at night	no	yes	no	yes	yes	yes	yes
Film thickness determination	Appearance of oil slick	no			yes, 50 μm to 2.5mm	yes, 0.1 μm to 20 μm	no
Measuring geometry	visual	Line-by-line, 20 Hz				Conical, 5Hz	image
Impaired by	no	no	clouds	clouds	no	clouds, flight altitude	no

Source: German Institute of Hydrology (BfG). Classification = oil type determination

Theoretically, many of the existing airborne sensors will detect and map oil among ice in some situations, but the limitations on their use in different ice conditions are not well understood. Features of the various primary airborne sensors are highlighted briefly below with some comments on their applicability in an ice environment.

Visual

Airborne sensors operating in the visible spectrum are mostly daylight or, at best, twilight tools (LLTV can extend surveillance into lower light levels). Standard aerial surveillance cameras or video cannot be considered primary detection tools for spills in ice where normal Arctic weather conditions are likely to present a mix of fog, marine layer, low cloud ceiling and darkness.

Even the relatively straightforward scenario of black oil on the ice under ideal spring conditions of extended daylight and unlimited visibility poses real problems in terms of reliable detection and mapping with visual sensors. For spills into brash and pack ice, the challenge of reliable visual detection becomes more difficult with a high probability of false positives, as discussed earlier.

UV/IR Scanners and FLIR

The infrared (IR)-channel responds to thermal emission from the sea surface. Detection of oil on the water depends on the oil having a lower emissivity than water. Very thin oil layers can actually appear colder than the water surface; however, oil films greater than approximately 0.5-mm thickness absorb thermal radiation and can be much warmer (up to 10°C or more) than the water surface. IR sensors can operate at night in good visibility but are impaired by clouds and fog, a severe drawback for Arctic offshore operations.

Given that the emissivity of ice and water in the IR band are comparable, detection of oil on ice should be similar to oil on water. This effect is demonstrated by the clear discrimination of a relatively warm oil discharge hose lying on the ice surface in field experiments conducted in 1993 with a vertical IR video camera operated from a helicopter.

In addition to vertical applications, IR technology is also employed in the forward-looking mode (FLIR) for detection of oil spills on open water. The performance of this sensor is similar to the IR scanner found on dedicated pollution surveillance aircraft, but non-fixed viewing angles make distance and area measurements less feasible. Some systems provide ‘laser flash’ capability for ship identification in darkness. Stabilized systems for both helicopters and aircraft are available and both 3-µm to 5-µm and 7-µm to 14-µm systems are in operational use (Andersen, pers. comm.). These systems operate within the mid-and thermal-infrared regions of the electromagnetic spectrum.

The UV-channel measures sunlight and is consequently limited to daytime operations in clear visibility free from clouds which limits the operational value of these systems in an Arctic environment. The detection principle is based on the higher reflectivity of oil compared to water in the 320- to 380-nm wavelength band. Oil present on the water in very thin films down to 0.01 µm can be detected because of the short wavelength. There is no discrimination with this sensor (nor with IR) between different oil thicknesses within the thickness band of detectability. Given the basic principle of detecting reflectivity differences, UV scanners should be able to detect oil on the water surface between ice floes and possibly oil exposed on the ice surface. The presence of substantial amounts of slush and brash mixed with oil in the water are likely to complicate the signal return.

Airborne Microwave Radiometer (MWR)

The MWR is theoretically sensitive to oil layer thickness over the widest range of all the sensors, 50 μm to 2.5 mm. This sensor is capable of penetrating fog and cloud and night-time operation.

Earlier tests (1980s) with MWR for spills in ice showed inconclusive results and no recent work has been done to develop the technology further. It is interesting that the latest generation of pollution surveillance aircraft specified by Iceland and Sweden do not employ a microwave line scanner and anecdotal evidence indicates that on aircraft where the sensor is employed, it tends to be the least utilized.

Airborne Laser Fluorosensor (ALFS)

Active UV sensors embody lasers as the excitation mechanism. Laser fluorosensors are active sensors that take advantage of the fact that certain compounds in petroleum oils absorb ultraviolet light and become electronically excited. This excitation is rapidly removed through the process of fluorescence emission, primarily in the visible region of the spectrum. Since very few other compounds show this tendency, fluorescence is a strong indication of the presence of oil. To date, while laser fluorosensors (LFS) have been primarily developed for airborne applications, both ship-borne and ground vehicle-based systems are in development in Europe. Havariekommando in Germany employs the only currently operational airborne system. Environment Canada operates an LFS mounted on a 60-year-old DC-3. Despite the age of the aircraft, it is capable of flying to offshore areas such as the Grand Banks of Newfoundland and has done so during the flights under the Birds Oiled at Sea (BOAS) Program. The aircraft and LFS Systems have also flown in the Canadian Arctic during the initial Arctic Marine Oil Spill Program (AMOP), as well as along the Labrador Coastline and West Coast of Canada.

Theoretically, the ALFS can determine oil layer thickness over a range of 0.1 μm to 20 μm and identify and classify the oil type (NB: this is the only sensor with this capability, and it is based on the fact that different oils fluoresce at different intensities and wavelengths). Although capable of operating well in low light or at night, the LFS is impaired by variations in flight altitude and the signal is blocked by cloud cover and/or surface fog and precipitation, all serious operational constraints for the Arctic.

A series of test overflights with an experimental laser fluorosensor developed by Environment Canada in the spring of 1992 showed that the sensor measured reproducible and distinct signatures from oil and oily material on snow and ice in test pans on land. Oil thickness was a fraction of a millimetre (Dick and Fingas, 1992).

The evaluation of LFS capabilities for oil in ice was initially a key component of the SINTEF JIP remote sensing project. Unfortunately, the only operational system in Europe (Germany) was not available to participate. More portable LFS systems are available for lease, but require an aircraft or helicopter platform with an open belly hatch (no glass)—these platforms are not easy to find on long or short notice. At this stage, the LFS should be considered a potentially useful sensor in the future for oil on the surface of solid ice and slush or on water between floes, but only under Visual Flight Rules (VFR) conditions. Major drawbacks against its operational use are cost and limited availability.

Airborne SAR/SLAR

Side-looking airborne radar (SLAR) provides a wide-swath view on each side of the flightline out to 30 km, but other data from near-range (±250 m) sensors are required to confirm the findings. In practice, SLAR is used as a regional screening tool for other more narrowly focused sensors. SLAR (and synthetic aperture radar, SAR) images can provide a misleading picture of the true presence of oil on water, overestimating in some cases because of false targets and underestimating or missing the oil altogether, for example, in high winds and high sea states.

Oil spill detection by radar imaging (both airborne and space-borne, see following) is based on the principle that thin oil layers will smooth sea surface roughness. Normally, X-band radar waves (9 to 10 GHz) are backscattered by ship wakes and capillary waves naturally present at the sea surface. The presence of oil reduces the radar backscatter by presenting a smoother reflecting surface. This leads to the appearance of ‘black’ spots on the image, delineating the oil slick. Possible other sources for ‘dark spots’ include windless areas, algae, upwelling water, sandbanks and fish oil, leading to high probability of false positives. These can be limited by high levels of operator competence and advanced image assessment procedures, but they remain a serious drawback to the practical reliability of airborne or spaceborne radar imagery.

In considering the capabilities of SLAR and SAR in mapping oil spills in ice, the primary question becomes, “What is the limiting ice concentration above which the wave damping effects of the ice are such that any further smoothing from the presence of an oil slick becomes undetectable in the radar image?” Detecting oil on the water between floes will depend on levels of pre-spill capillary wave action related, in turn, to the ice concentration (much reduced wave fetch, wind speed, etc.).

Based on the very limited effect of very open drift ice (1 to 3/10) on sea conditions it seems reasonable to expect that airborne SLAR is capable of ‘seeing’ a large oil slick spread between the widely spaced floes. This condition is closely analogous to a spill on open water. The limiting factor with spills in ice that may become fragmented and split into small patches will be the relative spill size in comparison to the radar resolution: the minimum resolution of airborne SLAR is in the order of 60 m long-track and 30 m perpendicular.

Ground Penetrating Radar

Radar technology was the subject of extensive research in the 1980s (Butt et al., 1981; Mann, 1979; Goodman and Fingas, 1983). Much of this work focused on determining whether or not scattering of radar waves at the ice bottom surface would be altered enough by the presence of oil to allow reliable detection. Several initially positive indications showing the potential presence of an oil layer in the ice could not be validated in subsequent re-examination of the results. Theoretical and laboratory/tank studies failed to identify an established physical mechanism for the radar detection of oil-in-ice. Practical considerations included a concern that natural anomalies in the internal structure of sea ice (cracks, voids and discontinuities) would attenuate the signals to such an extent that much of the data needed to identify the presence of oil in the ice would be lost.

Since the earlier studies were conducted, the field of impulse radar or ground-penetrating radar (GPR) has been transformed by advances in data processing in geotechnical science and dramatic reductions in signal-to-noise ratios, among other improvements. Over the past five years (2004 to 2009), significant progress has been made in oil-in-ice and oil-under-snow detection utilizing the latest hardware and software technology in commercially available ground-penetrating radar (GPR).

A series of related projects involving numerical modelling, laboratory trials and field tests in a range of ice conditions have demonstrated that existing GPR systems operated from the ice surface in the 500-MHz to 1-GHz frequency range are effective tools for dealing with the problem of detecting oil in, on and under ice, and capable of resolving trapped oil film thickness down to 1 cm to 2 cm.

Existing off-the-shelf systems operated in a low-altitude airborne mode (10-m to 15-m flight altitude) are capable of reliably detecting oil on the ice surface buried under snow and oil under ice, but only under ideal conditions of cold ice in mid-winter (Bradford et al., 2009 *under review*). A new project to develop a prototype airborne system optimized for detecting oil trapped under and within solid ice over a wide range of ice temperatures and salinities is scheduled for completion in 2010 with possible trials (no oil) at Prudhoe Bay (JIP *in progress*).

In a 2008 project sponsored by the SINTEF JIP and MMS, the GPR was successfully tested in an airborne mode on Svalbard in April 2008 over snow-covered oil on the ice surface (Dickins et al., 2008; Bradford et al., 2009, *in review*).

Satellite Systems

For satellite imagery to play a useful role in tactical monitoring for an oil spill in ice, the images must be available in all weather, day and night, with a resolution in the order of tens of metres or better. A number of very high resolution (0.6 m to 3 m) visual satellite products are available (e.g., IRS, SPOT, Ikonos and Quickbird), but there are issues involved with programming the satellite in an emergency to produce imagery in time to be useful. The most serious issue limiting the utility of visual satellite platforms is their inability to acquire data in darkness and with cloud cover. Synthetic Aperture Radar (SAR) is the only satellite sensor that can overcome this limitation and potentially provide close to real-time imagery regardless of daylight or weather conditions.

The number of commercial radar satellites available worldwide is expanding at a rapid rate and the resolution continues to shrink exponentially. Up until 2007, the most developed platforms were Canada’s Radarsat and Europe’s ERS 1&2 and Envisat, with useful resolutions in the order of 25 m. In late 2007 and early 2008, a series of new very high-resolution SAR satellites were launched by Germany, Italy and Canada; these satellites had the capability of resolving surface details down to a few metres. With the number of platforms in polar orbit it is now possible to obtain multiple passes on any single day in the Beaufort Sea from different satellites. Swath width (coverage area) depends on resolution and typically ranges from 35 to hundreds of kilometres. In the past, reprogramming to position the satellite coverage in an emergency could take three to four days, but the delay is now less than 48 hours.

In May 2009, the oil-in-ice Joint Industry Program (JIP) managed by SINTEF Norway examined the potential to use these latest-generation SAR satellites to detect and monitor Arctic oil spills. The same platforms are used today on a 24-hour real-time basis to search for potential oil slicks in coastal waters around the EU, including the Baltic Sea (Kongsberg Satellite Services contracted to EMSA). Results from the JIP study are not yet publicly available.

As explained earlier in a discussion of the capabilities of airborne SAR/SLAR, the ability to detect oil in pack ice with radar imagery is still not well understood. While the capabilities of radar imagery for sea ice mapping are well proven (most national ice maps now rely on this imagery as the primary data source), it is not known whether the same imagery can be used to discriminate between oiled and clean ice, or to detect oil on relatively calm water between ice floes. The key issue is whether the interruption to capillary waves on the ocean surface in the presence of oil will still occur to a sufficient degree with oil among ice to be observable in the radar reflection. See related earlier discussion under SAR/SLAR airborne sensors.

Existing radar satellite sensors have already demonstrated a potential for monitoring thick open ocean slicks; examples include the *Sea Empress* spill in Milford Haven, UK, the *Nakhodka* tanker spill off Japan (Lunel et al., 1997; Hodgins et al., 1996) and more recently the *Prestige* spill off Spain. As graphically pointed out by Coolbaugh (2008), all of these systems suffer from a high sensitivity to false targets (non-oil) and varying surface appearances in different windspeeds that complicates interpretation of slick whereabouts and extent from day to day. Ground truthing will always be essential to complement and validate satellite image results.

Surface-based Remote Sensing Systems

Depending on the ice conditions (floe size, thickness, stability), it may be possible to deploy a variety of remote sensing systems to work directly from the ice surface or from the deck or bridge of a nearby vessel.

Hand-held IR

Low-cost, non-cooled, hand-held IR systems can detect oil under certain conditions. They are in operational use on supply vessels, providing, for example, an overview of skimmer position relative to oil within booms as viewed from the ship's bridge. Stabilized and cooled FLIR systems with accurate positioning, distance and area measurement capability, including transformation of imagery into a 2D situation plot, are being developed (Andersen, pers. comm.). A series of hand-held IR camera images of oil contained within close pack ice were obtained during the 2009 JIP field experiment off Svalbard, but these results are not yet available for distribution.

Ship-based Microwave Radiometer

A ship-based system, believed to be based on MWR technology, is being developed in Denmark by OSIS Online Environmental Surveillance (see www.osis.biz) (technical information withheld). No further details are available at present. It should be noted that airborne MWR sensors have a mixed record in documenting spills in open water.

Dogs

A project to investigate the use of specially trained dogs to detect oil-in-ice was initiated in early 2007 as part of the SINTEF JIP Project. The objective for Phase 1 was to show the practical feasibility of using specially trained dogs to detect hidden oil spills. The basic course consisted of training in the laboratory and various outdoor environments (beach, frozen ground, snow, etc.). Results from the initial training clearly showed that dogs can be used to detect oil hidden in snow. Several of the most experienced dogs passed blind tests and detected different oil types (crude/bunker fuels), compared with blanks or other scents. Based on the encouraging results from the Phase 1 feasibility study, several dogs were airlifted (as main cabin passengers!) to the research station at Svea on Svalbard in April 2008 and successfully detected small quantities of oil buried on the ice surface from long distances (several kilometres or more).

In addition, several of the dogs participated in a small accidental spill in Norway early in 2009 and successfully delineated the extent of contamination of beach sediments. During this work, it was discovered that the Indian Army has used dogs for the specific purpose of detecting hydrocarbons for some years. Full results from the 2007-to-2009 dog training and testing program in Norway are part of the SINTEF Oil-in-Ice JIP (results to be released at a later date).

Optical Gas Sensors (Shell LightTouch™)

Shell Exploration and Production collected baseline data on methane emissions from oil on the ice at Svea in April 2007 (Hirst and O’Connor, 2007, proprietary). The primary goals of this effort were to obtain a useable estimate of the hydrocarbon emission rate resulting from oil spills onto icy water, and to use this to estimate the range of detectability of such spills. Results from this work have not yet been publicly released.

The general applicability of ‘gas sniffers’ in a real spill situation has been questioned because of the short time period in which any measurable concentration of extremely light components, such as methane or ethane, will be present, generally within a very short period (<10 minutes). The situation would be different for a continuous discharge with an unlimited supply of fresh light ends, but in that case, it is presumed that the location of the spill source would not be in doubt.

If it could be proven that ethane/methane components are detectable through ice over time, the use of gas sniffers to find oil trapped under the ice would be of interest. In such cases, the operational window using this technique for oil spill detection could be extended because oil trapped under ice does not weather to any significant extent. Preliminary testing of an early version of Shell's system in tank tests at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL), NH, provided some evidence of ethane flux occurring through a 35-cm-to-40-cm ice sheet, but the concentration levels were very close to background (Dickins et al., 2005).

Ground Penetrating Radar (GPR)

The progress made with airborne GPR since 2004 is described above. Computer simulation modelling carried out in 2008 shows that the existing commercial GPR systems operated from the ice surface are fully capable of detecting oil films down to a few cm through up to 2 m of cold mid-winter sea ice. Early and late in the season (e.g., in the Beaufort, October to November and May to June), much of the radar energy is attenuated by the conductive warm ice and GPR becomes less reliable. A new program to develop a higher-powered system optimized for the oil-in-ice problem is intended to overcome these issues. (Dickins and Boise State, JIP in progress).

In 2007, ACS acquired an existing commercial GPR system to deal with the ongoing potential problem of pipeline spills under snow in the Prudhoe Bay field. At present, the training and experience with this unit is all from the surface, but there are plans in the future to consider deploying the system from a low-flying helicopter—emulating the success achieved on Svalbard in 2008 in detecting oil under snow with the same system in an airborne mode (Bradford et al., 2009). See discussion above under Airborne and Spaceborne Remote Sensing.

Marine Radar, X-Band (Short and Medium Pulse)

Since 2001, the petroleum industry in Norway has been a driving force in the development and utilization of ship-based sensors for short-to-medium-range oil spill detection, supplementing airborne and satellite remote sensing. The Norwegian systems are based on X-band marine radars and the collection of up to 128 scans. An oil detection range of up to 3 km has been proven.

In the Netherlands, the SeaDarq system, developed by TNO, is in operational use on the ship *Arca* owned by the Reijkswaaterstaat Agency (www.seadarq.com). In Canada, the ice detection radar Rutter Sigma S6 (www.rutter.ca) is believed to be capable of oil detection. The Norwegian Coast Guard obtained positive test results with both the MIROS and Rutter systems during an oil-on-water exercise in March 2008. The capabilities of these radars for oil in ice are not known at present. A Rutter system was on board KV Svalbard for the 2009 oil-in-ice JIP field experiment, but there were no uncontained slicks to provide a useful test.

Tracking and Long-Term Monitoring

Spill Position

Tracking oil in ice involves assimilating field data and integrating real-time positions and observations with forecasting tools such as weather models, ice drift algorithms and oil spreading/weathering models.

Resources available to the modellers and forecasters may include the following:

- High-resolution satellite imagery;
- On-site meteorologists and ice forecasters (company employees);
- Off-site ice analysts and forecasters (e.g., Canadian Ice Service);
- Aircraft or helicopters with infrared, video and still-photo capabilities;
- Satellite tracking beacons; and
- Empirical models.

Outputs from spill tracking activities include the following:

- Maps of contaminated area boundaries for oil in ice and open water;
- Speed and direction of movement of oiled ice and oil slicks in open water;
- Predicted contaminated boundaries, e.g., 12 or 24 hours in advance; and
- Charts showing detailed composition of the ice cover where the oil is located, including mix of floe sizes, variability in ice coverage and boundaries of leads and polynyas.

The integration of information acquired from the tracking and surveillance activities is a complex process and involves the following:

- Data acquisition from sources such as satellites, aircraft, field crews, computer models, government ice centres, and weather services;
- Production of geographically referenced map products combining various data sets;
- Distribution and transmission of finished products and mapped GIS data; and
- Incorporation of monitoring products into briefing documents for strategic and tactical decision making within some form of response command structure.

There has been little new progress in this field over the past twenty years. The tracking beacons themselves are orders of magnitude more accurate and reliable than before, but the basic drift models that can accommodate multiple metocean and ice inputs to forecast positions and boundaries have scarcely advanced.

Tracking of a large accidental spill during the summer open-water period is relatively easy because of the extended periods of daylight and the fact that the vessel or offshore facility provides a known starting point. Response personnel would be available immediately to travel by boat to identify, map and report the leading edge of any spilled oil. Within hours, helicopter surveillance teams could join in the tracking of oil from the air visually and with the aid of forward-looking infrared radar (FLIR) systems, global positioning systems (GPS), digital cameras and other methods. Drift buoys (some tracked by satellite and others equipped with transmitters for vessel tracking) and various types of radar reflectors can be launched from vessels on location at the beginning of a spill and at appropriate intervals thereafter to help track the oil.

Conditions of high ice concentrations, slush and brash in the water at freeze-up, and situations where the oil is trapped beneath floes present major challenges. A late season spill close to freeze-up could quickly disappear from view under conditions of poor visibility and rapidly shrinking daylight as much of the oil becomes incorporated into rafting and rubbled young ice.

Specialized ice-strengthened beacons have been used successfully for many years to track ice movements over an entire winter season throughout the polar basin. Detection and tracking of the relative movement of potentially separated oiled areas within a converging and diverging ice cover is much more difficult.

Tracking oil spills in a moving ice cover involves deploying fairly large numbers of specialized GPS ice beacons at regular intervals at or near the spill source. Depending on the ice drift rate and desired fix interval in defining the most likely oiled path, it may be necessary to place buoys on the ice as often as every four hours, corresponding to a spacing in early winter of ~0.5 to 1 km. With this highly accurate ice movement track, the challenge is then reduced to narrowing the search area to find oil among or in the ice through a combination of airborne visual reconnaissance (where oil might be visible in leads and openings) and helicopter-mounted GPR or even surface GPR where on-ice work is feasible (unlikely until mid-winter).

Over time, pack ice will expand and contract with adjacent areas following slightly different tracks that start out being close but diverge over time. Hirvi et al. (1987) documented this behaviour following a tanker spill of 627 tons of crude oil in ice off the Finnish coast. Over eight weeks, the initial area of oiled ice split into about five discrete patches separated by up to 16 km.

Ground Truthing

Regardless of the accuracy of beacons or drift models, or the availability of remote sensing data, there will always be a need to ‘ground truth’ or validate the presence of actual oil. While always important for open water spills, ‘ground truthing’ takes on new meaning for spills trapped under or within pack ice. In that case, field validation may only be possible by landing on probable oiled floes and drilling a grid of two-inch auger holes. In many situations, icebreaking support vessels may provide the only safe, reliable platform that allows over-the-side sampling in dynamic ice with small relatively thin floes. An over-the-side basket can be used to collect samples and potentially drill holes. The act of disturbing the ice with the vessel may expose the oil and provide the necessary validation directly.

Possible Future Technologies

Several new technologies or new applications of existing technology could play a role in future oil-in-ice surveillance.

Nuclear Magnetic Resonance (NMR)

This concept was introduced by Nedwed (2007) as a potential basis for an airborne system that could detect oil under ice without being affected by the non-homogeneity of the ice structure and problems of signal attenuation in warm saline ice (as with existing GPR).

NMR works with magnetization of nuclei in a static magnetic field. The magnetization is caused by the ordering of magnetic moments of nuclei in the field. One or a few radio frequency (RF) pulses can excite these magnetic moments. Electromagnetic energy is emitted and measured as the magnetic moments return to equilibrium. Features of the electromagnetic response are specific to the molecular environment of the nuclei. This allows separation of the NMR signals of oil and water due to different responses from these types of liquids. In a similar manner to the detection of groundwater in aquifers using this technology, the method can utilize the Earth's magnetic field as the static magnetic field and thereby eliminate the complexity and cost of generating an independent magnetic field for remotely detecting fluids below a surface. (Nedwed et al., 2008)

For applications in oil spill detection, a very important aspect of NMR is that the signals from ice and snow are not normally detected under the experimental conditions used to detect signals from oil or liquid water. Thus, the presence of snow or ice does not create the interference problems for the detection of oil under ice or snow that are inherent in other detection methods such as GPR.

A joint project to address the technical issues of applying NMR to the oil-in-ice problem was initiated by the research departments of ExxonMobil and by the Institute of Chemical Kinetics and Combustion of the Siberian Branch of the Russian Academy of Science. Initial findings are published in Shushakov et al. (2009).

Numerical modelling indicates that separate transmitter and receiver antennae will be needed and that receiver antenna diameter plays a significant role in measurement sensitivity. NMR relaxation times in the Earth's magnetic field for medium and light crudes were found to be approximately three times less than for saline and fresh water. This large difference should allow discrimination of the oil signal in a background of water. These initial results validate the concept for remote detection of oil under ice using Earth's field NMR and provide motivation to develop a practical field measurement tool. Research is now under way to determine whether or not surface-based instruments currently used to characterize groundwater aquifers can be modified and placed on a helicopter.

Under-Ice Autonomous Underwater Vehicles (AUVs)

The technology needed to deploy wide-ranging autonomous underwater vehicles (AUVs) is maturing rapidly. The latest generation of large AUVs represented by Autosub6000 is capable of an ultimate range under ice of up to 1,000 km. Wadhams et al. (2006) reports on the results of a field test in the NE Greenland Sea in 2004 where highly detailed 3-D sonar maps were obtained of the undersurface of ice floes for the first time.

Surface-mounted acoustic transducers have achieved considerable success in the past in resolving oil layers trapped under ice and researchers have commented on how much easier it would be to deploy this technology in an upward-looking mode to detect oil under ice (Goodman, 2008). There would be no need to conduct careful surface preparation by removing snow and wetting the surface or bonding the transducers to achieve acoustic coupling. Unpredictable influences of trapped air pockets and inclusions or irregularities in the internal ice structure would be eliminated and the number of interfaces involved in the return signal would be greatly simplified without having to penetrate the highly variable ice sheet to reach the oil. The AUV would serve as the carrier vehicle for the oil-under-ice mapping sonar. (Liberty, pers. comm.).

