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Advances in Ice Management for Deepwater Drilling in the Beaufort Sea

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ABSTRACT

Recently awarded Canadian exploration licences in the Beaufort Sea are for water depths exceeding 100 m, which will require floating rigs to conduct drilling operations. Unmanaged sea ice can generate high loads on stationkeeping systems, and active ice management will be required. Moored drilling operations were conducted successfully in the late 1970s and early 1980s in primarily first-year ice. Also, more recent scientific expeditions to undertake shallow seabed coring programs have been successful, with active ice management to protect the drilling vessel from multi-year ice. This paper describes some advances and extensions to those earlier ice management techniques, which would enable exploration drilling in deeper water prone to multi-year ice incursions. These advances utilize the results of full-scale ice management trials conducted in 2009 by Imperial Oil Resources Ventures Limited (Imperial) in the Fram Strait.

Ice management strategies for Beaufort Sea operations must include tactics for dealing with a range of ice conditions, ice speed and changes in ice drift direction. The Fram Strait trials demonstrated the capabilities and limitations of two different vessel types under a range of ice management activities, and provided quantitative information on ice management fleet requirements for defending a stationkeeping vessel in an Arctic environment. The results also demonstrated the requirements for accurate ice forecasting and ice monitoring, and for a comprehensive control and communications system to maximize an ice management fleet's effectiveness and to prevent unmanageable ice from disrupting the drilling operation.

1. INTRODUCTION

Some of the recent exploration licence areas in the Beaufort Sea are at or beyond the continental shelf break and are consequently in significantly deeper water than previous exploration activity in the region. Figure 1 shows the exploration licences EL 446 (Ajurak) and EL 449 (Pokak). EL 446 was awarded in 2007 to Imperial and ExxonMobil Canada Ltd., and EL 449 was awarded to BP Exploration Operating Company Limited in 2008. In 2010, a Joint Operating Agreement was signed designating Imperial as operator of both licences.

Exploration drilling beyond the shelf break requires drilling in water depths greater than 100 m, and represents an extension from previous arctic exploration activities.