The detailed 3-D representation of the ice underside could be fed into an oil-spill model that predicts the likely pooling potential of different ice areas, effectively guiding other efforts to locate the areas with the greatest oil volumes for possible recovery. Wadhams' recent re-evaluation of under-ice oil-holding potential based on the new sonar mapping representations of under-ice geometry indicates that only about 5% of any given area of undisturbed first-year ice will be contaminated, making the probability of detecting and mapping an under-ice spill through the old fashioned but still state-of-the-art method of drilling holes very low. This finding is a significant departure from earlier estimates of up to 50% of the ice underside containing oil, based on a very limited understanding of the three-dimensional relief of the ice undersurface.

Practical problems with this concept include the speed at which oil would become incorporated into new ice forming beneath the spill. Depending on the location, time of year and type of ice, this process could take from 12 hours to months. For example, oil spilled under multi-year ice early in the winter may take most of the growth season to become encapsulated. What this means is that while there are situations where the oil spill will be quickly hidden from ‘view’ by new ice growth under first-year ice (November to March), there are also many scenarios in the Beaufort where deploying a system within 48 to 72 hours of a spill may give ample time to locate and map the distribution of oil under the ice in detail, for example, late in the season in April or at any time when there are high concentrations of old ice in the vicinity of the spill.

Containment and Recovery

This section documents improvements in the state of the art for containment and recovery as an oil spill countermeasure in response to spills in the Southern Beaufort Sea over the last twenty years. First, a brief summary is given of containment and recovery, as it existed in the early 1990s as described in the Beaufort Sea Steering Committee (BSSC) reports. Then, the research and development efforts to improve the technique over the subsequent two decades are described.

State of the Art in the Early 1990s

The containment and recovery technology that would have been used to respond to major (Tier 3) spills in the Southern Beaufort Sea is described in the BSSC report detailing the methodology for determining the costs associated with responding to a worst-case blowout (BSSC, 1991a). The main situation of interest at that time was as the response to a blowout in open water conditions. The use of skimmers to recover oil from amongst ice was not considered at that time.

The technique described for responding to a blowout in open water conditions consisted of a barge-based system for containment, recovery, storage and disposal (Figure 1) with the following main components:

- 980 m of Ro-Boom Ocean boom forming a J-shape for collecting and concentrating oil;
- one Transrec (or Desmi) weir skimmer;
- emulsion treater;
- flare burner; and
- 1,106 m^3 of barge storage capacity.

This system was intended for open water use; however, it was envisioned that it could be used in the late fall as ice began to form, but only during periods of 'light ice' at the spill site. At the time, it was believed that a system such as this could operate, albeit with reduced effectiveness, in ice concentrations up to 3/10ths coverage.

Research and Development on Containment and Recovery since 1990

Containment and Recovery as a Strategy for Large Spills

Containment and recovery (C&R) is generally regarded as the preferred response strategy for marine oil spills, and is mandated as the primary technique in many jurisdictions through regulation. Nonetheless, the technique has significant limitations when used for large spills

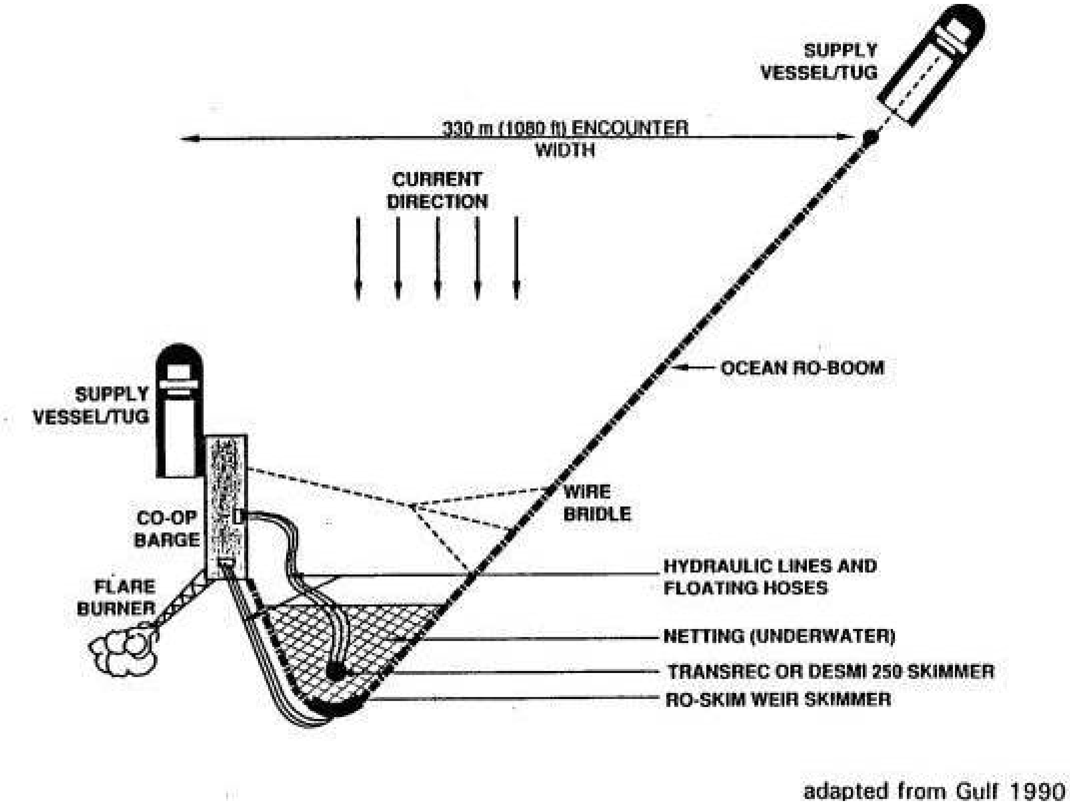


Figure 1: Barge-Based Containment and Recovery System Circa 1990

in either temperate or Arctic locations. There is a growing recognition of the limitations of C&R for large spills, mainly because of two issues:

- Encounter rate limitations: In any large spill, the oil will rapidly spread to form a thin layer on the water surface. The problem is worse for blowout spills, where the initial spill condition may be an average slick thickness in the range of 0.001 mm to 0.01 mm. In either case, long lengths of containment boom are required to concentrate the oil for effective recovery. To avoid entrainment losses, most conventional containment boom must be towed at a speed of less than 1 knot, which severely limits the rate at which the slick is encountered.
- Most high-capacity skimmers used in this application are weir skimmers. These generally have high-capacity pumps that satisfy regulatory requirements with their high nameplate capacities, but generally have low recovery efficiencies, i.e., they recover a significant amount of water along with the oil. The problem is magnified when the oil emulsifies on the water surface prior to recovery, and the volume of oily product recovered increases by four to ten times. The recovery of free water and possibly emulsions means that the storage and handling requirements become problematic, a particular dilemma for an area, such as the Beaufort Sea, that does not have a ready supply of barges.

The limitations noted above would apply to any large marine oil spill and not just those occurring in the Beaufort Sea. An additional limiting factor for spills in the Beaufort would be the availability of offshore vessels to tend booms, deploy and operate skimmers, position barges and shuttle recovered fluids to shore for disposal. In short, a large-scale containment and recovery operation can be logistically complex, and there has been growing recognition in recent years that in-situ burning and dispersant use should be given equal or, in some instances, greater consideration for responding to large spills. A state-of-the-art response to a large marine spill in the Beaufort Sea, particularly in the early stages of the resumption of exploration, is not likely to consist of containment and recovery, although the use of booms and skimmers will still likely be an option for smaller spills.

One additional note in terms of strategies is the limiting conditions with regard to ice coverage. Field tests of a large barge-based containment and recovery system in the Alaskan Beaufort Sea determined that the system was only functional in trace or minimal ice conditions, despite the use of ice management and ice deflection measures. With more than trace ice present, the system had to be idled, reconfigured or repaired for relatively long periods of time such that the response effectiveness was diminished to near zero (Bronson, 2002).

Technology Improvements to Containment

In terms of technological developments since the early 1990s, it is instructive to note that the specific boom and skimmer products noted in the Beaufort Sea plan of 1990 are still in common use today. Although there have been improvements and refinements to booms and skimmers, the basic technology remains much the same as it has been for over 20 years.

With containment booms, there are a multitude of good products available (Potter, 2007). For offshore applications, the most commonly used booms are air-inflatable and generally reel-mounted, which together provide a product that is relatively compact and 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.

In addition to general improvements in materials, packaging and fast-deployment capability, there are two areas of significant improvement worthy of note for the Beaufort Sea situation: high-speed containment and the use of boom vanes.

As noted above, conventional containment booms fail to contain oil at speeds greater than 0.7 to 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™. 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 United States Coast Guard 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 a Beaufort situation: 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.

Boom vanes are a recently developed product that provides superior positioning of containment booms 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. (An alternative use of the boom vane is to deploy the leading end of a boom from a riverbank out to the middle of the watercourse without the use of a boat). 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. An additional benefit is that fewer vessels would be required. A configuration similar to the system shown in Figure 1 could be managed by one towing vessel, with one towline to the barge and one towline each to the leading ends of two containment booms.

Technology Improvements to Recovery

As noted above, the specific skimmer products noted in the 1990s plan are still marketed and in common use today, reflecting the mature nature of the industry over the past 20 years. There is a wide variety of skimming devices on the market today, including a wide range of skimming principles (Potter, 2007). The selection of a particular skimmer will be based on the specific needs of the application, with products available to meet one or more of the following criteria:

- High rate
- High efficiency
- High-viscosity oil
- Non-flowing oil
- Debris tolerance
- Shallow water

The most commonly used skimmers for offshore application are high-rate weir skimmers of which there are several good examples, including the Transrec and Desmi models included in the Beaufort contingency plans of the 1980s and early 1990s. These skimmers have nameplate capacities in the range of 100 m^3/h to 200 m^3/h and can process small debris (including small pieces of ice), but typically have low recovery efficiencies—in the range of 50% or less.

Oleophilic skimmers are a class of device that includes disc, belt and drum skimmers. They have much better recovery efficiencies, typically recovering a fluid that is 90% or more oil, but generally have much lower recovery rates than weir devices. This may be changing with the recent development of a fibrous disc skimmer by Crucial Inc. that has a recovery rate in the range of 180 m^3/h and a recovery efficiency of 85% (SL Ross, 2009). Testing is planned in the upcoming year to evaluate its performance under Arctic conditions including the presence of ice.

In work sponsored by the Minerals Management Service (MMS), research and testing were carried out to investigate the optimization of oleophilic surfaces. Various materials and textures were examined in laboratory and small-scale studies, culminating in full-scale testing of a grooved drum skimmer. The grooved drums were found to collect significantly more oil than conventional smooth drum surfaces, not only because of the additional surface area provided by the grooved drum, but also because of the oil held by capillary action between the grooves. A final phase of the test program involved tests in a variety of ice conditions. The concept has been commercialized and is being produced as an option for Elastec drum skimmers (Keller and Clark, 2007).

Recovery in Ice-Affected Waters

Over the last 20 years, there has been a significant amount of research and development in this area in North America, Scandinavia and Japan, with both basic research and equipment development aimed at developing a method of removing oil from ice. Most of the work has focused on concepts involving some form of ice processing, which, by its nature, means the concept is limited to relatively small ice pieces such as would be found in unfrozen ship tracks and the brash (sometimes referred to as broken ice) that might be found around fixed installations such as drilling platforms.

One of the more developed concepts was the Mechanical Oil Recovery in Ice-Infested Waters (MORICE) study. The primary objective of the program was to develop oil-in-ice response methods that could be commercialized. Governments, research organizations and industry firms in Norway, Canada, the USA, Germany and Sweden sponsored MORICE (Mullin et al., 2003). A number of concepts were evaluated, including six selected for laboratory testing and one 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.

Lamor, a skimmer manufacturer known for its brush-type skimmers, has developed two different devices for skimming operations in ice. The first is the Arctic skimmer, which would be used to recover isolated pockets of oil within an ice field, as might result from a small tank or tanker spill in ice. The device is designed to be positioned by a crane arm from the deck of a ship. The recovery mechanism for the Arctic skimmer is a brush wheel-type skimmer. The need to regularly re-position the skimmer in pools of oil will severely restrict its encounter rate.

A second device, the Lamor Oil Ice Separator (LOIS), is intended for advancing operations and could be used to cover a wider area of oiled ice. The device would be mounted on the side of a ship, and as it advances through an ice field, the device would depress ice pieces, agitate them to facilitate the release of oil, and then recover the oil with a brush skimmer from an area within the device that is protected from ice (Lampela, 2007). The device is particularly suited to use in unfrozen ship tracks.

As noted, the bulk of research and development has focused on the problem of removing oil from relatively small ice pieces and may have some applicability in the Beaufort to spills in ship tracks or in the brash ice near fixed installations. There has been little research done with regard to the problem of removing oil from larger ice floes with diameters ranging from 10s to 1,000s of metres that typify breakup and pack ice conditions during winter in the Beaufort Sea.

Summary

There is a wide variety of containment and recovery systems available for responding to marine oil spills in the open water season. Given the current state of the art, it is unlikely that a large-scale containment and recovery system would be implemented for a Tier 2 or Tier 3 spill, particularly in the early stages of the resumption of exploration drilling, but such an approach is likely for smaller operational-type spills.

Skimmers are available for oil spilled among ice. They are best suited to working among relatively small ice pieces and for spills that cover a small area, based on limitations of both encounter rate and recovery rate.

In-situ Burning (ISB)

This section documents improvements in the state of the art for in-situ burning as an oil spill countermeasure in response to spills in the Southern Beaufort Sea over the last twenty years. First, a brief summary is given of in-situ burning, as it existed in the early 1990s as described in the Beaufort Sea Steering Committee (BSSC) reports. Then, the research and development efforts to improve in-situ burning over the subsequent two decades are described.

State of the Art in the Early 1990s

The in-situ burning technology that would have been used to respond to major (Tier 3) spills in the Southern Beaufort Sea is described in the BSSC report detailing the methodology for determining costs associated with responding to a worst-case blowout (BSSC, 1991a). In-situ burning was envisioned for two spill situations: response to a blowout in open water conditions and response to blowouts in ice conditions.

Open Water In-situ Burning System

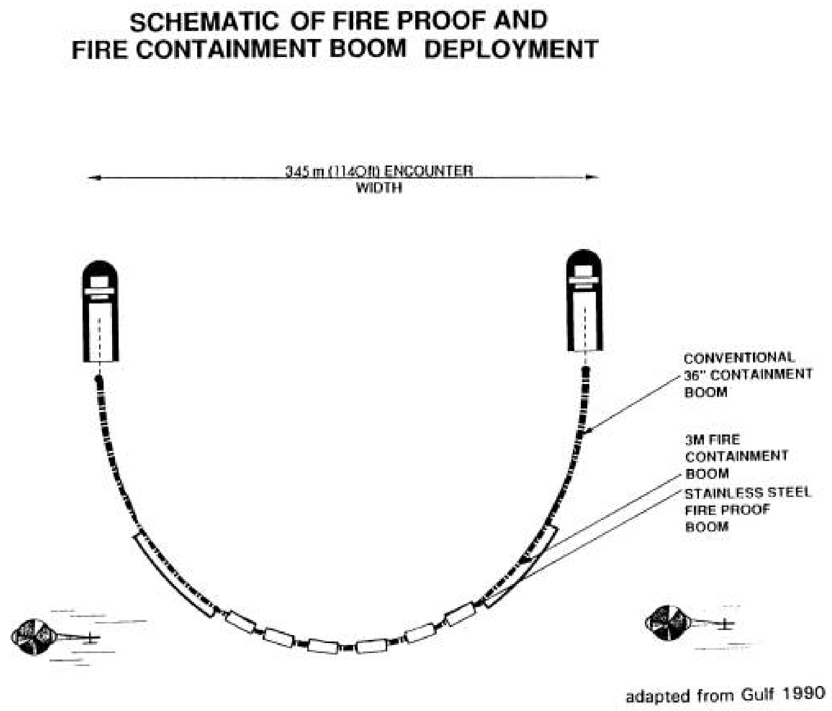
The system described for responding to a blowout in open water conditions consisted of the following (Figure 2):

- 77 m of stainless steel fireproof boom placed in the centre of the pocket;
- 455 m of 3M fire containment boom, one half of which is connected to each end of the fireproof boom; and
- 500 m of conventional, 36" boom, one half of which is connected to each end of the fire containment boom.

This system was intended for open water use; however, it was thought that it could be used in the late fall as ice began to form, but only during periods of ‘light ice’ at the spill site.

System for In-situ Burning in Ice

The assumption was made in the 1990s that safety considerations would preclude any attempt to undertake cleanup operations during the winter months in the transition zone. The strategy, therefore, was to track the oiled ice and commence a burning operation where oil surfaced in melt-pools and/or collected in open leads (Figure 3). The thickness of the oil layer originally discharged under the ice, the size of oil slicks on melt-pools the following spring, the operational capabilities and limitations of the Beaufort Sea Oil Spill Co-op's Helitorch System and Dome hand-held igniters, the operational capabilities and limitations of medium-lift helicopters and weather constraints on flying and oil ignition in spring time were combined to estimate both the



adapted from Gulf 1990

Figure 2: Beaufort Sea Oil Spill Co-op Open Water In-situ Burning System Schematic

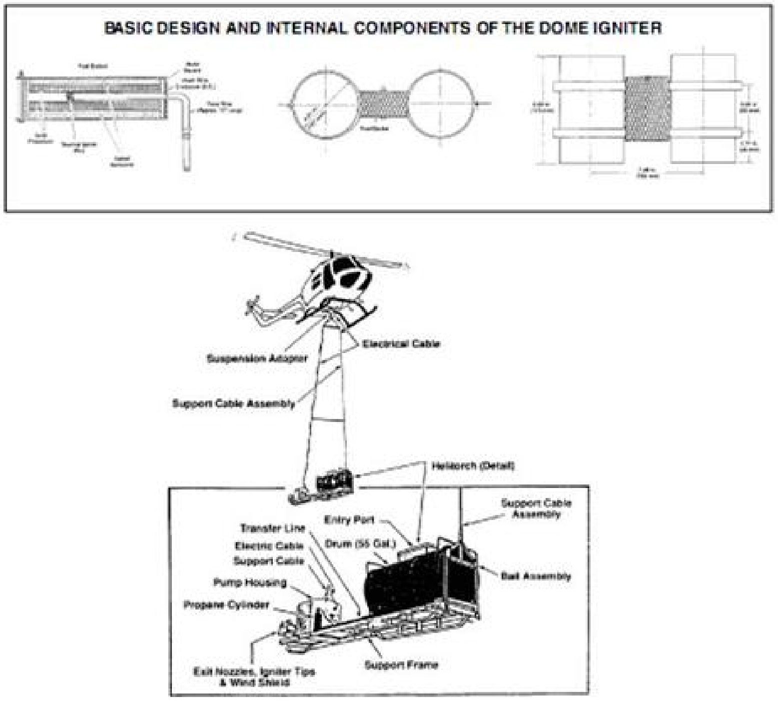


Figure 3: Beaufort Sea Oil Spill Co-op Aerial Ignition Systems for Spills on and under Ice

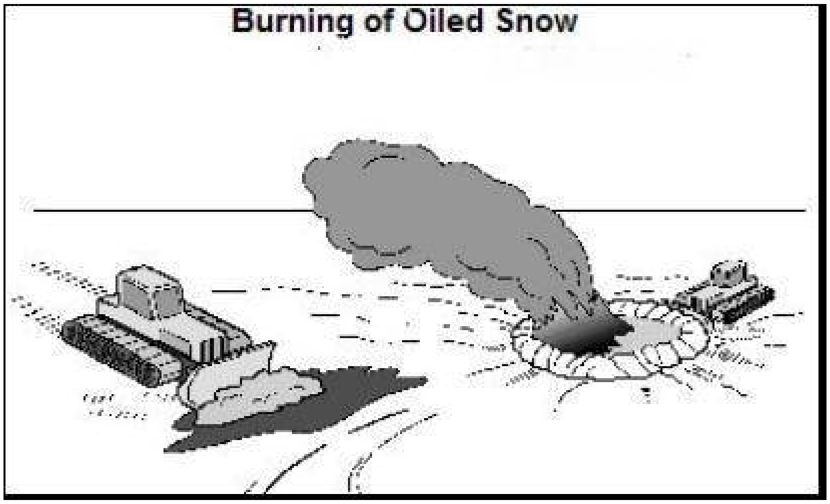


Figure 4: Burning of Oiled Snow, as Proposed in 1990

maximum achievable oil removal by in-situ burning of oil on melt-pools and the number of Helitorches and helicopters required to accomplish this in the time available prior to breakup.

For oil released onto landfast ice during winter, mechanized and manual scraping of the ice and subsequent burning of the collected oily snow in-situ were proposed (Figure 4).

Research and Development Relative to In-situ Burning since 1990

Research and development relative to in-situ burning since 1990 was spurred in part by the successful test burn of spilled Alaska North Slope (ANS) crude oil from the *Exxon Valdez* (Allen, 1990). R&D activities relevant to Beaufort Sea oil spill response in the past 20 years have focused on four aspects of in-situ burning:

1. Basic processes;
2. Environmental impacts;
3. Technology development; and
4. State-of-the-art reviews and decision-making.

Basic Processes Research

In the 1990s, research into ISB processes focused on the burning of water-in-oil emulsions, because the second attempted burn of Alaska North Slope (ANS) crude from the *Exxon Valdez* reportedly failed because of the high emulsion water content of the slick (Allen, 1991). Programs of research were carried out in Alaska (Buist et al., 1996 and 1998) and jointly in Canada and Norway (Bech et al., 1992 and 1993; Guenette et al., 1995; Guenette and Sveum, 1995; Guenette and Wighus, 1996) to investigate the burning of emulsified oil slicks on water and amongst ice in various environmental conditions, including waves. The basic conclusions of this research were that the following:

- For most crude oils, emulsified water content in excess of 25% precludes ignition (some very light crudes that do not form stable emulsions can be ignited where water content is up to 60%);
- The burn rate and efficiency for emulsions decline with increasing water content;
- Wave action makes ignition of emulsified slicks more challenging, slows in-situ burning rates and increases the thickness of residue that remains when the slick extinguishes naturally;
- The presence of ice pieces in the slick does not significantly reduce emulsion burning rates or efficiencies; and
- The maximum wind speed for successful ignition is 10 m/s.

Also in the early 1990s, a field research study of the burning of diesel and crude oil in snow was carried out in Norway (Sveum and Bech, 1991). The results showed that spills of 1 m^3 in snow could be easily ignited (snow/oil mixtures with as little as 3% to 4% oil could be ignited using a promoter) and efficiently burned (90+% removal) even two weeks after being spilled.

In the early 2000s, a research program was carried out to determine the effects of slush and frazil ice on the rules of thumb for in-situ burning (Buist et al., 2003a). The following rules were proposed based on the experiments:

- The minimum ignitable thickness for fresh crude oil on brash or frazil ice is 1 mm to 2 mm, or approximately twice that on water;
- The burn rate of thin (3-mm to 5-mm) slicks on frazil ice is approximately half the rate for the same size of slick on water, and the burn rate of these slicks on brash ice is approximately ¼ the rate on water. The presence of waves slightly reduces the burn rate on water, frazil and brash ice; and
- The residue remaining for thin (3-mm to 5-mm) slicks burned on water is 1 mm; on quiescent frazil or brash ice, it is approximately 1.5 mm; and on frazil or brash ice in waves, it is approximately 2 mm.

Environmental Impact Research

In the 1990s, there was a concerted research effort to determine the potential environmental impact (primarily from the smoke plume and burn residue) of in-situ burning. Environment Canada’s Emergencies Science and Technology Section (ESTS) and the U.S. National Institute for Science and Technology’s (NIST) Building and Fire Research Laboratory spearheaded the two main programs. Both organizations collected and analysed data from one another's research fires. The ESTS program focused on collecting data on smoke emissions from in-situ burning and involved a program of field measurements of smoke from a series of crude oil and automotive diesel fires on water over a large range of fire sizes, culminating with the Newfoundland Offshore Burn Experiment (NOBE) in 1994 (Fingas et al., 1994a, 1994b and 1995; Ross et al., 1996).

The NIST program focused on small indoor and mid-scale outdoor research fires (in Mobile, AL and Prudhoe Bay, AK) in order to collect soot production factors from in-situ fires of various types of crude oil and refined products and examine the behaviour of the smoke plume emitted by the fire (McGrattan et al., 1994, 1995). This program resulted in the development of two CFD models of smoke plumes from an in-situ oil fire that are used to predict downwind concentrations of airborne components for flat terrain (ALOFT-FT) and complex terrain with significant coastal relief (ALOFT-CT). Use of the models is discussed in more detail in the State-of-the-Art Reviews and Decision Making section that follows.

Although the two research programs sometimes came to different conclusions on the predicted values of emission factors from fires (e.g., Fingas et al., 1996 and Fraser et al., 1997), the work of both teams greatly advanced the understanding of what was contained in the smoke from an in-situ oil fire on water and how to predict its downwind impacts on the environment. Table 2 gives the range of generally accepted emission factors for various components of the smoke plume.

The burn residue (the unburned oil remaining on the water surface when the fire extinguishes naturally) was also studied in the 1990s. Another component of the ESTS research was to determine the aquatic toxicity of the burn residue (Daykin et al., 1994 and Blenkinsopp et al., 1997), while an industry-funded research program examined the likelihood of burn residue sinking as it cooled after the fire went out (Buist et al., 1995; SL Ross, 1998).

Bioassays with water-accommodated fractions prepared from laboratory- and field-generated burn residues of crude oil showed very little or no acute toxicity to marine life (echinoderm, bivalve, inland silverside, three-spine stickleback, white sea urchin) in salt water or to rainbow trout in freshwater for either the weathered oil or the burn residue (Daykin et al., 1994 and Blenkinsopp et al., 1997). This research was validated with studies on a marine amphipod and a snail species, which showed very low or low toxicity in lethal and sub-lethal tests when exposed to water-accommodated fractions or physical suspensions of burn residue in sea water (Gulec and Holdway, 1999).

Table 2: Airborne Emissions from an In-Situ Oil Fire on Water[a]

Constituent	Quantity Emitted[b], (kg emission/kg oil burned)
Carbon Dioxide (CO_2)	3
Particulate Matter	0.05–0.20[c, d]
Carbon Monoxide (CO)	0.02–0.05
Nitrogen Oxides (NO_x)	0.001
Volatile Organic Compounds (VOC)	0.005
Polynuclear Aromatic Hydrocarbons (PAH)	0.000004

[a] Updated from Buist et al., 1994, based on the Kuwait pool fire (Allen and Ferek, 1993) and the NOBE data (Ross et al., 1996)
[b] Quantities will vary with burn efficiency and composition of parent oil.
[c] For crude oils soot yield = 4 + 3 lg(fire diameter); yield in mass %, fire diameter in cm (Fraser et al., 1997)
[d] Estimates published by Environment Canada are considerably lower, ca. 0.2% to 3% for crude oil (Fingas, 1996).

Laboratory and test tank studies of burn residue showed that when thick slicks (thicker than approximately 50 mm to 100 mm) of crude oils with densities greater than 0.865 g/cm^3 at 15°C are burned on water, the residue can sink after it cools to ambient temperature (Buist et al., 1995). This density cut-off includes about half of the crude oils shipped around the world (SL Ross, 1998). The time required for burn residue to cool enough to sink can be as long as several hours (SL Ross, 1998; Fingas et al., 2005).

Sunken burn residues can affect benthos that would not otherwise be significantly impacted by a spill at the surface of the water. For example, during the *Haven* spill in Italy in 1991, approximately 102,000 metric tonnes of oil burned, and the residues sank. The residue was distributed over approximately 140 square kilometres of seabed. Local trawl fishermen were unwilling to fish in the area for two years after the spill because of the expected danger of contaminating their nets and catch (Martinelli et al., 1995). In 1983, cleanup contractors ignited the main slick of a spill of Arabian heavy crude from the *Honam Jade* in South Korea. The fire burned intensely for about two hours, and the resultant burn residue sank and impacted crabs in nearby aquaculture pens (Moller, 1992).

The final component of the research into in-situ burning impacts was to determine the overall mass balance of polynuclear aromatic hydrocarbons (PAHs) consumed and created by in-situ burning (Fingas et al., 2001; Wang et al., 1998). The PAHs in oil are largely consumed by combustion. During NOBE, PAH concentrations were much less in the plume and in particulate precipitation at ground level than they were in the starting oil. The mass of all PAHs, including multi-ringed PAHs, was reduced by about 6 orders-of-magnitude by combustion (Fingas et al., 2001).

Chemical analyses of crude oil burn residues show relative enrichment in metals and in the higher-molecular weight PAHs, which have high chronic toxicity, but are thought to have low bioavailability in the residue matrix (ARRT, 2008). Environment Canada carried out several series of burns on heavy oils and characterized the residues fully (Fingas et al., 2005). They found that the PAHs in the residue were pyrogenic, i.e., deriving from the fire, and there were few residual PAHs from the oil itself.

Technology Development

One of the first technological developments after 1990 was new formulations for Helitorch fuel to improve the ignition of emulsified and hard-to-light slicks (Guenette and Sveum, 1995). The enhancements included the following:

- Use of fresh crude oil instead of gasoline to provide a hotter flame;
- Addition of emulsion-breaking chemicals to the igniter fuel to aid in the ignition of emulsions with water content greater than 25%; and
- Addition of anti-foaming agents to suppress foaming of burning emulsions that can extinguish a burn.

Research into the use of emulsion-breaking chemicals added prior to ignition to enhance burning of emulsions was also carried out (Buist et al., 1997).

The following new handheld igniter designs were developed in the 1990s as well:

- Simplex Model 901 handheld igniter (Guenette and Thornborough, 1997); and
- ESSM Flare-type Igniter IG0010 (Moffatt and Hankins, 1997).

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 the following:

- Fire-resistant, water-cooled booms that employ water pumped through a porous outer fabric layer to protect the underlying floatation and membrane components (Allen, 1999; Stahovec et al., 1999; Walton et al., 1999; and Buist et al., 2003b);

- A smaller, lighter-weight, stainless-steel fireproof boom (Buist et al., 1999; Buist et al., 2003b) that was designed to be used as a fireproof pocket in a U-shaped configuration with arms of conventional and/or fire-resistant boom.

As a direct result of the fire boom development efforts, two 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). One of the fire resistance test protocols involves a 50-foot test section of boom, which is deployed as a circle, exposing it to the flames from an encircled diesel fire (Walton et al., 1999), while the other employs a 50-foot section of the candidate boom held in a straight line under tension while it is exposed to propane flames. Both tests involve exposing the test section of boom to waves and flames for one hour, followed by a one-hour period of waves with no flames. A full test involves three cycles of this, followed by an oil containment test to quantify the candidate boom's survival.

In-situ burning is an oil spill response option particularly suited to remote ice-covered waters. The key to effective in-situ burning is thick oil slicks. Concentrated pack ice can enable in-situ burning by keeping slicks thick (Buist and Dickins, 1987). In loose drift ice conditions, oil spills can rapidly spread to become too thin to ignite. Fire booms can collect and keep slicks thick in open water; however, even light ice conditions make using booms challenging (Bronson et al., 2002). A multi-year joint industry project was initiated in 2004 to study oil-herding chemicals as an alternative to booms for thickening slicks in drift ice conditions for in-situ burning.

Small-scale laboratory experiments were completed in 2004 and 2005 (Buist and Morrison, 2005) to examine the concept of using herding agents to thicken oil slicks among loose pack ice for the purpose of in-situ burning. 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 et al., 2006, 2007 and 2008).

The non-proprietary cold-water herder formulation used in these experiments proved effective in significantly contracting oil slicks in brash and slush ice concentrations of up to 70% ice coverage. Herded slicks in excess of 3-mm thickness, the minimum required for ignition of weathered crude oil on water, were routinely achieved. 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 only slightly less than the theoretical maximums achievable for equivalent-sized, mechanically contained slicks on open water.

The concept of using herding agents to burn free-drifting slicks in pack ice was field tested on a large scale in 2008 as part of a large Joint Industry Program on Oil Spill Contingency for Arctic and Ice-Covered Waters organized by SINTEF in Norway (Sorstrom, 2007).

State-of-the-Art Reviews and Decision Making

Two comprehensive reviews of in-situ burning of oil on water have been produced since 1990:

- "The Science, Technology and Effects of Controlled Burning of Oil Spills at Sea" produced by Marine Spill Response Corporation (Buist et al., 1994a); and
- "In-situ Burning: A Cleanup Technique for Oil Spills on Water" produced by Environment Canada (Fingas and Punt, 2000).

The former is a detailed review of the research literature and technology for in-situ burning as a countermeasure for marine spills on open water up to 1993 and contains operational considerations, a review of environmental (see also Campbell et al., 1994) and human health (see also Westphal et al., 1994) effects, a risk evaluation of the acceptability of burning spilled oil, a survey of U.S. regulations, and a decision-making guide and research recommendations (see also Buist et al., 1994b). The report provides extensive documentation to support the view that in-situ burning is a promising countermeasure that can be used on selected spills effectively and safely.

The latter review is more of a decision-making guide to in-situ burning. It sets out procedures for assessing the feasibility of burning and for selecting burn equipment and techniques for various spill situations, describes post-burn activities and lists health and safety precautions.

Several general reviews of in-situ burning for oil spills in ice have been presented (Buist 2000, 2004 and 2007). Generally, these summarize the basic processes involved with in-situ burning, the rules of thumb for removal rates and efficiencies, the pros and cons of burning and the capabilities and limitations of the technology in various ice conditions.

The smoke plume emitted by a burning oil slick on water is the main ISB concern. The concentrations of smoke particles at ground or sea level are of concern to the public and they can persist for a few miles downwind of an ISB. Smoke particles constitute the greatest risk in a plume. Carbon smoke particles are responsible for the characteristic black colour of the plume rising from a burn. The smoke is unsightly, but more importantly, the smoke particles can cause severe health problems if inhaled in high concentrations. Smoke particulates and gases, however, are quickly diluted to below levels of concern.

NIST (ALOFT-FT, Walton et al., 1996; Bronson, 1998 and ALOFT-CT, McGrattan, 1997), NOAA (In-situ Burn Calculator, http://response.restoration.noaa.gov/resource_catalog.php) and Environment Canada (Fingas and Punt, 2000) have developed computer models to predict downwind smoke concentrations. The first two 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. 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. Table 3 lists the approximate maximum distances downwind over land for the ground-level PM-10 (particulate matter smaller than 10 microns in diameter) concentrations from 1,000-bbl/h and 2,000-bbl/h fires to fall below 150 mg/m^3 for various terrain heights in winds from 1 m/s to 12 m/s. The tabulated results are consistent with a similar table produced by Environment Canada (Fingas and Punt, 2000).

If the plume passes over highly elevated terrain, the distances at which the ground-level concentrations of PM-10 decrease below 150 mg/m^3 are much greater than over flat terrain in equivalent meteorological conditions. The distance downwind for the smoke plume to dilute below 150 mg/m^3 would range from 1 km over flat terrain in a highly mixed atmosphere to 20

Table 3: Estimates for Maximum Downwind Extent of pm-10 Particulates[a]

Fire Size	Terrain Height (m)	Maximum Distance (km) Downwind for PM-10 Concentration to Reach 150 µg/m^3 at Ground Level for Given Mixing Layer Depth Ranges[b]				
		0 to 100 m	**100 to 250 m**	**250 to 500 m**	**500 to 1,000 m**	**>1,000 m**
1,000 bbl/h (160 m^3/h)	0 to 25 (Flat)	5	4	3	2	1
	25 to 250	10	8	6	4	3
	250 to 500	15	12	10	8	5
	> 500	20	17	15	12	10
2,000 bbl/h (320 m^3/h)	0 to 25 (Flat)	8	6.5	5	3	1.5
	25 to 250	16	13	10	6.5	5
	250 to 500	24	19	16	13	8
	> 500	32	28	24	20	16

a. Valid for wind speeds from 1 m/s to 12 m/s

b. Mixing layer depths loosely correspond to atmospheric stability class ranges as follows: Stability Class C » 200 m to 300 m; Stability Class D » 150 m to 200 m; Stability Class E » 100 m to 150 m.

km over mountainous terrain in a very stable atmosphere. Low mixing-layer depths (very stable atmospheres) generally occur only at night.

If the 65 mg/m^3 PM-2.5 criterion is to be applied, the mathematics of the NIST model show that the distances predicted in Table 3 should be increased by 2.5 km. If the newest PM-2.5 standard is applied (35 μg/m^3 in 2006), the distances should be increased by 7 km. It should be noted that the criteria are for 24 hours of human exposure, not a short-term exposure, as would be the case for an in-situ burn. As such, adding the incremental distances given above to those in Table 3 would result in a very conservative plume dispersion distance estimate. In these cases, it is recommended that one of the computer models be run with ambient conditions as inputs to estimate the distance, rather than using the maximums from Table 3.

The atmosphere over water is generally less well mixed than over land and a good rule of thumb is that it takes about twice the distance over water to achieve the same decrease in smoke plume concentrations as it does over land, using the Flat terrain height category. Mixing zone heights over large bodies of water are usually between 100 m and 500 m (Hanna et al., 1985). Data from coastal weather stations around the Beaufort Sea indicate that mean maximum mixing layer heights range from 100 m in winter, 200 m to 500 m in spring and autumn, to 400 m to 1,200 m in summer (Portelli, 1977). The atmosphere in the Beaufort area is usually close to neutral stability (60% Class D and 20% Class E – Arco Alaska, 1997).

In 1994, the Alaska Regional Response Team (ARRT) incorporated In-situ Burning Guidelines for Alaska into its Unified Response Plan. They were the first Arctic area to formally consider ISB as a response to oil spills and the ARRT guidelines are considered the pre-eminent ones in the world. The Guidelines include the following sections and appendices:

- Overall background information is described in Section 1;
- Technical background that supports the guidelines is included in Sections 2, 3 and 4;
- General guidelines for safe distances and the Cook Inlet and North Slope alternative guidelines for safe distances are described in Section 3;
- Public notification levels are described at the end of Section 3;
- Information on environmental considerations is included in Section 4; and
- Various appendices contain decision guides, checklists and information.

In 2008, they updated and revised the guidelines (ARRT, 2008). The most recent version (Revision 1) updates the original 1994 guidelines. Revision 1 includes the following changes:

- The safe distances recommended between an in-situ burn and populated areas are revised (see Section 3);

- The *ISB Review Checklist* and *Application for ISB* in the 1994 guidelines are streamlined; The new forms are *Application and Burn Plan* and *FOSC/SOSC Review Checklist*;
- The new safe distance guidelines are based on the smoke plume's predicted concentrations of PM2.5. The 1994 guidelines were based on PM10 concentrations. The change takes into account the new National Ambient Air Quality Standards for PM2.5 that became effective in 1997 (see Section 3). These guidelines are consistent with the revised national air quality standards (35 $\mu g/m^3$ for PM2.5);
- Revision 1 assumes that maintaining safe distances between populated areas and harmful levels of PM2.5 will also provide an adequate buffer to protect populated areas from air toxics and all other by-products of combustion;
- The new version of the smoke plume trajectory model, ALOFT-FT-Flat Terrain version 3.04 for PC, distinguishes between flat, complex terrain and water scenarios. This refinement is reflected in the new safe distance guidelines;
- Safe distance prediction uncertainty is expressed in graphs of mixing height and wind speed effects in McGrattan et al. (1997). Predicted distances are no longer multiplied by a factor of 2 to produce safe distance guidelines;
- Revision 1 considers the results of in-situ burning studies reported in the proceedings of the International Oil Spill Conferences and the Arctic Marine Oilspill Program Technical Seminars, in in-situ burning guidance of other Regional Response Teams and in guidance from the National Response Team;
- Revision 1 includes residue collection as a condition of authorization, where practicable;
- Revision 1 includes, as a condition of authorization, requirements for visual monitoring and/or sampling of the smoke plume (in accordance with the Special Monitoring of Applied Response Technologies [SMART] protocols) during a burn where there is a potential to impact populated areas (see Section 3);
- The process for considering the use of in-situ burning in all environments (inland and marine) is addressed;
- Discussions of the importance of in-situ burning in Alaska and general issues of smoke, residues and toxicology are updated; and
- Revision 1 incorporates the U.S. Endangered Species Act.

ASTM has been developing oil spill response standards for many years and in the late 1990s, began developing standards associated with in-situ burning. The existing standards are the following (ASTM 2009):

- F1788-08 Standard Guide for In-situ Burning of Oil Spills on Water: Environmental and Operational Considerations
- F1990-07 Standard Guide for In-situ Burning of Spilled Oil: Ignition Devices

- F2152-07 Standard Guide for In-situ Burning of Spilled Oil: Fire-Resistant Boom
- F2230-08 Standard Guide for In-situ Burning of Oil Spills on Water: Ice Conditions

The U.S. Coast Guard, after the *New Carissa* accident in 1999, began to prepare for the use of in-situ burning as an operational response tool. One USCG Region (Galveston) was equipped with a fire boom package and exercised its use (Bitting et al., 2001). Next, the USCG produced an operations manual for in-situ burning (Buist et al., 2003c) that details all the considerations and steps to be taken for open water in-situ burning with fire booms.

The U.S. National Oceanic and Atmospheric Administration (NOAA) Office of Response and Restoration has developed several online resources for in-situ burning that may be accessed at http://response.restoration.noaa.gov/index.php.Of particular interest is the Special Monitoring of Applied Response Technologies (SMART) Guidelines (http://response.restoration.noaa.gov/ book_shelf/648_SMART.pdf), which specify the smoke monitoring operations to be carried out during in-situ burning operations. In general, SMART is conducted when there is a concern that the general public may be exposed to smoke from the burning oil. It follows that monitoring should be conducted when the predicted trajectory of the smoke plume indicates that the smoke may reach population centres and the concentrations of smoke particulates at ground level may exceed safe levels. Monitoring is not required, however, when impacts are not anticipated.

SMART recommends deploying one or more monitoring teams with airborne particulate measurement devices downwind of the burn, at sensitive locations such as population centres. Before the burns start, the teams begin sampling to collect background data. After the burn starts, the teams continue sampling to determine particulate concentration trends, recording them both manually at fixed intervals and automatically in the data logger, and reporting to the Monitoring Group Supervisor if the level of concern is exceeded.

Dispersants and the Use of Oil-Mineral Aggregates

The unique challenges for the use of oil spill dispersants in the Canadian Beaufort Sea include cold conditions, presence of ice, potential for brackish water due to the Mackenzie River outflow or ice melt conditions, and remoteness. None of these challenges preclude the use of dispersants in the Beaufort as described below.

Dispersant Effectiveness (DE) in Cold Water

There is a general misconception that cold temperatures inhibit dispersant effectiveness (DE). Colder temperatures do increase the viscosity of the spilled oil and dispersant product, but as long as the oil viscosity does not exceed 20,000 cP to 40,000 cP and the pour point of the oil is lower than the ambient water temperature dispersants have been shown to be effective (Fiocco et al., 1999; Canevari et al., 2001; Daling, 1988; Belore et al., 2008). A new "gel" dispersant currently being developed also shows promise for improved dispersion of viscous oils (Nedwed et al., 2008; Nedwed, 2007). Conventional dispersants have been formulated to be relatively non-viscous in cold temperatures and can be successfully applied in cold weather.

A summary of past cold condition dispersant effectiveness testing is presented in Belore et al., 2009. The key findings of a number of international researchers identified in this report are summarized below:

- Cox et al. (1981) found that cold dispersant applied to warm oil-water systems worked better than warm dispersant and concluded that dispersants could be effective in cold Arctic environments.
- Farmwald and Nelson (1982) conducted tests using cold air (4°C to -40°C) over 1°C water and dispersant effectiveness (DE) was not impaired even at the lowest temperature. They concluded that low air temperature should not govern the decision to use dispersants.
- Byford (1982, 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.
- Lehtinen and Vesala (1984) tested DE at various salinities and temperatures and found reduced effectiveness at low salinities and low temperatures.
- Mackay et al. (1985) proposed mechanisms for chemical dispersion of oil slicks, based on results from bench scale testing and observations, and concluded that chemical dispersion under cold marine conditions is only marginally more difficult or requires only marginally more dispersant. The exception to this would be a marked increase in the oil viscosity because the temperature was less than the oil's pour point.

- 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.
- Fingas et al. (2006) achieved high DE for Alaskan crude oil in the swirling flask test at low temperatures (5°C and 10°C) and 25‰ to 35‰ water salinities. The DE decreased as the water salinity decreased to below 25‰.
- Tests conducted in a large outdoor wave tank, in coldwater conditions (1°C to 13°C), by Esso Resources Canada (Brown et al., 1985 and Brown et al., 1986) showed that dispersants could be effective in cold conditions under breaking waves (1% to 77% DE) and to a lesser extent (3% to 33% DE) in non-breaking waves of 10 cm to 20 cm in height. The authors noted that the DE measurements in these tests likely underestimated potential field effectiveness.
- 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 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 DE 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 the U.S. National Oil Spill Response Test Facility (Ohmsett) in cold water (-1°C to +10°C) on Alaskan and east coast Canadian crude oils (Belore, 2003, 2008; Mullin, 2004, 2007, 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.

Presence of Ice

Ice may affect a dispersant operation primarily through its influence on the mixing energy available to generate and then diffuse small oil droplets once the dispersant has been applied. The presence of broken ice in concentrations above 30% to 50% significantly dampens the wave field and changes the surface mixing conditions. Brandvik et al. (1999) questioned the use of dispersants in conditions with ice cover exceeding 50% because of wave dampening and oil targeting problems. Research has shown that ice generates localized energy through its mechanical grinding and pumping actions as it rises and falls and interacts in a dampened wave field. Tests have shown that the energy generated at these ice edges and in broken ice and slush fields is sufficient to disperse chemically treated oil (Brown and Goodman, 1996; Owens and Belore, 2004; Nedwed, 2007). The application of dispersants to oil present at ice edges in leads or between ice floes may be a viable countermeasures option depending on the ice conditions and prevailing environmental conditions (Ross, 2000). The use of containment booms to direct oil to a ship's propeller turbulence to disperse treated oil in low ice concentration waters has also been investigated and shown to be a promising option (Nedwed et al., 2007).

In a complete ice cover situation, there is insufficient natural mixing energy to generate oil dispersion once dispersant is applied and the oil may be trapped under the ice and be inaccessible to a spraying operation. Tests have demonstrated that the mechanical energy provided by a ship's propeller could be used to both expose trapped oil for dispersant application and to shear the treated oil into a fine oil cloud that will diffuse throughout the water column. (Nedwed et al., 2007; Spring et al., 2006) The use of azimuthal stern drive systems has been shown to be a promising option for applying the necessary mixing energy for a dispersant-use operation in a complete ice cover environment (Spring et al., 2006; Nedwed et al., 2007; Nedwed, 2007). The oil drops generated by the short term-intense mixing of these propellers must be small enough to remain suspended and diffuse throughout the water column under the limited natural turbulence present under the ice cover after the ship has moved on or the oil will simply rise back to the underside of the ice. The research to date (Spring et al., 2006; Nedwed et al., 2007; Nedwed, 2007) focused on a relatively light crude oil that formed very small oil drops when chemically treated and mechanically mixed by the propeller. These drops stayed suspended in a quiescent tank for several weeks. Additional research into 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 is required to assess the range of conditions where this countermeasures option might be viable. The concept of using ship's thrusters to disperse free-drifting slicks in pack ice after they have been sprayed with dispersants was field tested on a large scale in 2009 as part of a large Joint Industry Program on Oil Spill Contingency for Arctic and Ice-covered Waters organized by SINTEF in Norway (Sorstrom, 2007).

Brackish Water Influence

It has been well documented that traditional marine dispersant products are most effective in water with salinity between 25 ppt and 40 ppt. The effectiveness of these products drops off at both lower and higher salinities (Fingas and Ka'aihue, 2005; Fingas et al., 2006). 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 and Daling, 1992; Byford et al., 1983; George-Ares et al., 2001; Lehtinen and Vesala, 1984). Fresh-water dispersants could be sourced and stockpiled for use in the Beaufort Sea on spills occurring during oceanographic events that warrant their use.

Remote Location

The remote location of the Beaufort Sea and its limited logistical infrastructure dictates that careful planning and preparations be made prior to a dispersant operation for any chance of success. Dispersants generally must be applied on a timely basis to be effective. An appropriate dispersant stockpile, dispersant spraying systems and suitable vessels or aircraft must be identified and be available within prescribed times for successful operations. A study of the use of dispersants in Prince William Sound Alaska (S.L. Ross, 1997) concluded that a high percentage (81%) of a large oil spill (10,000 m^3) could be treated with dispersants during a carefully planned summer operation. Were an appropriate dispersant delivery capability to be established in the Beaufort Sea, the logistics of an operation would be somewhat similar to the Alaskan situation. On a positive note, the largest stockpile of dispersants in North America is located in Anchorage, Alaska, a relatively short distance from the Canadian Beaufort Sea.

Net Environmental Benefit Analysis and Planning

Dispersants provide environmental protection from spilled oil by dispersing oil slicks into the water column, where they can be more quickly diluted and degraded. As such, dispersants reduce risks posed by spills to species on the sea surface (e.g., polar bears and eider ducks), but temporarily increase risks to organisms in the upper water column (e.g., polar cod). Despite this obvious drawback, in most parts of the North America, dispersing oil spills has been shown to offer clear net environmental benefits (NEBs). This is because untreated oil slicks are persistent; they spread to involve large areas and can be transported considerable distances causing damage over large areas long distances away from the spill site. On the other hand, chemically dispersed spills pose risks only in the immediate area of the dispersant application and only for a brief time after which they dilute and degrade to non-injurious levels. Decisions about dispersant use involve making choices between risks posed by the untreated spills and those posed by the dispersed spill; in other words, deciding whether or not dispersants offer a net environmental benefit (NEB).

In Canada, guidance for dispersant use is contained in Environment Canada's "Guidelines on the Use and Acceptability of Oil SDill dispersants" (1984), which stipulate that dispersants must be used in situations where "adverse impacts associated with chemical dispersion are less than those without chemical dispersion." The guidelines provide no guidance as to how 'adverse impacts' are to be estimated. However, they do specify the information to be provided to Environment Canada concerning dispersant products that might be used in spill response operations in Canadian waters. Environment Canada has considered revising its operating procedures, but has

yet to formally publish these changes or submit them for review by the Canadian environmental and spill response community.
A general approach to conducting NEB analyses for a small number of realistic local spill scenarios is to estimate the impacts on key valued ecosystem components (VECs) that would occur if dispersants were not used and if dispersants were used, and then compare the two sets of impacts.

The main requirements to complete an NEB analysis are as follows:

1. A short list of realistic local oil spill scenarios, such as those developed in the Beaufort Regional Environmental Assessment and Monitoring report (Vonk et al., 1995);
2. Tools for estimating spill behaviour and ecosystem exposures to dispersed and untreated oil in the scenarios (e.g., Trudel et al., 1989; French et al., 1994; Mearns et al., 2003);
3. Specific information concerning spill-sensitivity of VEC populations (French-McCay, 2004; Trudel et al., 1986a,b, 1989). Note that several research projects have focused on oil sensitivity of Arctic species (e.g., Mageau et al., 1987; Percy and Mullin, 1975), but an oil industry-funded research project is currently studying sensitivity of Alaskan Arctic species (see Shell and API, in progress);
4. Specific information concerning spill vulnerability of VEC populations (e.g., Trudel, 1988; S.L. Ross, 2007); and
5. A simple NEBA model (e.g., Trudel et al., 2003).

A number of region-specific dispersant NEB studies have been completed in recent years in areas such as the Newfoundland Grand Banks (S.L. Ross, 2007) and Southern California (Trudel et al., 2003).

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. One such system was developed for the Southern Beaufort Sea area in the 1980s (Trudel, 1988).

Use of Oil-Mineral Aggregates (OMA)

In recent years, the Canadian Coast Guard has been researching the concept of adding mineral fines to oil spills in ice in the St. Lawrence River Estuary, then subjecting the treated slick to the prop wash from icebreakers in order to promote dispersion of the spills and enhance their biodegradation (Khelifa, 2005; Khelifa et al., 2005; Cloutier et al., 2005; Cloutier and Doyon, 2008; Blouin and Lee, 2007; Lee et al., 2009).

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. Terminologies such as oil-clay flocculation, oil-SPM interactions and oil-fine interactions have been used to describe this natural process (see Stoffyn-Egli and Lee, 2002, for a review). The simplest form of OMA consists of an oil droplet coated with micrometre-sized solid mineral particles. The formation of OMA enhances oil dispersion by decreasing the rise of the droplets and preventing the droplets from sticking to each other and reforming a slick. It is recognized that OMA formation enhances natural cleanup of oiled shorelines and biodegradation of spilled oil.

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.

In recent studies for the Canadian Coast Guard (Khelifa, 2005; Khelifa et al., 2005; Clouthier et al., 2005) to assess the feasibility of developing an OMA-based technology to disperse oil spilled in ice-infested waters in the St. Lawrence River Estuary during the winter season, it was shown that OMA can form at near-freezing temperatures (~ -0.5 °C) in seawater. A concentration of 400 ppm of suspended chalk fines was capable of forming aggregates with 100% of the Heidrun crude and 80% of the IFO 30 oils in a small reciprocating shaker apparatus. Bentonite was less effective, but could also form aggregates with most of the test crudes (it was even less effective with the IFO 30). This study also showed that more than half of the OMA formed within the first 10 minutes of oil-mineral interactions. After 20 to 40 minutes of interaction (depending on the oil type), all the OMA were formed. Based on findings and recommendations from this study, the CCG followed up with additional testing using a large basin (2.44 m x 2.44 m x 0.76 m) during the winter of 2006 at an ambient temperature varying between 0°C and -2°C (Cloutier and Doyon, 2008; Blouin and Lee, 2007). Experiments were conducted using 3,000 litres of brackish water (18‰) and both slush ice and broken ice. A boat propeller was used to introduce turbulent mixing in the basin. All of the experiments were performed using Heidrun crude oil and chalk fines. The study showed that OMAs formed instantly in both slush ice and broken ice. Most of the observed OMA were single droplet and less than one mm in size. A mixing time varying between 20 and 30 minutes was sufficient to disperse about 50% of the spilled oil.

In January 2008, with help from the Canadian Coast Guard icebreaker *Martha Black*, the theory of using an icebreaker's propeller to create OMA was tested in real ice conditions (Lee et al., 2009). Several experimental spills of about 200 litres of fuel oil were carried out in the St. Lawrence River near Matane, Quebec. Chalk fines were mixed with seawater and sprayed onto the spilled oil, while the propeller of the 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, as observed in the tests without treatment by addition of mineral particles. The researchers used microscopes to verify that the oil had formed OMAs, and they collected water samples for further experimentation in the lab. Results from the laboratory study showed that more than 56% of the total petroleum hydrocarbon (TPH) had been degraded after 56 days incubation at 0.5°C.

Additional laboratory testing, tank testing and fieldwork are being proposed to further develop this potential countermeasure in ice conditions. An issue that will eventually arise is obtaining regulatory permission to use OMA as a response technique.

Arctic Oil Spill Waste Management

This section documents improvements in the state of the art for oil spill waste management in Arctic conditions over the last twenty years. First, a brief summary of oil spill waste management as it existed in the early 1990s is provided. Then, the research and development efforts to improve the understanding of oil spill waste management in Arctic conditions over the subsequent two decades are described.

State of the Art in the Early 1990s

The report to the Beaufort Sea Steering Committee on the cost of responding to a worst-case blowout detailed the following operations under disposal operations.

Oil recovered offshore was to be flared using the Beaufort Sea Co-op's Response Barge system, which had the following capabilities:

- Emulsion treater (nameplate capacity of 29 m^3/h [4,400 BOPD] emulsion inflow, 10 m^3/h oil outflow)
- TOPS flare burner (nameplate = 80 m^3/h [12,000 BOPD]; operational capacity = 27 m^3/h [4,100 BOPD] based on available onboard water pumps)
- 1,106 m^3 (7,000 bbl) temporary storage.

If the oil recovered exceeded 27 m^3/h, the overage was to be temporarily stored offshore in barges until the Co-op Response Barge was available to flare the oil.

Oil and oily material collected from shorelines was to be either burned or placed in a specially constructed engineered landfill.

- Oily sediment from open coast and backshore beach cleanup was to be stockpiled at temporary sites along the coast, located in accordance with recommendations in the Environmental Atlas for Beaufort Sea Oil Spill Response (1987), then removed over ice roads constructed the following winter. The oily sediment was to be shipped either to a centrally located temporary processing site where it would be passed through a 10-m^3/h rotary kiln for cleaning or to a specially constructed engineered landfill located in the area.
- Fluid oil and oily debris from backshore beach and mainland lagoon cleanup was to be burned on site using heli-portable rotary cup burners for the fluids and heli-portable incinerators for the solids.

Research and Development on Arctic Oil Spill Waste Management since 1990

Surprisingly little work has been done on oil spill disposal operations in Arctic areas over the last 20 years. Only one reference was uncovered in the literature search on the subject. Owens et al. (2009) presents a series of guidelines for oil spill waste management in remote Arctic areas prepared for the Joint Secretariat of the Inuvialuit Renewable Resources Committees, on behalf of the Arctic Council. The guidelines are based on experiences at many spill response operations in southern waters and are modified to account for the remote nature and lack of logistics in many Arctic areas. The key is a Waste Management Calculator that allows spill planners to select preferred shoreline treatment options and generates estimates of the types and quantities of waste that will be generated with the selected option. The report itself (Polaris Applied Sciences, 2009) also contains a summary of existing government regulations pertaining to the temporary storage, transport and disposal of oil spill waste.

Shoreline Spill Response

The state of the art in cleanup response to oil spills in the Canadian Beaufort Sea up to 1990 included the pre-spill preparation of shoreline mapping and standardized assessment forms for each shoreline segment to document (Vanderkooy et al., 1991; SL Ross and COGLA, 1991):

- Shore types, shoreline sensitivities and oiling characteristics during a spill;
- Shoreline protection options (exclusion, diversion, containment and sorbent booms; beach berms and dikes); and
- Shoreline cleanup methods (front-end loaders and tractors for removal of oiled snow and beach materials, manual oil and material removal, portable skimmers and pumps, sorbents and low-pressure water flushing).

Since the 1990s, additional research has been done on the fate of oil stranded on Arctic shores and the appropriate pre-planning and cleanup response to oiled shorelines. A summary of this research is provided below.

Humphrey et al. (1990) documented the long-term fate of oil on an experimentally oiled low-energy Arctic beach from the BIOS project in the Canadian Arctic and concluded that only 10% of the originally stranded oil remained after 18 months of exposure to open water (approximately two months per year over a nine-year period). There was no reworking of the oil and sediments during the winter months in this situation because the stranded oil was protected by the formation of an intertidal ice foot prior to freeze-up and the movement of sea ice was not a littoral process on this beach. Owens et al. (1988) reported on the success of the countermeasures options tested during the BIOS experiments. The use of dispersants in high-energy situations provided a short-term benefit, but by the end of the first year of open water there was no difference between the control and dispersant-applied plot. Dispersants were ineffective in the low-energy shorelines. Low-pressure water flushing was also ineffective in the low-energy environment. Sediment mixing was conducted in the intertidal and backshore zones. The mixing in the intertidal zone delayed biodegradation and mixed the oil deeper into the sediments. In the backshore plots, mixing reduced the total hydrocarbon amounts on the surface sediments by about 50%. The subsurface hydrocarbon amounts were significantly higher than the control plots, indicating that the mixing simply moved the oil from the surface to greater depth.

A large field program was conducted in Svalbard, Norway in 1997 (Sergy et al., 1998; Sergy, 1999) to quantify the effectiveness of in-situ shoreline cleanup options, specifically sediment re-location (surf washing), tilling, bioremediation, tilling plus bioremediation and natural recovery. The key conclusions determined from the Svalbard field program (Sergy, 1999) are described below.

1. Mechanical relocation of oiled sediments into the surf zone significantly accelerated the rate of oil removal, even when the waves were only approximately 30 cm high. This technique is appropriate and may reduce oil persistence by months when the oil is stranded high on the beach above the normal (daily) limit of wave action. Sediment relocation can also increase the initial short-term rate (weeks) of oil loss on low or moderate wave-energy beaches where oil is within the active intertidal zone. The natural redistribution of relocated sediments occurred relatively rapidly.
2. Sediment relocation did not elevate toxicity in the nearshore environment to unacceptable levels, nor did it result in significant alongshore or offshore sediment oiling.
3. Mixing (by tilling) of the oiled layer of surface sediments in the upper intertidal zone did not clearly demonstrate short-term or long-term loss of oil. Changes in oil loading incurred by mixing do not support or justify operational use.
4. The initial natural rate of removal of oil stranded in the active intertidal zone was relatively rapid in this environment.
5. Biodegradation of the oil in sediment occurred in this Arctic environment. Fertilizer application was successful in delivering fertilizer nutrients to the indigenous microbial populations in the oiled beach sediment and in increasing oxygen consumption and carbon dioxide evolution consistent with a stimulation of oil biodegradation.
6. Microscopic observation and image analysis confirm that the OFI (oil fines interaction) process was active in the removal of oil from the beaches.
7. The trials demonstrated that it was possible and practical to conduct representative sampling and obtain meaningful results with respect to changes in oil concentrations on mixed sediments.

A considerable amount of research has been done on the process of oil and fines interaction (OFI) or oil mineral aggregation (OMA) (Bragg and Owens, 1995; Jezequel and Lee, 1999; Lee and Stoffyn-Egli, 2001; to identify just a few). Several studies show that this process also occurs in cold waters (Sergy, 1999; Cloutier et al., 2005; Khelifa et al., 2005; Lee et al., 2009). A better understanding of this process has led to the realization that in many circumstances, oiled shorelines will quickly ‘self-clean’ in the presence of wave action and/or currents without the need for outside intervention.

A field observation and modelling study was completed on two northern Norwegian coastlines to monitor the types of shoreline ice formations and attempt to model their occurrence based on weather data (Oskenvag et al., 2009). The most common types of ice observed were frozen swash and ice foot. Frozen spray and grounded floes also were common in the lower energy environment monitored. The probability of ice formation was successfully modelled using the meteorological data collected during the observations, but additional refinement of the marine icing models was identified in order to produce reliable results for shoreline icing conditions.

Owens et al. (1999) discussed the consequences of the decisions made to proactively respond to the Komi pipeline release and, conversely, to leave the oiled shorelines resulting from the *Metula* tanker spill to recover naturally. They concluded that the crucial element in making the decision to 'treat or not treat' lies in the understanding of the ability to estimate the fate and persistence of the residual oil and the potential effects of the proposed treatment option. They also indicate that the increased knowledge in these areas that has been gained in the past decade makes these types of evaluations more accurate. In the past, decisions to treat shorelines were often automatic. They suggest that the decision process should be changed to favour natural recovery, except where large amounts of viscous oil are present and natural removal will be slow or when other non-ecological factors are of greater importance.

Owens and Sergy (2003) attempted to develop a methodology for the selection of shoreline cleanup endpoints. They were unable to develop a single, manageable decision model for identifying the cleanup endpoint because of the many issues and variables that come into play. They conclude, however, that the treatment standards arrived at need to be defined at the beginning of the response so that the response activities can be tailored to meet the end requirements, with the end points being determined by the interested parties or stakeholders. "Clean is when the spill response has continued long enough to meet the end point criteria, whether they be visual, chemical, toxicological, ecological or economically driven." Sergy and Owens (2008) further developed the concept of defining and measuring cleanup endpoints for shoreline treatments. They provide a step-by-step guide to defining endpoints based on qualitative and quantitative field observations and examples of endpoint criteria to be considered during the shoreline cleanup planning process.

Owens and Michel (2003) identified three shoreline types unique to the Arctic, determined how spilled oil will behave on them and identified potential cleanup options for them. This information was incorporated into The Arctic Shoreline Cleanup and Assessment Technique (SCAT) Manual (Owens and Sergy, 2004). SCAT manuals provide a systematic approach for describing and documenting oiled marine or lake shorelines and riverbanks using standard terms and definitions that are in common use in spill response operations around the world. The Arctic SCAT Manual has been specifically designed for use in the Arctic and includes snow and ice considerations, unique shore types and supporting glossaries and visual job aids specific to the Arctic.

Owens (2007) presented a summary of shoreline response in the Arctic and concluded that the response and removal techniques for snow and ice conditions are well understood. He indicated that improvements in Arctic shoreline response will come with a better understanding of the behaviour and fate of oil on snow and ice in the shore zone, an improved ability to locate oil in shore ice and snow and the use of appropriate tools in the decision process to identify and implement the cleanup options.

Case Histories of Oil Spills in Ice Conditions Since 1990

Since 1990, 15 actual oil spills in ice or snow conditions have been described in the open literature (nine reports covering the 15 spills).

1. Whitney (1992) describes a small spill of 15 bbls of crude in dynamic broken ice at the Christy Lee loading facility in Redoubt Bay, Cook Inlet, AK in 1990. Skimmers proved ineffective, recovering mostly water, but 3 bbls was recovered using sorbent.
2. The *Bahia Pariso* slowly leaked 600 m^3 of Arctic diesel fuel into Arthur Harbour, Antarctica in summer conditions (Kennicut et al., 1991). The paper describes the sampling, analysis and distribution of hydrocarbons in the immediate vicinity over a one-year period.
3. Sienkiewicz and O'Shea (1992) describe a release of 1,006 bbls of water/crude mixture (containing between 100 and 400 bbls of Cook Inlet crude) into the waters of Cook Inlet in January of 1992. The management structure of the response team and a short description of the attempted cleanup techniques (skimming and dispersant application) are described.
4. D'Atri and King (1993) describe the response to a tanker truck spill of 8,000 gallons of Arctic diesel fuel into 18 inches of snow at Atigun Pass in the Brooks Range of Alaska. The paper describes the use of in-situ burning and mechanical and manual cleanup techniques.
5. Several papers describe the 1994 Komi pipeline spill (actually several large spills from a pipeline network totalling some 600,000 bbl), the international response to the incident and the subsequent cleanup (Nadeau and Hansen, 1995; Zoltai and Kershaw, 1995; Lambert et al., 1995; Hartley, 1996; Stillings, 1996; Sienkiewicz and Owens, 1996; and Owens and Sienkiewicz, 1997).
6. Rivet (2000) describes three spills in the St. Lawrence River in winter conditions that occurred in February 1998 when the *MV Saraband* spilled bunker fuel in three areas in the ice. The two spills dockside were 90% recovered by removing the ice containing the oil mechanically (1,369 tons of ice were removed to recover 10 tons of oil at one dock site). The oil offshore (approximately 10 tons) was surveyed by divers and left until spring. An icebreaker that opened the bay in the spring sprinkled the remaining oil with fine sand to promote OMA formation. In March 1999, the *MV Gordon Leitch* spilled 49 tons of bunker oil in Havre St. Pierre and wind blew the oil into ice floes left in the small bays. No containment or recovery of the oil in the ice floes was attempted. In February 2000, an overflow of bunker oil from a dock resulted in the release of a few tons of oil into a moving ice field. Although oil could be seen between the floes, no cleanup was attempted because of a lack of equipment and techniques to recover the oil.
7. The responses to four spills on the North Slope of Alaska, in particular the March 2006 pipeline release from an infield pipeline onto snow-covered tundra, are described by Majors (2007) and Majors and McAdams (2008). The response at temperatures as low as –45°C involved over flights with a FLIR system to map the affected area, direct suction of oil pools

8. Another recent spill in ice was the sinking of the *Runner 4* in Estonian territorial waters in the Gulf of Finland in March 2006 (Wang et al., 2007; Lampela, 2007)). The former paper describes the motion of the oil in the ice conditions at the time. The drift of these slicks was not well predicted by a computer model for the drift of the surrounding ice. The latter presentation describes some of the mechanical recovery systems used to clean up the spill.
9. The final incidents involved two spills of AN-8 (an Antarctic grade of aviation kerosene) onto snow-covered ice near McMurdo Station, Antarctica (Christensen, 2008). In both cases, the fuel migrated down to the ice-snow interface and then spread out across the ice, under the snow. Differences in the spreading and penetration of the oil into the ice were presumed to be due to differences in the nature of the ice (one spill site was on first-year ice and the other on multi-year ice).

Acute and Long-term Impacts of Spills and Countermeasures

This section is a brief summary of the advances in knowledge of the environmental impact of spills and spill countermeasures that are relevant to spills from offshore development in the Canadian Beaufort Sea. It addresses risks from marine oil spills, countermeasures (such as dispersants) and practices for managing the impact of spills on the local human community. This section focuses on risks to critical valued ecosystem components (VECs) in the Beaufort Sea involved in planning for marine spills as identified in the Beaufort Environmental Monitoring Project (BEMP), the Mackenzie Environmental Monitoring Project (MEMP) and the Beaufort Region Environmental Assessment and Monitoring Program (BREAM) in 1970 and the 1980s and 1990s. This includes marine mammals, birds, finfish and the harvesting activities for each. Emphasis is on lessons learned from the selected spills from 1989 to the present (Table 4), important advances in research and planning, and studies that are particularly relevant to spills in the Arctic.

In addition, this section focuses on spill impacts on the types of biota harvested in the Beaufort Sea and recovery of spill-impacted stocks. However, it is clear that long-term persistence of oil in intertidal and subtidal sediments has played a role in the post-spill recovery following some major spills. The fate and persistence of spilled oil in these sediments could fill a chapter on its own, but in the interest of brevity, we have included here only the most relevant results, namely those from the Baffin Island Oil Spill (BIOS) study in the Canadian Arctic (Sergy, 1985).

Fate of Stranded Oil: The BIOS Experiment

In the BIOS experiment, an untreated oil slick was deposited on a gravel beach in a protected bay in order to study the fate of that oil in the intertidal zone, if it were not cleaned up. (Other portions of the experiment examined the effectiveness of various cleanup techniques, noted in the chapter on Shoreline Spill Response). Some of the stranded oil was re-floated and carried away by tides within the first few hours, with some of the remainder penetrating into the gravel sediments forming a stable pavement within the next few months. The pavement disintegrated over the next decade (Owens et al., 2002). A portion of the oil that was originally re-floated was deposited in the nearby subtidal sediments. Within the first two years after stranding, biodegradation appeared to have been restricted to the beached oil, with no significant degradation occurring subtidally (Boehm et al., 1987). One portion of the experiment involved a comparison of a dispersant-treated spill with the untreated spill. Although the in-water oil cloud in the dispersed spill caused temporary narcosis in benthic species, neither the dispersed nor untreated spill caused any detectable longer-term effects on the seabed biological communities (Cross et al., 1987).

Marine Mammals

As identified in BREAM, the critical mammal species during spills in the Southern Beaufort Sea from an ecological and harvesting perspective include marine-associated mammals (polar bear, muskrat, mink), pinnipeds (ringed seal, bearded seal) and cetaceans (bowhead whale, white whale). Effects of oil spills on these groups had been studied and results reviewed prior to the 1990s (e.g., Duval, 1985; Engelhardt, F.R., 1985; Geraci and St. Aubins, 1987, 1990; Harwood, 1985; Martin, 1985; Neff and Anderson, 1981). That work suggested that mammal groups differed markedly in their sensitivity to oil, with marine-associated mammals (e.g., bears and sea otters) being most sensitive and whales least sensitive. These groupings have been treated separately here.

Marine Associated Mammals

Marine-associated mammals include species such as polar bears, sea otters and muskrat that derive their insulation from their fur alone (Duval, 1985). As per BREAM, the VEC species in the study area include polar bears, mink and muskrat.

Pre-1990

Duval (1985) suggested the following reasons why marine-associated mammals might be the most sensitive to oil spills: they depend exclusively on their fur as thermal insulation and oil contamination disrupts the insulating properties of fur; and they have been shown to be highly sensitive to oil ingested when the animal grooms it from its fur. Duval (1985) reported that mortalities of small numbers of sea otters had been unequivocally linked to a few spills. No occurrences of mortalities of large marine mammals, such as polar bears, could be linked to actual spills, but mortalities of polar bears and sea otters had been observed when these had been contaminated with oil in experiments. The disruption of thermal insulating properties of fur and effects on metabolic rate were established in a number of experiments. Little information was available in the early 1990s concerning the toxicity and pharmacokinetics of hydrocarbons in mammals.

Since 1990

Detailed studies of both the *Braer* (UK, 1993) and *Erika* (France, 1999) spills showed little impact on local sea otter populations. During the *Exxon Valdez* oil spill (EVOS) (Alaska, 1989), no mortalities of large terrestrial hairy mammals were reported, but estimates of mortalities among sea otters ranged as high as 2,650 individuals or approximately 40% of the local Prince William Sound population. Of particular interest here was the recovery of those populations that showed, as recently as 2005, that otter groups in areas that were not oiled during EVOS were recovering slowly, while those in oiled areas continued to decline (Ballachey et al., 1994; EVOSTC, 2005). Effects of petroleum spills and experimental exposures of marine-associated mammals have been reviewed by Boertmann and Aastrup (2002) and USGS (2007).

Pinnipeds

This category includes seals, fur seals, sea lions and walruses that derive their insulation from a combination of fur and an insulating layer of body fat (Harwood, 1985). The important VECs in the Beaufort Sea are ringed and bearded seals.

Pre-1990

Reviews published in the 1980s reported that mortality of pinnipeds had been reported during some spills, but impacts could seldom be linked unequivocally to the spills. However, oil exposure was lethal to seals in laboratory experiments. These impacts and experimental results were described in a review by Harwood (1985).

Since 1990

More recent spills have shown clear evidence of sublethal effects in several spills, but acute mortalities of seals were documented in only EVOS. In the case of the *Braer* (Conroy et al., 1997), *Sea Empress* (Edwards and White, 1999) and *Erika* (Laubier et al., 2004; Ridoux et al., 2004) spills, studies showed no acute mortality of seals, but sublethal effects occurred, including eye irritation in some cases. There are no reports of longer-term effects in these incidents. Since the 1990s, authors have developed indirect methods for estimating the acute impact (mortalities) on marine mammal and seabird populations in the spill location.

In EVOS, Stellar sea lions showed no effects from the spill (Calkins et al., 1994), but estimates of seal mortalities were as high as 43% (300 individuals) of seals in oiled areas (Frost et al., 1994; Weins et al., 1999). Recovery studies concluded that harbour seal populations had recovered from effects of the oil spill within a decade.

Cetaceans

Whales are bare-skinned and derive their insulation from an insulating layer of body fat (Duval, 1985). The important VECs in the Beaufort Sea are bowhead and beluga whales.

Pre-1990

Reviews (e.g., Martin, 1985) reported no evidence of mortalities of cetaceans resulting from spills. In addition, until that time very few studies of the sublethal and behavioural effects of oil on cetaceans had been done.

Since 1990
Most spill studies conducted since the 1990s continue to show little risk to cetaceans from spills, with certain exceptions. During EVOS, studies failed to identify any acute or chronic effects on the local humpback whale (baleen whale) population (von Ziegesar et al., 1994). Studies of the common dolphin (toothed whale) following the *Erika* spill came to similar conclusions (Laubier et al., 2004; Ridoux et al., 2004). On the other hand, post-EVOS studies of PWS killer whale populations identified significant acute effects, including apparent mortalities. In two populations studied, one population was apparently recovering and the other continued to decline 15 years after the spill. There is no clear link between the spill and the population effects (Matkin, 1994; EVOSTC, 2005).

Marine Birds and Waterfowl

In BREAM, the concerns were related to the waterfowl and marine birds of the Southern Beaufort Sea and their harvesting by local communities. The VECs identified in planning documents in the 1990s included terrestrial water fowl (tundra swan, snow goose, white-fronted goose, Canada goose, brant) and marine birds (thick-billed murre, black guillemot, loons, phalaropes), sea ducks (common eider, king eider, oldsquaw [long-tailed duck], scoter [marine duck]) and diving ducks (scaup). Those that figure most prominently in the local economy from a hunting perspective are the snow, white-front and Canada goose and the common and king eiders (Usher, 2002).

Pre-1990
The high impact of spills on marine birds has long been recognized (e.g., Bourne et al., 1968). The toxic mode of action of oil, physiological and pathological effects, high sensitivity of marine birds to oiling and the strong variation in oil vulnerability between species have also been long recognized. This material had been reviewed by a number of authors prior to the 1990s (e.g., Bourne, 1976; Brown, 1982; Hunt, 1987; Leighton et al., 1985; Trudel, 1985).

Since the 1990s
Studies of major spills since 1990 have confirmed repeatedly that marine birds are highly sensitive to marine spills; that species vary in vulnerability with auks and seaducks being most vulnerable; and that impacts vary to a degree with spill size and the level of use of the local area by bird populations at the time of the spill. Spills since 1990 have provided additional information on acute direct impacts of spills and about indirect and long-term impacts. Accounts of specific studies are provided below. Reviews of these have been prepared (Burger, 2003; Camphuysen and Heubeck, 2001; Jessup and Leighton, 1996; Leighton, 1995; USGS, 2007). In

addition, a number of authors have developed and used methods for estimating acute impacts of spills on local bird populations based on monitoring data (e.g., Heubeck et al., 2003).

Studies during the *Exxon Valdez* spill showed heavy mortalities of seabird species such as auks, loons and seaducks (e.g., Barrow's goldeneye ducks). Selected recovery studies showed the following:

- Healthy populations of many species, including murres, appeared to recover to pre-spill levels as quickly as expected, generally within a decade of the spill (EVOSTC, 2005);
- Certain populations that were in decline prior to the spill (e.g., pigeon guillemot) continued to decline after the spill (EVOSTC, 2005); and
- Some species, like harlequin duck and Barrow's golden eye that use oiled areas of Prince William Sound (PWS) continued to show population effects and evidence of contamination of individuals until as recently as 2005 (EVOSTC, 2005).

Following the *Braer* spill, neither Heubeck (1997) nor Monaghan et al. (1997) identified sublethal or population level impacts of the spill on local species, despite the fact that the area traditionally supported large numbers of marine birds. According to Kingston (1999), because of the season and harsh weather conditions, few birds were present at the time of the spill. A somewhat similar situation occurred during the *Sea Empress* spill in that local nesting populations had not yet returned to the area. However, large numbers of through-migrant species like common scoters were present and the latter accounted for most of the oiled birds collected (Edwards and White, 1999). The *Sea Empress* spill site supports internationally important numbers (>16,000) of non-breeding common scoters. Casualties were high and numbers were greatly reduced following the spill. Ten years after the incident, the numbers of scoters were no different than those recorded immediately before the spill (Banks et al., 2008).

Several thousand oiled or injured marine birds were collected on shore following the *Prestige* spill, including mostly auks (common murres, razorbills and puffins) (Balseiro et al., 2005). A study of a nearby colony of cormorants showed reduced reproduction in the year of the spill that was attributed to a spill-caused reduction in the local sandeel population; the cormorants preferred forage fish (Velando et al., 2005).

Fish and Fisheries

The fish species and fisheries that are identified as VECs in BREAM include both anadromous (Arctic and least cisco, broad and lake whitefish and dolly varden) and marine species (Pacific herring). All species use inshore marine and brackish water habitats for part of each season and support subsistence fisheries in either coastal marine areas or inland parts of rivers. As such, fisheries may be disrupted directly if spills contaminate areas where fishing takes place or indirectly if fish traverse an oil-contaminated area during migration. None of the VECs identified in BREAM support fisheries in deep offshore waters.

Pre-1990

The impact on fish and fisheries of marine oil spills and countermeasures such as dispersants has been intensively studied since the *Torrey Canyon* spill. This is due to the economic and subsistence value of fisheries and the need to manage spill impact on local fisheries and compensate the fishing industry for economic losses caused by spills. The impacts of spills, such as the *Torrey Canyon* (UK, 1967) (e.g., Smith, 1968), the *Amoco Cadiz* (France, 1978) (e.g., Seip, 1984) and others, were studied in depth. The effects of oil and hydrocarbons on fish and shellfish were also studied experimentally in the laboratory and in field studies, which examined a range of parameters, including the following: lethal, sublethal and physiological effects; variations in sensitivity between species and life history stages; bioaccumulation of hydrocarbons and tainting; and exposures via oil in water and in sediment. This material and its implications for spills in the Arctic have been reviewed by several authors (e.g., Malins, 1977; Trudel, 1985).

The environmental risks associated with countermeasures, such as dispersants, were studied during the *Torrey Canyon* spill and experimentally in laboratory and field experiments (e.g., Baffin Island Oil Spill experiment, Sergy, 1985). Methods for assessing the net environmental benefit (NEB) of dispersant use on spills were developed in the 1980s and were applied to spill planning on Canada's three coasts and in the U.S. A system was developed for assessing the NEB of dispersants for spills in the Southern Beaufort Sea in the late 1980s (Trudel et al., 1988).

Since 1990

Advances have been made in acquiring knowledge of the acute and long-term impacts of spills and countermeasures, as well as in developing practices for managing the impact of spills on the local human population. Overview papers and reviews have been prepared on these subjects (IPIECA, 1997; Moller et al., 1989; Mosbech, 2002).

Acute and long-term effects of spills on fish populations

Many of the acute effects of spills were well known; so most of the work since 1990 has served to refine existing knowledge of acute effects. Intensive studies following the *Exxon Valdez* oil spill (EVOS) provided insights into the long-term consequences of spills or the lack of them and the causes.

- During EVOS, although young pink salmon were chronically exposed to hydrocarbons leaching from nearby oil-contaminated beaches, population-level effects from the spill could not be detected or were short-lived (Weins et al., 1999).
- Pacific herring that spawned in oil-contaminated areas of Prince William Sound in the weeks after the oil spill became contaminated by oil and suffered lesions, egg mortality and larval deformities, but no adult mortality. However, four years after EVOS, the herring population and fishery collapsed and by 2005 had been closed for 11 of the 17 years since the spill. Studies suggest that disease may be limiting recovery of herring in PWS, but the link to oil exposure or persistent contamination is unclear (EVOSTC, 2005).

The *Haven* spill (Italy, 1991) provided information on impacts of in-situ burning of oil. Approximately 100,000 tonnes of the crude oil cargo burned and the residue sank contaminating 140 km^2 of offshore seabed, causing the local fisheries to close for two seasons. There was some PAH contamination of edible fish tissue, but it was well below the U.S. Food and Drug Administration threshold for unsafe consumption. However, the fishery remained effectively closed for two seasons because of fishermen’s concerns that trawl gear and catch might be contaminated with the burn residue, rendering the catch unmarketable (Martinelli et al., 1995).

During the *Braer* spill (UK, 1993), severe weather dispersed all of the spilled oil quickly, generating high concentrations of oil in nearby waters (up to 50 ppm TPH) and contamination of sediments over an area of 300 km^2. According to Kingston (1999) and Law and Kelly (2004), elevated concentrations of TPH were observed in all fishery species, but contamination returned to background levels at species-specific rates as follows: lobster within 1 month; caged farmed salmon, 6 months; edible crab, 12 months; scallops, 12 to 18 months; and Norway lobster (a species that burrows in the sediments), 7 years. The very lengthy persistence of spill-related hydrocarbons in tissues of the Norway lobster was due to its unique habitat use (Fisheries Research Services, undated).

During the *Prestige* spill of heavy fuel oil (France and Spain, 2002), fishery exclusion zones were put in place in Spain immediately after the incident and were lifted in October 2003 (Punzón et al., 2009).

Closures and Reopening of Local Fisheries during Spills

The most significant oil spills have resulted in the temporary closure of local fisheries in areas contaminated with hydrocarbons. Fishery closures are put in place to ensure that fish contaminated by oil from the spill do not find their way to market (Moller et al., 1989). Historically, closed fisheries have been re-opened in stages within months or years when trustees were convinced that environmental and tissue contamination had returned to acceptable levels. Prior to the 1990s, procedures for reopening fisheries were highly variable and were developed as required during each event (Law and Hellou, 1999). By the mid-1990s, more systematic procedures and standards were being developed. Following the *Sea Empress* spill (UK, 1996), closed fisheries were reopened on a species-by-species and area basis. Criteria for reopening included tissue burdens of total petroleum hydrocarbons (TPHs) and selected polynuclear aromatic hydrocarbons (PAHs) in fishery species declining to background levels and the catch being free from 'off-flavours' (Law and Kelly, 2004). However, in many other spills the background levels of TPHs and PAHs were not known; so an alternative standard was required. Following several U.S. spills, fisheries were re-opened when tissue PAH levels declined to below accepted regulatory standards for PAH concentrations in all foods as set by local food and drug agencies (Mauseth et al., 1997). These standards were based on human consumer cancer-risk calculations that assumed average fish consumption habits in the national population as a whole. These standards, however, might underestimate risks to groups, such as subsistence fishermen, whose consumption may differ from the average. Studies following the *Exxon Valdez* and *Selendang Ayu* (Alaska 2004) spills include questions related to the closure of subsistence fishing (Walker and Field, 1991; Svarny-Livingston et al., 2008).

Environmental Issues with Dispersant Use

In the late 1980s, dispersant-use policies in North America were restrictive largely because of concerns about the environmental risks from the dispersed oil. Methods for assessing the potential net environmental benefit (NEB) of dispersants for local spills had been developed in the 1980s (Baker, 1995; Fraser, 1989; Trudel and Ross, 1987) and were leading to development of environmentally rational dispersant-use policies and pre-approval zones in some areas (Trudel et al., 1989). However, these NEB tools were models that had not been ground-truthed and suitable dispersant toxicity data were available for only a limited number of important species.

Following the *Sea Empress* spill (UK, 1996), in which dispersants were used extensively, UK scientists credited dispersants with helping to minimize the environmental damage from the spill (Edwards and White, 1999). This effectively proved the NEB approach. More recently, dispersants were used extensively in the *Tasman Spirit* spill in Pakistan in 2003 (CEDRE, 2006), but to date, little scientific material has been published concerning that spill. In the 1990s in the U.S., a major testing program (Chemical Response to Oil Spills: Ecological Effects Research Forum, CROSERF) gathered toxicity information for important local species using a standardized toxicity testing protocol. CROSERF used exposure conditions (brief exposures) that were consistent with exposure conditions for fish and shellfish species during dispersed spills (Singer et al., 1995). This showed that risks from dispersed oil, though present, were lower than previously believed (Pace et al., 1995). From the late 1990s to 2005, numerous U.S. Coast Guard-sponsored NEB workshops were held in the U.S. to consider the environmental aspects of dispersants in local spills (Aurand et al., 2005). These led to the establishment of dispersant pre-approval zones in all coastal jurisdictions in the U.S. From the late 1990s to the present, a series of projects were completed that assessed the NEB and the operational feasibility of using dispersants to treat spills from offshore production operations in the Gulf of Mexico, Southern California and the Grand Banks of Newfoundland (e.g., Trudel et al., 2003).

An important consideration in establishing pre-approval for dispersant use in the U.S. was the need for a formal monitoring process during dispersant operations that assessed the effectiveness of dispersant applications and the dispersed oil concentrations generated in the water column (to which VECs would be exposed). The U.S. Coast Guard and NOAA developed a dispersant effectiveness monitoring protocol, "Special Monitoring of Applied Response Technologies (SMART)" (Barnea and Laferriere, 1999). After 15 years of use, the SMART dispersant protocol was critically evaluated and recommendations were made for improvement (Trudel et al., 2009).

Environmental Issues with In-Situ Burning

In the early 1990s, in-situ burning technology was proven, but there were two environmental concerns about its use, namely risks to humans from the smoke and environmental risks from the burn residue (Allen and Ferek, 1993). The question of risk to humans from smoke was addressed when U.S. government agencies, including the U.S. Centers for Disease Control, developed the in-situ burning component of the SMART monitoring protocol. That protocol incorporated a newly adopted human exposure standard for environmental smoke in order to develop decision-making and monitoring protocols for protecting sensitive human population centres during burns.

Until the early 1990s, environmental concerns about toxicity risks from burn residue were addressed by proposing the collection of any floating residue from burns with nets (Allen and Ferek, 1993). However, during the *Haven* spill, very large amounts of burn residue sank, causing local fisheries to close for two years and posing unknown risks to local fish populations (Martinelli et al., 1995). As described elsewhere in this report, subsequent research identified oil characteristics that lead to the sinking of burn residue (Buist et al., 1995) and showed that burn residue is relatively non-toxic (Blenkinsopp et al., 1997).

Table 4: Summary of Selected Major Spills 1989 to Present

Date	Vessel Name	Location	Type of Oil Spilled	Spill Volume (tonnes)	Comments
1989	*Bahia Paraiso*	Antarctica	Diesel/ Jet Fuel	1,000	Antarctic spill
1989	*Exxon Valdez*	U.S. Alaska	ANS Crude	33,000	Heavy persistence of oil on shorelines; research into long-term impacts and recovery
1991	*Haven*	Italy	Heavy Iranian crude	30,000	Effects of residue from in-situ burning
1993	*Braer*	UK, Scotland	Gulfaks crude	84,700	Natural dispersion
1996	*Sea Empress*	UK	Forties	72,360	Dispersants primary countermeasure
1999	*Erika*	France	Heavy fuel oil	19,800	Heavy fuel oil
2001	*Jessica*	Galapagos Is., Ecuador	No. 2 and Bunker	547	
2002	*Prestige*	Spain	Bunker fuel oil	63,000	Heavy fuel oil
2003	*Tasman Spirit*	Pakistan	Iranian light crude	30,000	Dispersant heavily used
2004	*Selendang Ayu*	U.S. Alaska	Heavy marine diesel	1,330	Arctic spill

Present Oil Spill Response Capability

Any offshore exploration or development program will likely need a dedicated initial response (Tier 1) either on-scene or stationed relatively close to the proposed activity. This would be used to respond to small spills and for an initial response to larger incidents. In the latter case, additional resources would be required from regional, national and perhaps international sources. In the absence of a specific well location or drilling program, the following is restricted to a general discussion of the capabilities, areas of operation and mandates of some of the more likely candidates for assistance at the Tier 2 and 3 levels.

Response organizations with a potential capability to respond to Beaufort Sea spills include those listed below. They are listed solely as possible options; pre-planning and agreements would be required prior to a spill for there to be any realistic hope of accessing their resources. In some cases, as described below, spills related to oil exploration and development in the Beaufort Sea may be outside the mandate of some organizations.

Mackenzie Delta Spill Response Corporation (Calgary)

The Mackenzie Delta Spill Response Corporation (MDSRC) is a non-profit organization of companies that have joined together in support of onshore drilling within the Mackenzie Delta of the Northwest Territories. Its geographic area of responsibility is the Mackenzie River Delta extending from lands north of Inuvik and Aklavik to the shores of the Beaufort Sea. MDSRC has 20 containers of response equipment stored in Inuvik, including a variety of equipment for dealing with open-water river spills and winter inland spill response. Some equipment and manpower could potentially be used for Beaufort Sea nearshore or harbour spills in the right circumstance. It may be possible to investigate the potential for expanding MDSRC’s mandate to include the offshore; however the equipment and owners remain focused on Mackenzie Delta onshore lands at present.

Burrard Clean Operations / Western Canada Marine Response Corporation (Burnaby, BC)

Burrard Clean Operations (BCO; also known as Western Canada Marine Response Corporation) provides marine oil spill response services to the responsible party, the Canadian Coast Guard or to any other government lead agency. Its mandate is to provide its members with a regional, focused marine spill response. As one of two approved response organizations in Canada, BCO provides response for spills associated with vessels and oil handling facilities in accordance with regulations referenced in the Canada Shipping Act. Based on the west coast, BCO has a network of pre-staged response equipment to meet the 10,000-tonne certification requirements. BCO will also provide support for incidents involving more than 10,000 tonnes to the best of its ability. Equipment depots are located in Vancouver, Duncan and Prince Rupert, B.C.

It is conceivable, either through an arrangement made with a government lead agency or through a third party agreement with the responsible party, that BCO's expertise and equipment may be applied to a spill in the Canadian Beaufort Sea, though not as a primary responder. Further investigation is required to clarify whether or not such an arrangement is realistic given the stringent requirements to maintain minimum equipment resources on the west coast.

Canadian Coast Guard (CCG; various locations in NT, NU and nationwide)

The main base of operations, with environmental response personnel dedicated to the location, is in Hay River, Northwest Territories. The response package warehoused in Hay River is maintained in 100% readiness during the shipping season. It contains air-transportable equipment for containment and recovery in accordance with the 150-tonne standard for Canadian response organizations. Three unmanned depots with an incremental 1,000-tonne capability are located in Tuktoyaktuk, Iqaluit, and Churchill, Manitoba. Smaller caches of equipment, known as Arctic Community Packs (ACPs), are located in 10 locations (Arctic Bay, Cambridge Bay, Cape Dorset, Clyde River, Coppermine, Coral Harbour, Gjoa Haven, Holman, Rankin Inlet and Resolute) with additional locations planned for Baker Lake, Broughton Island, Chesterfield Inlet, Churchill, Hall Beach, Kimmirut, Iqaluit, Pangnirtung, Tuktoyaktuk and Yellowknife. The ACPs consist of various types and amounts of equipment based on local circumstances; in general, they consist of a small boat, a nearshore containment boom, a medium-sized skimmer and portable storage for recovered fluids. The 1,000-tonne depots have more equipment, but they too are most suited to nearshore countermeasures. It is important to note that the CCG's mandate is to respond to spills associated with vessels and oil-handling facilities rather than those related to oil exploration and development, which are the responsibility of the National Energy Board (NEB). Nonetheless, under the National Contingency Plan, the NEB could request the use of CCG equipment to assist in a response.

Alaska Clean Seas (ACS; Prudhoe Bay, Alaska)

ACS is a co-operative based on the North Slope of Alaska that was established for spills associated with oil exploration and development in and around Prudhoe Bay. Until recently, this mainly comprised spills on land, in rivers and in nearshore waters, but with the development of several offshore fields and ongoing exploration activities, they do have some offshore capability. It is conceivable that a co-operative arrangement between ACS and a Beaufort-based response group could be developed. This would be particularly applicable for countermeasures such as in-situ burning and dispersant use, for which there are less restrictive requirements for maintaining response equipment levels on the North Slope.

Eastern Canada Response Corporation (ECRC; Ottawa headquarters and various depots in eastern and central Canada)

The ECRC is a certified response organization established to provide a tiered response capability for spills associated with vessels and oil handling facilities in accordance with regulations and guidelines contained in the Canada Shipping Act. It has major response depots in St. John’s, Dartmouth, Quebec City, Sept Îles, Verchères and Corunna. ECRC has mutual aid support allowing the cascading of people and equipment from the other response organizations, including the Western Canada Marine Response Corporation (WCMRC) in Vancouver, BC, the Atlantic Emergency Response Team (ALERT) in Saint John, NB, and Point Tupper Marine Services (PTMS) in Point Tupper, NS. Because ECRC was established expressly for vessel and facility spills under the Canada Shipping Act and is subject to strict conditions regarding its equipment stockpiles and specified areas of responsibility, it is not in a position to be considered a primary resource for other spills or for spills outside its specific region.

Oil Spill Response (OSR; Southampton, Aberdeen, Bahrain and Singapore)

The recent amalgamation of OSRL and East Asia Response Limited (EARL) provides worldwide coverage for Tier 2 and particularly Tier 3 response. OSR will establish response arrangements with any interested party, including exploration programs, oil-handling facilities, shippers and governments. Equipment covers the spectrum of countermeasures options, including packages of equipment to deal with offshore containment and recovery, nearshore containment and recovery, and shoreline cleanup. Of particular note is its ability to deliver equipment for a large-scale dispersant operation, specifically, Aerial Dispersant Delivery System (ADDS) packs, which are roll-on containers designed for dispersant application from Hercules aircraft. If a pre-arrangement were in place, these could conceivably be delivered on scene within 24 to 48 hours of notification.

Beaufort Sea Spill Response Co-operative (Tuktoyaktuk)

This was a co-operative effort in the early 1980s involving Dome Petroleum, Esso Resources and Gulf Canada, which were active in the Beaufort at the time. The equipment included offshore and nearshore equipment, and a barge-based response system that included an offshore containment boom, a skimmer, an oil/water separator, an emulsion-breaking system, storage within the barge and a flare-type burner for disposal. All of the equipment was disposed of in the 1990s when Beaufort Sea exploration activities ceased.

Summary

There are a number of resources within Canada and Alaska that could conceivably be called upon to supplement a Tier 2 or Tier 3 response. However, there are a number of caveats:

- The equipment is suited to nearshore response operations;
- Transit times to the Beaufort would be excessive in most cases;
- Much of the equipment has been acquired to satisfy local legislative requirements and therefore may not be readily released; and
- Importing equipment from foreign sources may present difficulties.

Oil Spill Response offers a potential resource for Tier 2 and Tier 3 response, particularly for a large-scale airborne dispersant operation.

General Reviews and Research Recommendations

The focus in this section is on reviews and research recommendations published in the last five years on the subject of Arctic oil spill response. As a point of reference, the R&D recommended in two publications from the early 1990s is presented first.

Research Recommendations in the Early 1990s

In May 1992, the U.S. Arctic Research Commission issued a series of findings and recommendations entitled "Research Needed to Respond to Oil Spills in Ice-Infested Waters". Specifically, the seven main recommendations were the following:

1. The U.S. federal government should "consider, emphasize and support research of in-situ burning as a procedure for ice-infested waters.
2. Conduct research to understand combustion properties and processes in the Arctic as they may relate to oil spill cleanup in ice-infested waters.
3. Conduct applied research and field testing of the equipment and processes that may be involved in in-situ burning.
4. Conduct research on logistics systems for spilled oil detection and cleanup.
5. Conduct ecological studies of marine mammals and birds that may be affected by oil spills in ice-infested waters.
6. Analyse institutional barriers to the development and acceptance of new oil spill cleanup technologies, to the meaningful involvement of Artic residents in planning and evaluating cleanup procedures, and to an active program focused on transferring relevant information to the public.
7. That the oil industry collaborate with international bodies in developing environmental guidelines for Arctic oil exploration, development and production, and assist in monitoring key variables."

The State of Alaska Hazardous Spill Technology Review Council listed the following research recommendations at a 1994 workshop on spill response in dynamic broken ice:

- "In-situ burning of oil
- Short-term and long-term bioremediation
- Satellite tracking of spills
- Plasma torch technology development
- On board response capabilities
- Dispersing agents for use in cold water
- Human factors in the transportation of oil and other hazardous substances
- Human factors in spill response

- Chemical treatment of spills
- Effectiveness of skimming systems in ice and various oil types
- Utilization of vessels of opportunity in spill response
- Sorbent technology improvement"

Reviews and Research Recommendations in the Last Five Years

Following the International Oil and Ice Workshop in 2000 (ACS 2000), the Prince William Sound Oil Spill Recovery Institute and the U.S. Arctic Research Commission funded a two-year study to identify critical deficiencies in the current state of knowledge regarding oil spills in ice (Dickins, 2004). Some 60 potential research and development ideas were initially derived from the proceedings of the 2000 workshop. These ideas were screened and assessed through a process of expert reviews, public comment and a two-day workshop. The priority program areas identified in this project included the following:

- Detection of oil in ice;
- Enhancing mechanical recovery systems;
- Dispersants in ice;
- Oil deflection in broken ice;
- Chemical herders in ice;
- Oil simulants to allow more frequent field trials; and
- Transfer of viscous oily waste under freezing conditions.

The project also highlighted the need for progress on non-R&D issues such as training, public education and development of realistic regulations and standards. Field spills with oil were identified as critical to improving spill response capabilities under all marine conditions (ice and open water).

ARCOP (Arctic Operational Platform) was a European Community research and technology development project with the overall objective of establishing an operational platform for the development of oil and gas in the Arctic region, and primarily for increased shipping of Russian crude oil from Varandey to Murmansk and in the Norwegian sector of the Barents Sea. A state-of-the-art report on oil spill weathering in the Arctic and the effectiveness of spill response alternatives in ice (Evers et al., 2004) concluded that in-situ burning was the most important countermeasure for spills in ice and made a series of recommendations for future research. The major topics were the following:

- Oil weathering, fate and behaviour in ice, particularly transport and spreading of oil in ice and oil weathering validation experiments and the development of better algorithms;
- Training exercises and testing of equipment in ice;

- Mechanical oil recovery, particularly winterizing equipment and heating systems for equipment, mechanical recovery equipment for broken ice conditions, oil/ice separation and further development of the MORICE and LOIS vibrating skimmers; and
- In-situ burning, particularly field testing of new technologies and identifying of windows of opportunity for burning through simple, small-scale tests.

In a subsequent ARCOP study (Evers et al., 2006), it was concluded that there was “no proven response method for recovering large-scale oil spills in ice-infested waters.” The study also concluded that the preferred response to a large-scale spill from a tanker en route from Varandey to Murmansk would be a combination of mechanical recovery and in-situ burning. The winterizing of response equipment and field training and testing were also recommended. The strategy for shoreline cleanup focused on natural processes and in-situ techniques (bioremediation, dispersants, shoreline cleaning agents, in-situ burning, sorbents and washing/flushing).

In a paper presenting the results of an in-house state-of-the-art review of oil spill in ice response Singsaas et al. (2006) identified the following research priorities:

- Improve and adapt existing skimmer concepts for use in Arctic and ice-infested waters;
- Field-test in-situ burning techniques in high and low ice concentrations;
- Further develop monitoring and remote sensing systems for oil in ice in order to detect and follow oil in ice floes and on ice, detect oil under ice, and follow oil covered with snow or encapsulated in ice over winter until the melt season arrives; and
- Strengthen the basis for Arctic spill risk assessment, response analysis and NEBA through improvements in oil/ice modelling, particularly oil behaviour and fate models for Arctic conditions, ice formation and ice drift/hydrodynamic models.

The World Wildlife Fund (WWF) released a report analysing the spill response techniques proposed for the Sakhalin II project (DeCola et al., 2006). The main concern is the “Dynamic Ice Response Gap”, defined as the percentage of time that environmental conditions at the spill site preclude cleanup. The report is critical of several key technical areas of spill countermeasures in dynamic pack ice, primarily the following:

- The use of in-situ burning for spills in pack ice (the criticism is based primarily on a limited window of opportunity afforded by a combination of appropriate ice conditions and visibility and the possibility that the burn residue might sink and pose a significant risk to the Western North Pacific gray whales that frequent the area); and
- The challenges involved in removing oil released below the surface that is trapped under ice floes.

The report recommends the following work on oil spill countermeasures that is necessary to address the dynamic spill response gap at Sakhalin:

- Conduct a response gap analysis;
- Study the behaviour of Sakhalin crude oil burn residues;
- Develop oil spill trajectory models for well blowouts;
- Consider the response requirements for a worst-case tanker spill;
- Continue R&D efforts to improve oil spill cleanup technologies in ice-infested waters, focusing on developing response systems for use in large-scale recovery efforts; and
- Conduct a NEBA that considers potential ecological impacts and trade-offs associated with spill response options.

In a subsequent WWF publication (Nuka, 2007), it is recommended that response gap analysis be carried out in all Arctic regions in which offshore oil activity is ongoing or proposed. From the perspective of this report, the following specific spill response-related recommendations are put forward:

- The oil spill response gap for a specific area should be factored into oil spill vulnerability and risk assessments;
- Local response and infrastructure/support capabilities should be factored in;
- Contingency plans should contain realistic response scenarios that show the resources and personnel required to respond to a worst-case discharge as well as provide realistic time frames for mobilization and deployment and realistic cleanup effectiveness estimates; and
- Research and development efforts to improve spill response technologies should address logistical support and deployment considerations and should be field-tested in the context of the overall response system.

The WWF reiterates its recommendation to assess spill response gaps in Arctic areas in its most recent publication on oil spill response in Arctic areas (WWF, 2009).

In March 2008, the Coastal Response Research Center (CRRC) worked with the U.S. Arctic Research Commission and the U.S. Coast Guard to host a workshop to identify current international incident response capabilities, assess future needs and identify research gaps and activities to improve the ability of Arctic nations and indigenous communities to prepare for and respond to marine incidents (CRRC, 2009). The participants made 17 recommendations that they believed would significantly improve response and recovery. Of these, the following eight were related specifically to oil spill response operations:

- Conduct comprehensive environmental risk assessments and impact assessments for the Arctic;

- Increase emergency response assets, equipment and supplies in the Arctic, placing emphasis on regions of active development;
- Improve knowledge for Arctic incident response through training and engagement of the local community, responders and industry;
- Consider alternative countermeasures for oil spill cleanup (including approval processes);
- Expand communications capabilities throughout the Arctic;
- Improve logistical support capabilities for responders;
- Involve indigenous people and local communities in planning, response, recovery and restoration decisions and operations; and
- Conduct outreach to the local community and keep stakeholders well informed.

The participants also developed the following three specific research requirements:

- Update weather data and navigational charts for the Arctic;
- Study the behaviour of oil in cold water and technologies for spill response ("Researchers should expand their knowledge of the behaviour of oil in cold water and explore technologies for cold water spill response. The Arctic nations should invest in examining new technologies for the detection of oil under ice, as well as mechanical and alternative cleanup countermeasures, including in-situ burning and chemical dispersants and herders. Environmental spill models for the Arctic should also be improved."); and
- Improve baseline information for Arctic resources that could be affected by potential incidents.

In response to the recommendations of the CRRC workshop, the Ocean Studies Board of the National Research Council of the U.S. National Academies is proposing to take an in-depth look at the issues associated with response to oil spills in pack ice. A committee of experts would be assembled to report on the following:

- Spill scenarios that could occur in ice environments and an assessment of the challenges of responding to these, in comparison to responding in open water;
- Compare the effectiveness and drawbacks of current spill cleanup methodologies for oil spills in ice-covered waters;
- Assess techniques for detecting, mapping and tracking spills in ice; and
- Identify promising new concepts for spill response in ice and recommend strategies for advancing research and addressing information gaps.

Geo-References

In addition to a literature review of oil spill countermeasures, one of the goals of the study was to prepare a geographic database of coastal resources, vulnerabilities and sensitivities that may influence the choice of oil spill containment and recovery methods.

Environment Canada's Arctic Environmental Sensitivity Atlas System (AESAS) was created to "provide a synthesis of environmental information relevant to the planning and implementation of year-round oil spill countermeasures in both coastal and offshore areas of the Beaufort Sea." This electronic atlas was last updated in 2004 (David Tilden, pers. comm., 2009) and includes data references dated up to 2003. This atlas remains the most comprehensive geo-referenced summary of environmental information for the region. A considerable body of new information has been generated since the most recent update of the atlas and the goal of this task was to identify data sources that could be used to update and supplement the atlas. A review of primary literature sources was completed through an electronic library search completed by the Canadian Institute of Scientific and Technical Information (CISTI). Searches of the Internet, the Inuvialuit Settlement Region Database (www.aina.ucalgary.ca/isr/) and the Arctic Science and Technology Information System (ASTIS) (www.aina.ucalgary.ca/astis/) were also completed.

The results of this search process are provided in tabular form in Appendix B. Only spatially referenced data have been included in this summary; this includes geo-referenced tabular data as well as mapped data. It was beyond the scope and budget of this project to evaluate how the newer data sets might contradict, reinforce or complement the existing atlas data. The new data sources are identified for future consideration in an updated GIS. New data have been identified for most of the major valued ecosystem components (migratory birds, marine mammals and fish) as well as climate and geophysical data. No new sources of archaeological data were identified. Considerable on-going research is being carried out in the Beaufort Sea Region, especially in the area of migratory bird assessments. Descriptions of some of these activities are also provided in Appendix B, although no data are yet available from these studies for inclusion in a final database. A bibliography of the data sources is also provided.

Links are provided in the Appendix to either Web-based documents or digital copies of the original research reports and papers, where they were readily available. The digital report copies have been delivered with this document for convenient retrieval and review. The data in the table are categorized under the following headings:

- Library Sources (convenient links to the two online libraries with extensive Arctic collections)
- Government/Industry Initiatives and Overviews

- Traditional Knowledge
- Physical Environment (Climate, Ice, Oceanography)
- Wildlife
    - Observations
    - Key Habitats
    - Polar Bears
    - Seals
    - Whales
    - Birds
    - Fish
    - Phytoplankton/Benthos

Stakeholder Views of Oil Spill Response Options

Task Objectives

The main objective of this task was to conduct a comprehensive review and compile relevant stakeholders' policies, positions and views on oil spill response options, and more specifically to

- Understand stakeholder positions and views on various spill response options;
- Limit the scope to the Canadian Beaufort Sea;
- Focus on present-day, as compared to historical, activity in the Beaufort Sea;
- Document the findings in a final report; and
- Collect the common themes and issues for discussion at the workshop.

Approach and Process

The approach was to obtain a snapshot of current viewpoints on response options from various stakeholders. A detailed approach was developed to facilitate the most effective communication with and feedback from the stakeholders concerned.

To accomplish the above objectives, the following tasks were undertaken:

1. Develop a list of representative stakeholders;
2. Identify key response strategies for discussion;
3. Conduct a survey of and document positions and viewpoints relative to key response options; and
4. Gather general viewpoints and identify common elements (positives and opportunities).

Representative Stakeholders

The list of potential stakeholders was drawn up based on the earlier history of Beaufort Sea activities, current and planned operational initiatives, key federal regulatory agencies and government departments with oil spill and Arctic responsibilities, and northern interest groups. Suggestions were also received during consultations with oil and gas industry members active in the Beaufort Sea region. The list included representatives from

- Industry,
- Regulators (northern and federal), and
- Inuvialuit agencies.

Industry representatives that were approached included the following:

- BP Canada
- BP Alaska
- Canadian Association of Petroleum Producers

- Chevron Canada
- ConocoPhillips Canada
- Imperial Oil
- MGM Energy
- Shell Energy

Regulatory agency representatives approached included the following:
- Canada Coast Guard
- Fisheries and Oceans Canada
- National Energy Board
- Transport Canada

Northern-focused agencies and stakeholder representatives approached included the following:
- Environment Canada
- Indian and Northern Affairs Canada
- Inuvialuit Game Council
- Inuvialuit Joint Secretariat

For each group selected, individuals were targeted based on responsibility or focus on oil spill and Arctic response. In addition, interviewees suggested additional individuals who might also provide useful viewpoints. A list of contacted individuals is provided in Appendix C.

Key Response Strategies for Discussion

The next step was to develop a list of potential oil spill response strategies, tactics and topics to be discussed with the stakeholders. The list was drawn up based on the proposal, historical Beaufort Sea response strategies and current Arctic tactics intended to cover the broadest range of potential Beaufort Sea response options.

The list of strategies included the following:
- Mechanical containment and recovery
- Dispersant use
- In-situ ignition and burning
- Shoreline protection and cleanup
- Waste handling and disposal
- Remote sensing and detection

Other suggestions and topics were covered during the interviews and reviews and are noted in the results of the conversations. These included discussion of the following:

- Novel approaches with merit
- Further testing, demonstrations, research, and experiments
- Technology transfer from other Arctic offshore regions (Alaska, Russia, Norway)

Survey Tools

In order to obtain the most comprehensive information, a variety of survey and review instruments were developed to gather feedback from the stakeholders. These included the following:

- Initial contact to verify and validate the stakeholder and identify the person in that organization best able to answer questions;
- Scheduled telephone interviews to allow time for the person to prepare for the session and provide consistency in approach and response. These consisted of either one-on-one sessions or conference-call sessions in which a group of stakeholders participated (e.g., a government department);
- Email correspondence was initiated in advance to provide potential stakeholders with background on the ESRF study, the objectives and the specific questions and topic areas to be addressed. It also provided respondents with an opportunity to provide written feedback if an interview session were not possible; and
- One-on-one interviews were scheduled where practicable.

As well, a follow-up was done to get in touch with stakeholders who could not be contacted initially or to clarify viewpoints expressed.

Throughout the interview and communication process, it was clearly stated that the sources of individual comments would not be disclosed and that the intent was to have an open conversation in which the topic of oil spill response in the Beaufort Sea would be discussed.

Stakeholders' general views, policies and opinions were to be expressed as being representative of the group being interviewed (e.g., company approach versus an individual's personal view). The objective was to cover the general themes, topics, concerns, agreements and opportunities in order to provide a current state-of-the-art snapshot of stakeholder views on oil spill preparedness and response in the Beaufort Sea.

Survey Form and Questions

A series of key questions and probing statements was developed and used as the interview baseline for all conversations with stakeholders. The question areas focused on the following:

- What are the response strategies that are effective in and applicable to the Beaufort Sea?

- What response strategies are ineffective or would not be considered and what are the barriers, hurdles or impediments that prevent some options from being fully utilized?
- What techniques, strategies or options are promising and merit further research and development?
- What are the key issues for spill response in the Beaufort Sea and where should we focus our efforts?

The specific questions are provided in Appendix D (email version) and Appendix E (interview form excerpts).

Feedback Results

The following is a review of the feedback received for of each of the key questions that were asked. The information is organized according to the response strategies discussed.

Effective and Applicable Response Strategies and Techniques

All of the options listed (mechanical containment and recovery; dispersant use; in-situ burning; shoreline protection and cleanup; waste handling and disposal) have a potential role in response operations, depending on the scenario, time of year, water depth and ice conditions. Most participants believed that there was no single preferred response option; rather a matrix of options might be the best way to describe effective and applicable response options.

Mechanical containment and recovery was thought to be the best-known option in the Beaufort, based on historical Beaufort Sea Oil Spill Co-operative operations. Participants said repeatedly that mechanical containment and recovery had recognized limitations; logistics and ice were cited frequently as significant barriers.

Respondents suggested that mechanical containment and recovery had a role to play in the case of small, incidental spills where the waste (solid and liquid) volumes were minimal. Typically, this was seen as applicable to minor Tier 1-type responses where the spill could be quickly handled by resources immediately on scene.

It was also recognized that there was no longer any effective cache of containment and recovery equipment in the Beaufort and that this would have to be re-established.

Some recent international research may show promise for new oil-in-ice skimmer adaptations.

Most participants thought that in-situ burning was well understood and an effective and efficient option in certain situations in the Beaufort Sea. For conditions in ice, it seemed to be the preferred response option. Additional in-situ burning development was identified for thickening slicks in ice and use of chemical herders. Techniques of aerial ignition, burning oil in melt-pools and use of fireproof and fire-resistant booms were familiar to most respondents.

Dispersant use was widely cited as being a potential strategy for the Beaufort Sea that warranted further investigation and understanding. This would be a new response technique for the region and further research was essential. Recent work in other Arctic regions also showed promise for the use of dispersants in certain ice conditions, using vessel thrusters to introduce artificial mixing energy and using gel dispersants for application (see subsequent section on limitations).

Several participants noted waste handling and disposal as a priority item that needed to be revisited to improve understanding. Much had changed in the region with respect to facilities, locations, techniques and overall strategies for waste management. The consensus seemed to be that any discussion of spill response strategies had to take a systems approach and ensure that waste handling, transfer and disposal were included in the process.

Remote sensing was identified as an area with some good and well-known established techniques for detecting and tracking slicks on open water. There had also been some progress in detection of oil under ice. Ground-penetrating radar was mentioned as a technique that looked very promising and warranted further research and development. The current challenge was to turn the ground application into an airborne sensor application.

There was not a lot of discussion about shoreline protection and cleanup as a response option: respondents either felt that it was well understood or that no new issues had arisen since the earlier period of Beaufort exploration. Respondents did say that the Beaufort Sea Environmental Atlas was a tool that should likely be updated to take advantage of new technology and to document changes in shoreline characteristics over the last decade.

Several respondents made a general comment that Canada should continue or increase its participation in global Arctic oil spill research and development, particularly to stay abreast of emerging techniques and equipment. Although some groups had been active in Arctic initiatives (e.g., Emergency Prevention, Preparedness and Response (EPPR) Working Group, Arctic Council and SINTEF Joint Industry Programs) and information on these initiatives was generally available to the public in the form of conference proceedings and Internet-posted material, it was important to find more proactive ways to provide the latest research information to a broader northern audience.

Ineffective Options and Barriers to Success

There were no countermeasure options thought to be totally ineffective or not permitted, or that would never be considered by regulators and stakeholders. This is refreshing and seems to open the door to exploring all options to find the most effective mix of response strategies.

With some options, there were barriers, hurdles and impediments that needed to be addressed in order to further development and increase effectiveness and efficiency. These include the following.

<u>Overall Logistics and Infrastructure Concerns</u>: One of the greatest challenges in the present-day Beaufort Sea is the lack of infrastructure and logistics support, compared with what was in place in the earlier period of Beaufort exploration. Respondents mentioned support vessels, logistics bases, personnel and equipment as being challenges to any company starting a new exploration program and establishing an effective spill response operation.

<u>Waste Handling and Disposal in the Three Northern Territories</u>: One of the key aspects of any response option is the ultimate fate of recovered fluids, solids and recovery materials resulting, in particular, from mechanical containment and recovery. Several respondents acknowledged that, regardless of the response strategy adopted, the problem of collected wastes would have to be addressed. Since the previous era of Beaufort Sea exploration operations, a focused effort was needed to identify how waste materials from a major spill incident would be handled. This should include identifying the type and quantity of wastes generated by various response options and identifying viable options for waste handling and ultimate waste disposal (e.g., temporary storage locations in the Yukon and Northwest Territories; offshore and inshore waste processing; incineration standards, etc.). Recent experience on the East Coast, where it had been difficult to obtain approval for offshore incineration, was a topic that needed to be reviewed for the purposes of Arctic application. As potential operators developed contingency plans, it was essential to develop and have a good understanding of an overall Arctic regional waste management strategy.

<u>Dispersant Pre-Approval Understanding and Process Development</u>: The overall topic of dispersant use in the Beaufort generated considerable discussion among respondents, and it was recognized that work needed to be done before this could be considered a viable response strategy in the Beaufort. Discussion focused on the hurdles of pre-approvals and protocols, understanding existing approval mechanisms, dispersant effectiveness and effects testing on

Arctic cold-water species. Regulators saw the concept of using Net Environmental Benefit Analysis and Habitat Recovery as vitally important in assessing the benefits of dispersants, compared with other options or natural recovery.

One option for furthering understanding and engaging the regulators would be to consider using the Arctic Regional Environmental Emergency Team (AREET) as a forum for discussions and advice on dispersants as a response option. During a response, the purpose of the AREET is to provide the government lead agency with a consolidated compilation of environmental and scientific advice taken from various environmental and resource agencies. The objective of the REET is to minimize damage to sensitive resources and habitats while maximizing the use of limited response resources. The contingency plans of AREET contain a basic framework to ensure that all partners work together efficiently. It was suggested that industry could take the lead in or encourage AREET to investigate and provide advance guidance on the use of dispersants in the Beaufort Sea.

Another potential opportunity for dealing with this issue is through the Beaufort Sea Emergency Preparedness Working Group, chaired by Indian and Northern Affairs Canada.

In-Situ Burning: Along the same lines as dispersants, there was a general lack of clarity as to how in-situ ignition and burning would be implemented for a Beaufort Sea spill. Again, the focus was on clarifying the existing protocols and approval mechanisms, if any actually existed. As well, the issue of burn residue, smoke and particulate effects and impacts were topics that needed to be clearly documented because these were seen as impediments to full acceptance of in-situ burning as a primary response option.

Communications and Education: Another key element that was mentioned consistently was the need for an overarching common spill response (re-)education and communications program with regulators, stakeholders and Inuvialuit. Much has been learned with respect to spill response options, research and effectiveness, both in the previous Beaufort era and subsequent to it, that makes sharing this knowledge crucial to any further success.

The memory of the research, spill history information, technology development and operational implementation is fading and needs to be re-kindled as operations move forward. This is true not only for regulators and northern stakeholders, but also for industry members. Key personnel have either retired or moved on and the steady information flow has now dwindled.

It is important to preserve this current knowledge and continue passing along new knowledge as projects move forward. Informing those engaged in spill response issues and ongoing stakeholder dialogue is critical to successful spill response implementation, particularly with respect to the amount of time elapsed since the previous active drilling operations in the Beaufort. It may even be beneficial to re-state and re-publish accepted knowledge from prior Beaufort Sea research, operations, environmental assessments and other such information to ensure that we do not re-focus on areas that have already been researched. It is essential to make individuals and departments currently engaged in Beaufort Sea spill response aware of what was done in previous operational endeavours.

Adopting a common approach to the sharing of spill response information, including the holding of workshops and information sessions and developing spill response brochures and information briefs, were all mentioned as ways to address this information gap.

Regulatory Jurisdiction and Approach: Another fundamental issue that was frequently mentioned as a potential hurdle was the role of regulatory agencies. It was cited as an issue among regulators in the north and between regulators and industry. Having a clear understanding of how response management would be handled in a major incident was identified as a priority issue. It was suggested that further work be done to clarify how various agencies would work together and how they would advise operators. It was vitally important to understand roles, responsibilities, systems and jurisdictions. Tabletops, workshops and exercises were identified as potential ways to explore this issue further.

Associated with this was the issue of trans-boundary spill response. Regulators identified Alaskan and Canadian spill response requirements and how the two countries would work together should a spill cross into Alaskan waters as an issue that needed further study (NB: Trans-boundary events are addressed in the 2003 Canada-United States Joint Marine Pollution Contingency Plan, Canusnorth Annex, http://www.ccg-gcc.gc.ca/folios/00025/docs/canadaus_pub-eng.pdf).

Other Strategies

Respondents cited some new potential strategies and options that merited further study, including the following:

- Oil Mineral Aggregates (OMA): This potentially effective strategy to enhance dispersion has shown promise in recent trials and should be followed up with additional research;
- Ice Processing Vessels: Recent developments and trials in other Arctic regions might prove to have potential applicability for the Beaufort Sea;

- ARKTOS^{TM} amphibious vehicle adaptations for nearshore response operations; and
- Oil in/under ice detection techniques (Nuclear Magnetic Resonance Imaging application, Airborne Ground Penetrating Radar, etc.).

In addition, other issues were raised that, although not directly categorized as response strategies or tactics, were seen as essential to any further discussion of Beaufort Sea spill response planning efforts. These are discussed below.

<u>Response Standards</u>: Several respondents raised the issue of what constituted adequate equipment and support, and what guidelines were applicable. The issue of response standards, guidelines and best practices was one area that regulators might consider should exploration activity resume. Some suggested investigating existing State of Alaska and Alaska Clean Seas standards, operational documents and best practices, particularly those pertaining to oil-in-ice response. The NEB was focusing on goal-oriented regulation and management systems rather than on prescriptive standards.

<u>Field Tests and Demonstrations</u>: Over the last twenty years, Canada has benefited from extensive field trials held in other Arctic countries. One of the hurdles mentioned by respondents was the need to demonstrate that the proposed response techniques, particularly dispersant use and in-situ burning, were both feasible and operationally sound. Many respondents said that field trials were of utmost importance for new exploration activities, but recognized that there must be some sensitivity to the prevailing mood in Inuvialuit communities about having field trials and demonstrations in the Beaufort Sea. There had been mixed messages both in the previous period of Beaufort exploration and more recently as to how supportive local communities would be to the use of oil in demonstrations and experiments.

Summary and Key Focus Areas

The following summarizes the key messages received during the feedback sessions:

- There was open and honest feedback from respondents, who generally appreciated the opportunity to discuss the issue of spill response;.
- The majority of respondents were in general agreement as to the existing, effective strategies and options for spill response in the Beaufort Sea. They agreed that
    - Mechanical containment and recovery had a place in the Beaufort, but the technique was limited by ice, logistics and applicability.
    - In-situ burning was a well understood response strategy

- Surprisingly, respondents did not reject any particular spill response strategies outright. This was a change from the previous Beaufort Sea era when dispersants were not considered to be a viable option.
- There was some degree of common agreement on strategies warranting further investigation and development. These included the following:
  - A better understanding of dispersant use and the potential for pre-approval; and
  - Using a systems-based approach to study waste management, recognizing that the options that existed in previous years were no longer viable.
- Some common hurdles were identified by the stakeholders, including the following:
  - Lack of infrastructure and changes in logistics since the previous Beaufort Sea era;
  - Need to clearly define the requirements for pre-approvals and approvals for dispersant use and in-situ burning; and
  - Lack of a clear understanding of the regulatory roles and jurisdictions for spill response in the Beaufort Sea.
- Stakeholders seemed to genuinely want to obtain a better understanding of spill response options and to work together to develop effective, practical strategies and guidelines for assisting operators who were considering further exploration in the Beaufort Sea.

Focus Areas and Key Issues for Additional Work

The following summarizes the strategies, options, and issues that need to be further addressed in order to better understand the overall response approach in the coming decade.

- Develop a pre-approval process for dispersant use as a response option.
- Further investigate the issue of waste generated by the response options, including waste handling and disposal (e.g., temporary storage locations in the Yukon and Northwest Territories and offshore and inshore waste processing), using a systems-based approach to review handling, storage and transportation aspects.
- Develop and implement communications plans and education programs relative to oil spill response options that involve regulators, stakeholders and Inuvialuit organizations in a common dialogue and information-sharing opportunities. There is a strong need to consolidate and disseminate the knowledge and findings of the key research carried out since the previous Beaufort era, especially since many of the key people concerned have moved on.
- Recognize the need for and further develop oil spill field demonstrations, trials and tests in the Beaufort Sea in order to determine key response options. This is a common goal that must be included for effective understanding and development of what can be undertaken in the Beaufort Sea. It is vitally important to involve local communities in this effort.

- Investigate the concept of a tiered response mechanism for the Beaufort Sea that involves some form of mutual assistance or a focused co-operative approach.
- Obtain a better understanding of the current regulatory jurisdictions and response frameworks of government departments and regulatory agencies in the event of a major oil spill in the Beaufort Sea. In addition, investigate and clarify the issues associated with a transboundary spill (e.g., spills that cross the Canada/U.S. border, transportation of workers and equipment across borders)
- Continue research into and development of spill response best practices and guidelines.

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Appendix A
Workshop and Discussion of Key Issues

Workshop on Beaufort Sea Oil Spill Countermeasures

A one-day workshop was held in Calgary on October 15, 2009. The main objectives of the workshop were to

- Review draft results of the above-noted study;
- Achieve a consensus on the response capabilities based on current technologies; and
- Identify priority items for further research and consideration.

Specifically, the workshop focused on the following topics with regard to Beaufort Sea exploration and development activities:

- Current effectiveness of oil spill response technology;
- Response capability in the context of potential spills in the Beaufort;
- Environmental effects for a range of potential spills;
- Mitigation measures required to protect key Arctic marine resources; and
- Significant issues raised in previous workshops, hearings and reviews of DPAs and EISs.

Each study team member gave a summary of the key findings of the study, covering the following specific topics:

- Introduction
- Behaviour and Modelling
- Surveillance and Monitoring
- Containment and Recovery
- ISB
- Dispersants and OMA as Dispersing Agent
- Waste Management
- Shoreline
- Case Histories
- Effects and Geo-references
- Contingency Planning
- Present Capabilities
- General Review and Research Recommendations
- Stakeholder Views

This was followed by a presentation by Dr. Ken Lee on recent and planned research activities by DFO.

Lastly, a list of key issues identified by the study team was submitted to the workshop participants for an open discussion. While it was not expected that a consensus would be achieved on any or all of the items, the discussion was intended to identify key points of concern and establish key areas for further work by the various stakeholders. The issues discussed are summarized below, followed by a summary of points raised in the ensuing discussions. A list of workshop participants is provided at the end of the Appendix.

ESRF Beaufort Sea Oil Spill Countermeasures Workshop - Issues for Discussion

1. In-situ burning appears to be a viable and important countermeasure for some situations. Will it be approved? Can it be implemented?

2. Dispersant use appears to be a viable and important countermeasure for some situations. Will it be approved? Can it be implemented?

3. What is the availability of regional and national resources in the event of a spill? (e.g., CCG, MDSRC, WCMRC, ECRC and ACS)

4. Need to clarify regulatory agency jurisdiction during both approval phase and, in the event of a spill, the response phase. Need to understand how the agencies will work together in supporting and working with the responsible party during a major spill response incident (e.g., strategy, tactics and planning; role of lead agency; and role of REET).

5. Associated with the above, it is also necessary to understand the requirements for operators working in the Beaufort with respect to regulator expectations and spill response (e.g., best practices for response strategies).

6. How will a major response be implemented in the absence of logistics and marine infrastructure, as there was in the 1970s and 1980s?

7. Will the Beaufort Sea Oil Spill Co-operative be resurrected in some form?

8. Is there a need for further field experiments in the Beaufort? What is the likelihood of obtaining permits for an experimental spill?

9. How can the knowledge and experience in terms of spill behaviour and countermeasures acquired in the 1970s and 1980s be applied to the currently proposed drilling locations (deeper water, further offshore)?

10. Who will take the lead in investigating waste disposal options?

11. There have been a number of workshops and working groups in recent years, and a fairly well-defined set of R&D priorities has been established (below). How will these following priorities be promoted?
    a. Detecting and tracking oil in ice-covered waters
    b. Fate and behaviour of oil in ice
    c. Modelling of oil spills in ice
    d. Improved mechanical recovery systems
    e. Field testing of in-situ burning, including the use of herders
    f. Dispersant use in Arctic waters and ice

ESRF Beaufort Sea Oil Spill Countermeasures Workshop – Summary of Discussions

1. In-situ burning appears to be a viable and important countermeasure for some situations. Will it be approved? Can it be implemented?

- It was generally agreed that there are, at present, no specific Canadian guidelines regarding in-situ burning (ISB) or regulatory approval.
- The National Energy Board (NEB) is the regulatory agency with the mandate for contingency plan approval. If ISB is to be used, the plan for its use must be included in the emergency response plan filed as part of the Drilling Program Approval (DPA). The NEB will circulate the submission for comment and input from stakeholders, but if the plans for ISB are approved as part of the DPA then its use, as specified in the plan, is approved. The process for consultations at the time of a spill is not well defined.
- Industry considers both ISB and dispersant use to be primary countermeasures for any large spill or worst-case spill scenario.
- Some of the offshore locations currently under consideration (e.g., Ajurak) have much greater water depths and different ice conditions than those considered in the R&D of the 1970s and 1980s. Consequently, surveillance and tracking might be more challenging and the melt-pool burning scenarios might be quite different.
- The Government of Northwest Territories (GNWT) Environmental Protection Act may apply in the Beaufort Sea. Environment Canada also noted that an EC Air Issues Specialist is examining air quality issues associated with mining and petroleum development.
- GNWT deals with these on a case-by-case basis. There are protocols for onshore: the main issues are human health effects and toxicity of particulates.
- The Regional Environmental Emergencies Team (REET) expects to be consulted, although this is not required under legislation. The team will provide comments and advice on a plan or proposed burning operation, but will not approve a plan per se.
- Differences noted between EC and DFO: EC looks at toxicity to single species; DFO looks at risks to ecosystem health under the latest mandate.

2. Dispersant use appears to be a viable and important countermeasure for some situations. Will it be approved? Can it be implemented?

- Again, it was noted that industry considers both ISB and dispersant use to be primary countermeasures for any large spill or worst-case spill scenario.
- Currently, the only regulations governing dispersant use are the Guidelines on the Use and Acceptability of Oil Spill Dispersants (Environment Canada Regulations, Code and Protocols Report EPS 1-EP-84-1, 1984, 2nd edition). REET's position in the planning process was to provide advice, which the spiller could choose to accept or disregard. It was noted that REET should be consulted in the decision-making process, but that there was no regulatory requirement to do so.
- As with ISB, NEB considers this to be an issue that should be handled in the contingency planning process as part of the DPA. If dispersant use is to be included as a response option,

it should be included in the contingency plan, and if the plan is approved, dispersant use is approved implicitly.

- It was suggested that dispersants could be considered to be a "deleterious substance" and therefore prohibited under the Canadian Environmental Protection Act (CEPA) or the Fisheries Act. The consensus was to keep this matter out of the hands of lawyers.
- Several options for dispersant application were discussed. There are no dispersant stockpiles or spraying equipment currently available in Canada, but they could be obtained from OSR (Southampton) and SERVs (Anchorage, AK) within a period of 24 to 48 hours.
- On the question of dispersant products approved for use in Canada: In recent conversations with Environment Canada, the term "approved" is inappropriate. EC has sufficient information to formulate an opinion only on Corexit 9500 and 9527.

3. What is the availability of regional and national resources in the event of a spill? (e.g., CCG, MDSRC, WCMRC, ECRC, and ACS)

- The Canadian Coast Guard (CCG) has a number of depots in the North, but mostly relatively small, inshore equipment. These and other CCG resources nationwide would be available, if required, but the transport times to the Beaufort would be excessive.
- Alaska Clean Seas (ACS) in the Alaskan Beaufort is a possibility, with the following caveats:
    - Much of the ACS equipment is best suited for spill response in shallow, protected nearshore waters; it has few offshore response resources.
    - Only a fraction of available resources might be available (they may have to reserve equipment to satisfy state legislative requirements).
    - Crossing international borders with equipment and labour would be a significant problem that is solvable but requires planning beforehand.
    - Liability issues would also be involved.
    - The ACS Board of Directors would have to approve the loan of any equipment, but this should not pose a problem.
    - Containment and recovery equipment would be difficult to loan (logistics and legislative commitments), but ISB equipment, dispersants and personnel would be much easier.
- Other resources were mentioned briefly: Marine Spill Response Corporation (MSRC), Western Canada Marine Response Corporation (WCMRC), Eastern Canada Response Corporation (ECRC) and Oil Spill Response (OSR).
- Some had the opinion that ECRC could not send equipment because of legislative commitments. A waiver can be granted by Transport Canada, if requested.
- It was noted that Canadian Shipping Act (CSA) standards allow up to three days to mobilize, plus transit time to deploy: this could add up to weeks. Communities do not view moving large volumes of equipment from far away as a credible means of responding to a large spill.

4. **Need to clarify regulatory agency jurisdiction during both the approval phase and, in the event of a spill, the response phase. Need to understand how the agencies will work together in providing support for and working with the responsible party during a major spill response incident (e.g., strategy, tactics and planning; role of lead agency; and role of REET).**

- The NEB's role is clear with respect to the authority over planning and managing a response related to oil exploration and production operations.
- The roles of other agencies (NWT, CCG, INAC, Environment Canada and REETs) need to be clarified and should be addressed in pre-spill planning and exercises.
- The Canada Shipping Act (CSA) requires a Shipboard Oil Pollution Emergency Plan (SOPEP) for activities north of 60°, but does not require an arrangement with a Response Organization (RO), as is required in the south.
- Need to clarify differences between an RO for vessels, as required under the CSA, and an RO for industry, as required by the NEB.
- Look to REET and Beaufort Sea committee chaired by INAC for possible answers.
- Need to clarify the process beforehand during submission and plan development stage.
- Need to understand how government agencies will work with the operator during a major spill incident. Will there be a Unified Command through the Incident Command System?
- Consider involving agencies in communications exercises, tabletop exercises and demonstrations prior to operations.
- Use REET to understand how agencies work together.
- Need to clarify role of Lead Agency concept: NEB and how other agencies will work with NEB to advise, consult and review.

5. **Associated with the above, it is also necessary to understand the requirements for operators working in the Beaufort with respect to regulator expectations and spill response (e.g., best practices for response strategies)**

- It was noted that there are no established standards or guidelines for contingency planning, but the expectation by industry and the regulator is that a reasonable plan will include a dedicated Tier 1 response capability, with Tiers 2 and 3 sourced from national and international arrangements.
- Industry has made clear that dispersants and ISB will be considered primary response options.
- Need to follow up on question of "regulator expectations."

6. **How will a major response be implemented in the absence of logistics and marine infrastructure, as there was in the 1970s and 1980s?**

- It was noted that plans for upcoming drilling programs will include very limited infrastructure offshore and onshore (at Tuktoyaktuk), compared with the situation in the 1970s and 1980s.
- Offshore response options must be developed with this in mind. For example, offshore dispersant spraying operations can be carried out using outside resources (e.g., Oil Spill Response [OSR] from Southampton) and using only limited logistical support in the region.
- During a worst-case spill, the offshore drill ship may not be available to support a significant spill response. Consideration being given to use of a "warship" to support drilling operations: may be stationed in the offshore during the drilling season and might be available for use as an offshore base for operations, such as dispersants and ISB.

7. **Will the Beaufort Sea Oil Spill Co-operative be resurrected in some form?**

- This may be an expectation of local interests, but may not have much justification on purely technical grounds.
- Local communities will likely expect a co-op in some form because there was one before, and would expect equipment, personnel and training facilities.
- Industry needs to inform and educate stakeholders on what spill response and infrastructure will look like in the Beaufort in 2011 and beyond.

8. **Is there a need for further field experiments in the Beaufort? What is the likelihood of obtaining permits for an experimental spill?**

- Acquiring a permit will be a significant hurdle (application to Regional Ocean Dumping Advisory Committee [RODAC]).
- Community approval will be crucial. Need to identify those to be consulted: CWS, CEAA, Communities, EC, IGC, Hunters and Trappers.
- After the 1986 dispersant experiment (Swiss and Vanderkooy, 1988), some local people said, "no more". More recently, it appears that leaders may be neutral or in favour of a new round of testing. The Inuvialuit Game Council (IGC) has not said yes, nor has it said no.
- Inuvialuit are knowledgeable and well aware of research and the need to have industry and government provide a summary of Arctic research and how much has been gained. Experiments and/or demonstrations may be required to establish that a credible capability exists.
- Communities will want to see field demonstrations, not tank trials.
- Need to include shoreline experimental spills as part of the mix, often left out for no good reason. High priority to test and validate response techniques for dealing with oil on Arctic shorelines.

- Need a program of experimental spills in ice to study effectiveness of dispersants and oil-mineral aggregation and fate of treated oil in ice. DFO expressed confidence that permits could be obtained: hoping to do spill in 2011 with focus on dispersion.
- It was noted that, after hosting the most recent three major field trials involving experimental spills, Norway is resisting additional field trials in its waters in the immediate future.
- Clear distinction between trial spills conducted for purposes of filling specific knowledge gaps related to spill response versus field trials conducted to demonstrate either spill behaviour or effectiveness of cleanup. He pointed out that outcomes of field trials were seldom predictable in specific terms. As such, proponents might not see much benefit from a field trial conducted as a demonstration because of the potential negative impacts of failure.
- DFO was implementing a communications plan to inform communities of the need for field experiments.
- Need to gauge interest and build upon Joint Industry Project approach successfully used in Norway.

9. How can the knowledge and experience in terms of spill behaviour and countermeasures acquired in the 1970s and 1980s be applied to the currently proposed drilling locations (deeper water, further offshore)?

- Some of the offshore locations currently under consideration (e.g., Ajurak) have much greater water depths and different ice conditions than those considered in the R&D of the 1970s and 1980s. Consequently, surveillance and tracking might be more challenging and the melt-pool burning scenarios might be quite different. Devenis pointed out that ice-tracking buoys were to be deployed this winter to gather information on the movement of ice leaving the Ajurak site.
- Recognized knowledge gap with respect to oil migration through second-year ice.
- Need to understand the relative concentrations of second-year and multi-year ice at the proposed sites.
- Need to understand plume dynamics in deeper waters.
- The offshore locations currently under consideration (100+ kilometres from shore in 600 m of water) have implications for decision-making regarding dispersants and ISB, compared with the situation in the 1970s and 1980s. In the earlier situation, smoke from burning spills could conceivably reach a settlement, posing health risks, and dispersed oil from a dispersant-based response could produce clouds of dispersed oil in shallow, nearshore waters.

10. Who will take the lead in investigating waste disposal options?

- The regulatory landscape has changed since the 1980s: Inuvialuit Land Administration (ILA) and Environment Canada now have new processes and permitting procedures.
- Industry should work with ILA, GNWT and Environment Canada to understand available options.

- Suggest encouraging local business opportunities for waste disposal.
- Lack of infrastructure and logistics complicates the problem and there are no simple solutions. Need to consider waste minimization in response plans and operations: dispersants and ISB offshore reduce waste and prevent shoreline oiling; in-situ treatments on shorelines.

11. There have been a number of workshops and working groups in recent years, and a fairly well-defined set of R&D priorities has been established (below). How will these following priorities be promoted**?**

Specific issues:

Detecting and tracking oil in ice-covered waters

Issue of multi-year ice at the Ajurak site

Fate and behaviour of oil in ice

Fate and behaviour of oil under multi-year ice during breakup

Modelling of oil spills in ice

Modelling of oil in ice is still primitive.

Improved mechanical recovery systems

Several approaches have been used. Most involve some form of cleaning oil off ice blocks. Each has shown some success, but the approach is limited to small areas because of low encounter rate.

Field testing of in-situ burning, including the use of herders

Dispersant use in Arctic waters and ice

Some experiments have been conducted in this area in tanks and at sea. Dispersant have shown some effectiveness on oil in ice, both with and without addition of mixing energy using prop wash.

Coastal mapping

Need to remap the shoreline to check changes from 15 years ago. Expect significant shift in outer Delta area, for example. The Geological Survey of Canada (GSC) is currently doing remapping.

Wave climate

Need to assess changes in wave climate resulting from changes in ice cover (IOL recently put out six wave buoys to monitor summer wave climate.)

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Potential funding sources:

- ESRF: oil-under-ice detection; two projects funded in 2010
- Program on Energy Research and Development (PERD)

- Current project by IPIECA/API: summary of Arctic R&D

12. Re-education and Communications

- It is critically important that new initiatives in regard to this issue be implemented. Communications materials should include differences in scale of the proposed developments (compared with the 1970s and 1980s) as well as differences in scale of the infrastructure.

13. Environmental operating conditions are changing as the ice conditions change

- As the extent and amount of sea ice decreases in the summer season, its dampening effect on waves is reduced. As a result, nearshore wave conditions are more severe than in the 1970s and 1980s. Shorelines are also changing as a result of increased exposure and wave energy. There is a need to remap the shoreline and gather new data on current wind/wave conditions in nearshore areas.

14. How clean is clean?

- The topic of cleanup endpoints was covered in the shoreline cleanup presentation.
- The selection of endpoints for cleanup must take into account the question of waste disposal.

ESRF Beaufort Sea Oil Spill Countermeasures Workshop – List of Participants

Evan Birchard	Imperial Oil Resources
David Tilden	Environment Canada
Ian Denness	ConocoPhillips
Linda Graf	ConocoPhillips
George McCormick	Indian and Northern Affairs Canada (INAC)
Dave Kerr	Environmental Studies Research Funds (ESRF)
Norm Snow	Inuvialuit Joint Secretariat
Robert LeMay	National Energy Board
Chantal Guenette	Canadian Coast Guard (CCG)
Allen Williams	Transport Canada
Ken Lee	Fisheries and Oceans Canada (DFO)
Mike Peters	Canadian Association of Petroleum Producers (CAPP)
Lynn Huntley	BP
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Jennifer Wyatt	Chevron
Ed Owens	Polaris Applied Sciences
Heidi Mairs	ExxonMobil
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Study Team

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Dave Dickins	DF Dickins & Associates
Peter Devenis	Envision – Planning Solutions

Appendix B
Geographic Databases of Coastal Resources, Vulnerabilities and Sensitivities

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
Libraries					
Inuvialuit Settlement Region Database: 10,000 publications and research projects		Joint Secretariat	http://www.aina.ucalgary.ca/isr/	MapOfSettlement Region	
Arctic Science and Technology Information System		Arctic Institute of North America	http://www.aina.ucalgary.ca/astis/		
Gov't/Industry Initiatives/Overviews					
Arctic Environment Sensitivity Atlas		Environment Canada		Power Point description	Overview of contents of AESAS Arctic Atlas
Beaufort Sea Research Priorities – Inuvialuit Settlement Region			Beaufort Sea Research Priorities Relevant Research in the Inuvialuit Settlement Region		Ongoing research program descriptions
Development of a Decision Support Tool for Resource Management in Support of a Strategic Environmental Assessment for the Canadian Beaufort Sea	Gartner Lee Limited	Report prepared for DIAND	http://pubs.aina.ucalgary.ca/misc/66070.pdf DIAND Web site with summary maps http://www.ainc-inac.gc.ca/nth/og/rm/ri/bsm/bsm08/index-eng.asp#chp4	DIANDSupportTool2008	2008 VECs: polar bear ringed seal beluga whales migratory birds
Beaufort Sea Large Ocean Management Area:	D. Cobb, H. Fast, M.H. Papst, D.	Central and Arctic Region Freshwater	http://www.beaufortseapartnership.ca/documents/EOAR2008March.pdf	LOMAoverview2008	2008 has maps

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
Ecosystem Overview and Assessment Report	Rosenberg, R. Rutherford and J.E. Sareault	Institute			
On Thin Ice: A Synthesis of the Canadian Arctic Shelf Exchange Study (CASES)	Fortier, L. Barber, D. Michaud, J.	The Canadian Arctic Shelf Exchange Study (CASES)		onThinIceABS	2008 abstract of report contents
Marine Ecosystem Overview of the Beaufort Sea Large Ocean Management AREA (LOMA)	North/South Consultants Inc	Report prepared for DFO	http://www.dfo-mpo.gc.ca/Library/320674.pdf	DFOecosystemOverview2005	2005 primarily tabular records 2 maps
Technical Assessment: Proposed Beaufort Sea Marine Protected Area		Prepared for DFO	http://www.dfo-mpo.gc.ca/Library/319221.pdf	bsProtectedAreaAssessment	2002 maps of proposed protected areas
Traditional Knowledge					
Integrating Science and Traditional Knowledge in the Inuvialuit Settlement Region: Perspectives from a Beluga Community- Based Monitoring Program	Nasogaluak, S., Loseto, L.L., Pokiak, N.			ScienceAndTraditionalKnowledge	2008 abstract only from 2008 Arctic Change Conference
Inuvialuit Settlement Region Traditional Knowledge Report	Inuvik Community Corporation, Tuktuuy-aqtuuq Community		http://www.ngps.nt.ca/Upload/Letters%20of%20Comment/Inuvik%20Community%20Corporation/ICC-ISR_TK_Study/070402_ICC-ISR_TK_Study_FINAL%20_Aug18-06-1.pdf	Report1 Report2	2006 includes mapping

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
	Corporation, Akłarvik Community Corporation				
Fisheries Joint Management Committee Annual Report, 2006−2007				FJMC2006	2006−2007 abstract only One of a series of yearly reports
Inuvialuit Harvest Study 1988−1997		Joint Secretariat	http://www.jointsecretariat.ca/pdf/js/IHS10yrDataMethodsReport.pdf	Methods and Data Report	2003 primarily tabular reports
Community Conservation Plans			http://www.screeningcommittee.ca/resources/reports.html		
Community-Based Monitoring			http://www.taiga.net/coop/community/index.html		
Physical Environment					
Arctic Environment Sensitivity Atlas		Environment Canada		Power Point description	Overview of contents of AESAS Arctic Atlas
Environmental Atlas of the Beaufort Coastlines		Geological Survey of Canada	http://gsc.nrcan.gc.ca/beaufort/index_e.php	Environmental, Vegetation, Wildlife, Terrain, Coastal Processes, Coastlands Surficial Maps	Good online overview of features identified to the left; detailed coastal surficial mapping
Mackenzie Mapping Program for Northern Oil &	Jesse Jasper et al.	Various Gov't, Native and Industry	http://www.bsstrpa.ca/pdf/nogr/dem_obrien.pdf	DEM_obrienPDF	NOGR Workshop PowerPoint overview of

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
Gas Development					activities primarily for the Mackenzie Valley, but includes Delta
Underwater Mapping in the Beaufort Sea	Travaglini, P.	Canadian Hydrographic Service		underWaterMappingABS	2007 abstract Nearshore data would be useful for spill response logistics
Climate					
Nearshore Beaufort Sea Meteorological Monitoring and Data Synthesis Report	B. Veltkamp, J.R. Wilson	Hoefler Consulting for MMS Alaska	Primarily U.S. Beaufort Sea data Komakuk Beach data included	MetDataUSBeaufortSea	2007 Komakuk Beach data included
Ice					
Annual Arctic Ice Atlas, International Polar Year, 2007−2008		Canadian Ice Service		AnnualArcticIceAtlas20072008Abs	2008 Abstract
Multi-Year Sea-Ice Conditions in the Western Canadian Arctic Archipelago Region of the Northwest Passage: 1968−2006	Howell, S.E.L., Tivy, A., Yackel, J.J., McCourt, S.	University of Calgary and Canadian Ice Service	http://cmos.metapress.com/content/673jq1g511531r4j/		2008
Spatial and Temporal Variability of Sea Ice in the Southern Beaufort Sea and Amundsen Gulf:	Galley, R.J. Key, E. Barber, D.G. Hwang, B.J., Ehn, J.K.	Canadian Ice Service		seaIceVariabilityAbst	2008 abstract with link to journal article

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
1980−2004					
Mapping of Spring Leads and Landfast Ice in Beaufort and Chukchi Seas	H. Eicken et al.	Geophysical Institute, U of Alaska Fairbanks	The study area extended from the eastern Chukchi Sea, southwest of Barrow to Wainwright, Alaska across the Beaufort Sea to the Canadian Mackenzie River Delta System, with the northern boundary at roughly 74°N (qualitative analysis of lead patterns included areas extending into the Canada Basin and the High Canadian Arctic as well).	IceLeadMappingEicken2005	2005
Oceanography					
Seasonal Circulation over the Canadian Beaufort Shelf	Ingram, R.G., W.J. Williams, B. van Hardenberg, J.T. Dawe, E.C. Carmack, E.C.	Canadian Arctic Exchange Study		seasonalCircAbs	2008 abstract only data would be useful in spill behaviour modelling
Oceanography of the Canadian Shelf of the Beaufort Sea: A Setting for Marine Life	Carmack & MacDonald	Institute of Ocean Sciences	http://pubs.aina.ucalgary.ca/arctic/Arctic55-S-29.pdf	Beaufort Oceanography	2001 useful data for spill behaviour prediction
Wildlife					
Observations	Harwood, L.A.	Fisheries and Oceans	http://www.springerlink.com/content/w7rb5bm8v8racj4u/	fieldObservation2005	2002 field program Wildlife sightings from this work could be used to validate/update existing mapping
Key Habitat Sites	Paul Latour	Env Can Canadian Wildlife Service	http://www.pnr-rpn.ec.gc.ca/nature/ecb/da02s09.en.html		Web site that identifies ongoing work in this area

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
		(CWS)			by CWS
Polar Bear					
Ongoing Field Projects: Polar Bears	Ian Stirling	Canadian Wildlife Service (CWS)	www.mb.ec.gc.ca/nature/ecb/da02s14.en.html	Movements	abstract only describes ongoing work
Population assessment of polar bears in the Beaufort Sea and Amundsen Gulf	Ian Stirling	Canadian Wildlife Service (CWS)		PopAssessPolarBearAbs	2006 abstract ongoing research description
Unusual Predation by Polar Bears in the Beaufort Sea	Ian Stirling	Canadian Wildlife Service (CWS)	http://pubs.aina.ucalgary.ca/arctic/Arctic61-1-14.pdf	BearPredationStirling2008	2008 Arctic article
Assessment of Possible Impacts of Oil and Gas Activities on Polar Bears in the Outer Mackenzie Delta and Nearshore Areas of the Southern Beaufort Sea	Ian Stirling	Canadian Wildlife Service (CWS)	http://www.bsstrpa.ca/pdf/nogr/polarbears_nunn.pdf	PolarBears2005	2005 PowerPoint with overview mapping
Polar Bears and Seals in Eastern Beaufort Sea	Ian Stirling	Canadian Wildlife Service (CWS)	http://pubs.aina.ucalgary.ca/arctic/Arctic55-S-59.pdf	BearsSealsEasternBSStirling2002	2002 Arctic article
Devon Canada Corporation – Marine Mammals Study for the Beaufort Sea	Evans, K	Kavik-Axys		DevonMarineMammalSurvey	2002 abstract
Habitat Preferences of Polar Bears in the Western Canadian	Stirling, I. Andriashek, D. Calvert, W.	Canadian Wildlife Service (CWS)		polarBearWinterSpringHabitat	1993 abstract data from 1971

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
Arctic in Late Winter and SPRING					through 1979
Seals					
Assessing the Potential Effects of Near Shore Hydrocarbon Exploration on Ringed and Bearded Seals in the Beaufort Sea Region, 2006	Thomas Smith and Lois Harwood	ECO Marine Corp DFO Yellowknife	http://www.bsstrpa.ca/pdf/bsstrpa/Smith%20and%20Harwood%20beaufort%20seals%202006%20progress%20report%20FINAL.pdf http://www.esrfunds.org/documents/ESRF162_000.pdf	HydrocarbonEffectsonSealsHarwood2007	2007 Web links to progress and final reports Document link to final report
Potential Effects of Hydrocarbon Development on Near-Shore BS Seals	Lois Harwood	DFO Yellowknife	http://www.bsstrpa.ca/pdf/nogr/sealeffects_harwood.pdf		2005 NOGR Workshop PowerPoint overview of activities
Beluga Whale (*Delphinapterus leucas*), Bowhead Whale (*Balaena mysticetus*) and Ringed Seal (*Phoca hispida*) in Southeastern Beaufort Sea	Pooi-Leng Wong			marineMammals1998.pdf	1998
Distribution of Ringed Seals in the Southeastern Beaufort Sea During Late Summer	L. Harwood, I. Stirling	CWS University of Alberta		RingedSealDist1992	1992

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
Whales					
Habitat Use by Different Size Classes of Bowhead Whales in the Central Beaufort Sea During Late Summer and Autumn	Koski, W.R. Miller, G.W.			bowheadJournalArticle bowheadWhaleHabitatUseAbs	2009 abstract
Early Migration Of Beluga (*Delphinapterus leucas*) into the Amundsen Gulf in the Spring of 2008	Asselin, N.C., Richard, P.R., Barber, D.G., and Ferguson, S.H.			earlyMigrationBelugaAbs	2008 abstract with link to 2008 Arctic Change Conference article
Status of Knowledge of Killer Whales (*Orcinus orca*) in the Canadian Arctic	Jeff Higdon	DFO	http://www.dfo-mpo.gc.ca/csas/Csas/DocREC/2007/RES2007_048_e.pdf	KillerWhalesArctic2007	2007
Beluga Tagging	Lisa Loseto	DFO	http://www.bsstrpa.ca/pdf/nogr/beluga_loseto.pdf		NOGR Workshop PowerPoint overview of activities
Whales of the Inuvialuit Settlement Region in Canada's Western Arctic: An Overview and Outlook	Lois A. Harwood and Thomas G. Smith	DFO, Eco Marine Inc	http://pubs.aina.ucalgary.ca/arctic/Arctic55-S-77.pdf	WhalesInuvialuit2002	2002
Beaufort Sea Beluga Management Plan	Fisheries Joint Management Committee		http://www.fjmc.ca/publications/Beluga%20Management%20Plan%20%28%202001%29as%20printed%20with%20covers.pdf	BelugaManagement2001	2001
Belugas and Narwhals: Application of New	Randall R. Reeves, David	Cetacean Specialist	http://pubs.aina.ucalgary.ca/arctic/Arctic54-3-iii.pdf	BelugaNarwhal2001	2001

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
Technology to Whale Science in the Arctic	J. St. Aubin	Group, Mystic aquarium			
Summer and Autumn Movements of Belugas of the Eastern BS Stock	P.R. Richard	DFO		BelugaRichard2001	2001
Cetacean Habitat Selection in the Alaskan Arctic during Summer and Autumn	Sue E. Moore, Douglas P. Demaster and Paul K. Dayton		http://pubs.aina.ucalgary.ca/arctic/Arctic53-4-432.pdf	WhaleHabitatSelection2000	2000
Satellite-Monitored Movements of Radio-Tagged Bowhead Whales in the Beaufort and Chukchi Seas During the Late-Summer Feeding Season and Fall Migration	Bruce R. Mate, Gregory K. Krutzikowsky and Martha H. Winsor		http://rparticle.web-p.cisti.nrc.ca/rparticle/AbstractTemplateServlet?journal=cjz&volume=78&year=2000&issue=78&msno=z00-045&calyLang=eng	BowheadTracking2000	2000 reference 1992 survey data
Aerial Survey	Harwood & Norton	Dept. Fisheries & Oceans (DFO)	http://www.dfo-mpo.gc.ca/Library/194125.pdf	mackenzieEstuary	1996
Distribution and Abundance Of Beluga Whales in the Mackenzie Estuary, Southeast Beaufort Sea, and West Amundsen Gulf during late July 1992	Harwood, L.A., Innes, S., Norton, P. and Kingsley, M.C.S.			BelugasMackenzieEstuary1996	1992 abstract
Estimates of Bowhead Whale (*Balaena mysticetus*) Numbers	Moore & Clarke	SAIC	http://pubs.aina.ucalgary.ca/arctic/Arctic44-1-43.pdf	BowHead1991	1991

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
in the Beaufort Sea during Late Summer					
Summer Distribution of Bowhead Whales, *Balaena rnysticetus*, Relative to Oil Industry Activities in the Canadian Beaufort Sea, 1980−1984	W. John Richardson, Rolph A. Davis, C. Robert Evans, Donald K. Ljungblad, and Pamela Norton	various	http://pubs.aina.ucalgary.ca/arctic/Arctic40-2-93.pdf	BowheadSummer1987	1980 to 1984 survey results
Birds					
Shorebirds	Vicky Johnston	CWS	http://www.pnr-rpn.ec.gc.ca/nature/ecb/da02s20.en.html http://www.pnr-rpn.ec.gc.ca/nature/migratorybirds/sb/dc31s02.en.html	cwsArcticShorebirdProjects	Abstracts of ongoing work at CWS
Sea Ducks	Lynne Dickson	CWS	http://www.pnr-rpn.ec.gc.ca/nature/ecb/da02s19.en.html	Corridors	Abstract only Describes ongoing research
Geese and Swans			http://www.pnr-rpn.ec.gc.ca/nature/ecb/da02s07.en.html	GeeseAndSwans	Abstract only Describes ongoing research
Key Migratory bird Terrestrial Habitat Sites in the Northwest Territories and Nunavut	Paul Latour et al.	Canadian Wildlife Service (CWS)	http://www.ngps.nt.ca/Upload/Interveners/Environment%20Canada/key_terrestrial_part1_mar06.pdf http://www.ngps.nt.ca/Upload/Interveners/Environment%20Canada/key_terrestrial_part2_mar06.pdf	MigBirdSitesA MigBirdSitesB	2006 Web and document links to bird habitat mapping

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
Migratory Birds	Schultz & Hazell	Ecovision	http://www.naturecanada.org/pdf/Mackenzie%20Gas%20Project%20and%20IBAs%20-%20Final%20Report.pdf	mackenzieGasMigratory	2005 primarily Mackenzie River + delta
Key Marine Habitat Sites for Migratory Birds in Nunavut and the Northwest Territories	Mark L. Mallory, Alain J. Fontaine	Canadian Wildlife Service (CWS)	http://www.cws-scf.ec.gc.ca/publications/papers/109/op109_e.pdf	MarineBirdHabitat	2004, mostly Eastern/Central Arctic data pages 51-52; refer to B. Sea data
Status of Marine Birds of the southeastern Beaufort Sea	Dickson, D.L. Gilchrist, H.G.			marineBirdStatusBS	2002
Marine Bird Study of the Environmental Studies Program for the Proposed Beaufort Sea Offshore Drilling Program (Devon Canada Corporation)	Evans, K.	Kavik-Axys for Devon Petroleum		devonMarineBirdSurvey	2002 abstract
Radar Observations of Arctic Bird Migration at the Northwest Passage, Canada	Gudmundur A. Gudmundsson, Thomas Alerstam, Martin Green and Anders Hedenström	Iceland, Sweden	http://pubs.aina.ucalgary.ca/arctic/Arctic55-1-21.pdf	radarObsBirdMigration	2002 NW passage extent that includes Beaufort Sea
Status of Waterfowl in the Inuvialuit Settlement Region		CWS		Waterfowl in the Inuvialuit Settlement Region1999.doc	1999 abstract describing work
King and Common	Dickson, D.L.			EidersArctic1997	1997

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
Eiders of the western Canadian Arctic					abstract
Spring Migration of Waterbirds in the Beaufort Sea, Amundsen Gulf and Lambert Channel Polynya, 1992	Alexander, S.A., Westover, S.E. and Dickson, D.L.	CWS		SpringMigration1993	1993 abstract only
Key Areas for Birds in Coastal Regions of the Canadian Beaufort Sea	Alexander, S.A., Barry, T.W., Dickson, D.L., Prus, H.D. and Smyth, K.E.	CWS		keyBirdAreasBS	1988 abstract only
Fish					
Detection of Winter Aggregations of Cod in Franklin Bay Beaufort Sea	D. Benoit, Yvan Simard, Louis Fortier	U. of Laval, U. of Quebec, DFO		CodAggregationFranklinBayBenoit2008	2008
Cisco in the Colville River: U.S. Beaufort Sea	various	Various for MMS Alaska		CiscoColvilleRiver	2007 Primarily a U.S. BS study Significant only in its description of Cisco life history with all stock originating in Mackenzie River
Harvest Studies in the Inuvialuit Settlement	Stephenson	Fisheries and Oceans Canada,	http://www.dfo-mpo.gc.ca/Library/284031.pdf	FishHarvetStudyInuvialuit	2004

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
Region, Northwest Territories, Canada: 1999 and 2001−2003					
Fish Catch Data Mackenzie River Estuary	A.R. Majewski and J.D. Reist	Fisheries and Oceans Canada	www.dfo-mpo.gc.ca/Library/326236.pdf	FishCatchDataMajewski2006	2004 tabular by geo-referenced location
Long-Distance Migrations by Inconnu (*Stenodus leucichthys*) in the Mackenzie River System	S.A. Stephenson, Jeff A. Burrows and John A. Babaluk	DFO and BC Ministry of Water	http://pubs.aina.ucalgary.ca/arctic/Arctic58-1-21.pdf	InconnuMigration2004	2004 primarily inland water migration
Larval and Post-Larval Fish Data from the Canadian Beaufort Sea Shelf, July to September 1985	D.B. Chiperzak	Central and Arctic Region Fisheries and Oceans Canada	http://www.dfo-mpo.gc.ca/Library/278176.pdf	LarvalFishDataChiperzak2003	2003 tabular by geo-referenced location
Devon Canada Corporation − Fish, Plankton and Benthic Communities Study for the Proposed Beaufort Sea Offshore Drilling Program Within the Inuvialuit Settlement Region	Kevin Evans	Kavik-AXYS Inc. for Devon		DevonFishPlusSurvey2002	2002 abstract only data described would be useful addition to AESAS
Fisheries Investigations in Coastal Waters of Liverpool Bay, Northwest Territories	W.A. Bond, R.N. Erickson	Fisheries and Oceans Canada		ArcticCiscoLiverpoolBayNWTBond1993	1993

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
Distribution of Fish and Fish Habitat in the Nearshore Beaufort Sea and Mackenzie Delta during Ice-Covered Periods (October–June)	A.D. Sekerak et al.	LGL report for ESRF	http://pubs.aina.ucalgary.ca/misc/40788.pdf	FishDistrESRF1993	1992
Fish Catch Data from the Landfast dl; Ice of the Mackenzie River Estuary, March 1985, and May 1986, 1987	D.B. Chiperzak, G.E. Hopky and M.J. Lawrence	Dept of Fisheries and Oceans	http://www.dfo-mpo.gc.ca/Library/123688.pdf	fishCatchDataLandfastIce1991.pdf	1985,1986,1987 data report out in 1991
Fishes, Invertebrates and Marine Plants: The Beaufort Sea and the Search for Oil	Percy, R., Smiley, B., Mullen, T. and Childerhose, R.J.	DFO		FishOverview1985	1985 abstract
Phytoplankton/ Benthos					
Circulation and Ecological Model	John Walsh et al.	Many international authors	A coupled, three-dimensional circulation and ecological model provided numerical analysis of daily carbon/nitrogen cycling by the planktonic and benthic components of western Arctic shelf/basin ecosystems during 2002 (primarily U.S. waters).	CirculationEcologyModelWalsh2005	2005 regional model
Dynamics of Sea Ice and Phytoplankton Abundance	K.R. Arrigo and G.L. Van Dijken	Dept of Geophysics, Stanford Univ.		SeaIcePhytoplanktonArrigo2004	2004
NOGAP B2; Data on the Meio- and Macrobenthos, and Related Bottom	G.E. Hopky, M.J. Lawrence and D.B. Chiperzak	Department of Fisheries and Oceans	http://www.dfo-mpo.gc.ca/Library/181430.pdf	BenthosHopky1994	1994

Data Description / Report Title	Authors	Author Affiliation	Web Links (www)	Document Links	Publication Date/ Comments
Sediment from Tuktoyaktuk Harbour and Mason Bay, NWT, March 1985 to 1988					

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Canadian Ice Service, 2008. Annual Arctic Ice Atlas. International Polar Year, 2007-2008: Winter 2008.

Canadian Wildlife Service, 2009. Web site describing current research activities in the Northwest Territories and Nunavut, http://www.pnr-rpn.ec.gc.ca/nature/ecb/index.en.html.

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Appendix C
List of Stakeholders Contacted

List of Stakeholders Contacted

Company/Organization	Name
BP	Cynthia Pyc
BP	Ed Thompson
BP	Dave Fritz
CAPP (Canadian Association of Petroleum Producers)	Mike Peters*
Chevron	Jennifer Wyatt
Chevron	Bill Scott
ConocoPhillips Canada	Ian Denness
Imperial Oil Resources	Evan Birchard
MGM Energy	Ed Kustan*
Shell	Geoff Merrell

Environment Canada	David Tilden
INAC	George McCormick
Coast Guard	Chantal Guenette
DFO	Ken Lee
DFO	Larry Trigatti
NEB	Robert LeMay
NEB	John Korec
Transport Canada	Craig Miller**

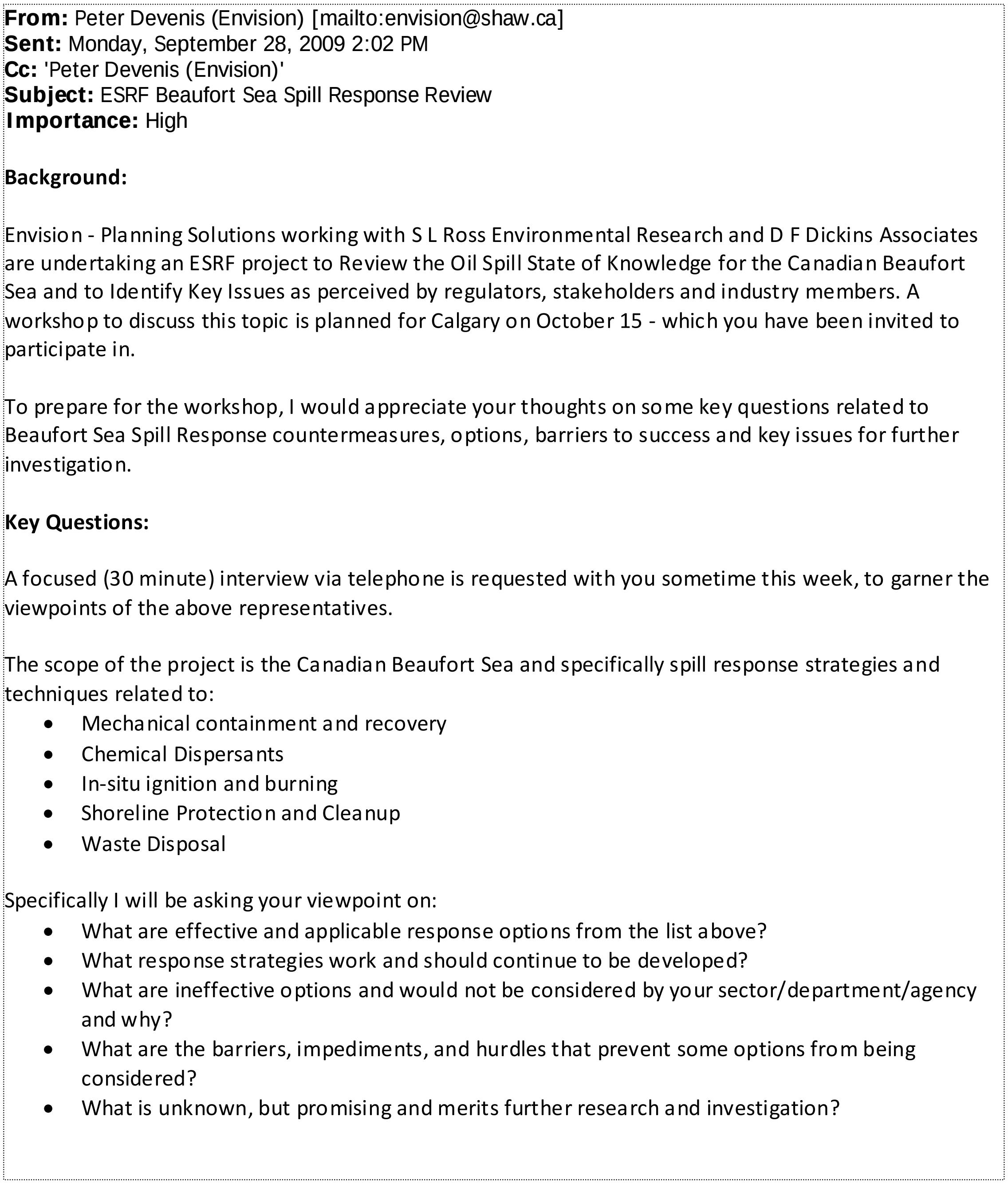
Inuvialuit Joint Secretariat	Norm Snow
IGC	Frank Pokiak**

*Indicates no formal feedback provided

**Contacted after workshop for completeness of review

Appendix D
Beaufort Sea Spill Response Sample Email

Beaufort Sea Spill Response Sample Email



From: Peter Devenis (Envision) [mailto:envision@shaw.ca]
Sent: Monday, September 28, 2009 2:02 PM
Cc: 'Peter Devenis (Envision)'
Subject: ESRF Beaufort Sea Spill Response Review
Importance: High

Background:

Envision - Planning Solutions working with S L Ross Environmental Research and D F Dickins Associates are undertaking an ESRF project to Review the Oil Spill State of Knowledge for the Canadian Beaufort Sea and to Identify Key Issues as perceived by regulators, stakeholders and industry members. A workshop to discuss this topic is planned for Calgary on October 15 - which you have been invited to participate in.

To prepare for the workshop, I would appreciate your thoughts on some key questions related to Beaufort Sea Spill Response countermeasures, options, barriers to success and key issues for further investigation.

Key Questions:

A focused (30 minute) interview via telephone is requested with you sometime this week, to garner the viewpoints of the above representatives.

The scope of the project is the Canadian Beaufort Sea and specifically spill response strategies and techniques related to:

- Mechanical containment and recovery
- Chemical Dispersants
- In-situ ignition and burning
- Shoreline Protection and Cleanup
- Waste Disposal

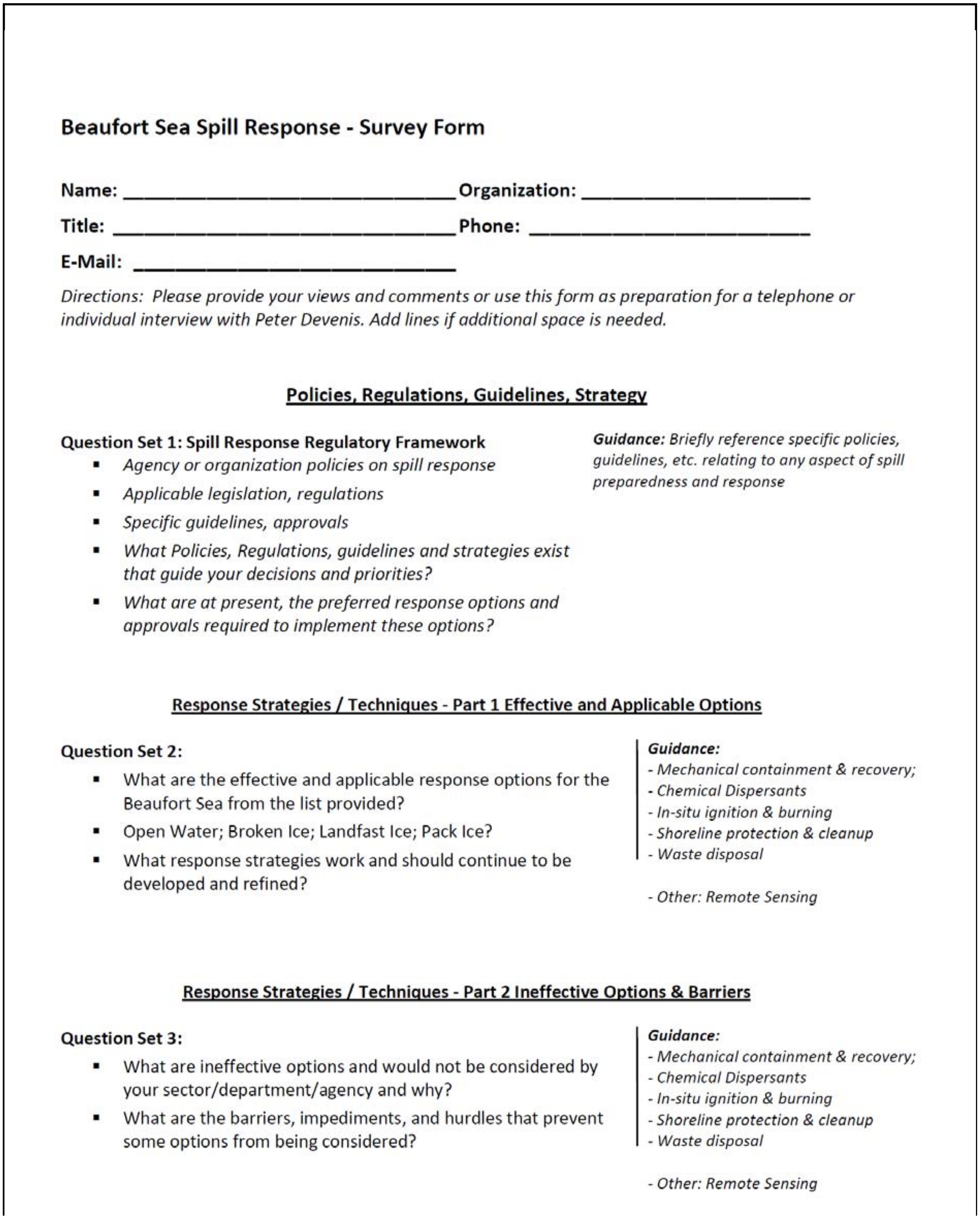
Specifically I will be asking your viewpoint on:

- What are effective and applicable response options from the list above?
- What response strategies work and should continue to be developed?
- What are ineffective options and would not be considered by your sector/department/agency and why?
- What are the barriers, impediments, and hurdles that prevent some options from being considered?
- What is unknown, but promising and merits further research and investigation?

Appendix E
Beaufort Sea Spill Response Survey Form

Beaufort Sea Spill Response Survey Form

The following are excerpts from the individual interview survey form that was used to focus discussion with stakeholders.



Beaufort Sea Spill Response - Survey Form

Name: ______________________________ **Organization:** ____________________

Title: ______________________________ **Phone:** ________________________

E-Mail: ______________________________

Directions: Please provide your views and comments or use this form as preparation for a telephone or individual interview with Peter Devenis. Add lines if additional space is needed.

Policies, Regulations, Guidelines, Strategy

Question Set 1: Spill Response Regulatory Framework

- *Agency or organization policies on spill response*
- *Applicable legislation, regulations*
- *Specific guidelines, approvals*
- *What Policies, Regulations, guidelines and strategies exist that guide your decisions and priorities?*
- *What are at present, the preferred response options and approvals required to implement these options?*

Guidance: *Briefly reference specific policies, guidelines, etc. relating to any aspect of spill preparedness and response*

Response Strategies / Techniques - Part 1 Effective and Applicable Options

Question Set 2:

- What are the effective and applicable response options for the Beaufort Sea from the list provided?
- Open Water; Broken Ice; Landfast Ice; Pack Ice?
- What response strategies work and should continue to be developed and refined?

Guidance:
- Mechanical containment & recovery;
- Chemical Dispersants
- In-situ ignition & burning
- Shoreline protection & cleanup
- Waste disposal

- Other: Remote Sensing

Response Strategies / Techniques - Part 2 Ineffective Options & Barriers

Question Set 3:

- What are ineffective options and would not be considered by your sector/department/agency and why?
- What are the barriers, impediments, and hurdles that prevent some options from being considered?

Guidance:
- Mechanical containment & recovery;
- Chemical Dispersants
- In-situ ignition & burning
- Shoreline protection & cleanup
- Waste disposal

- Other: Remote Sensing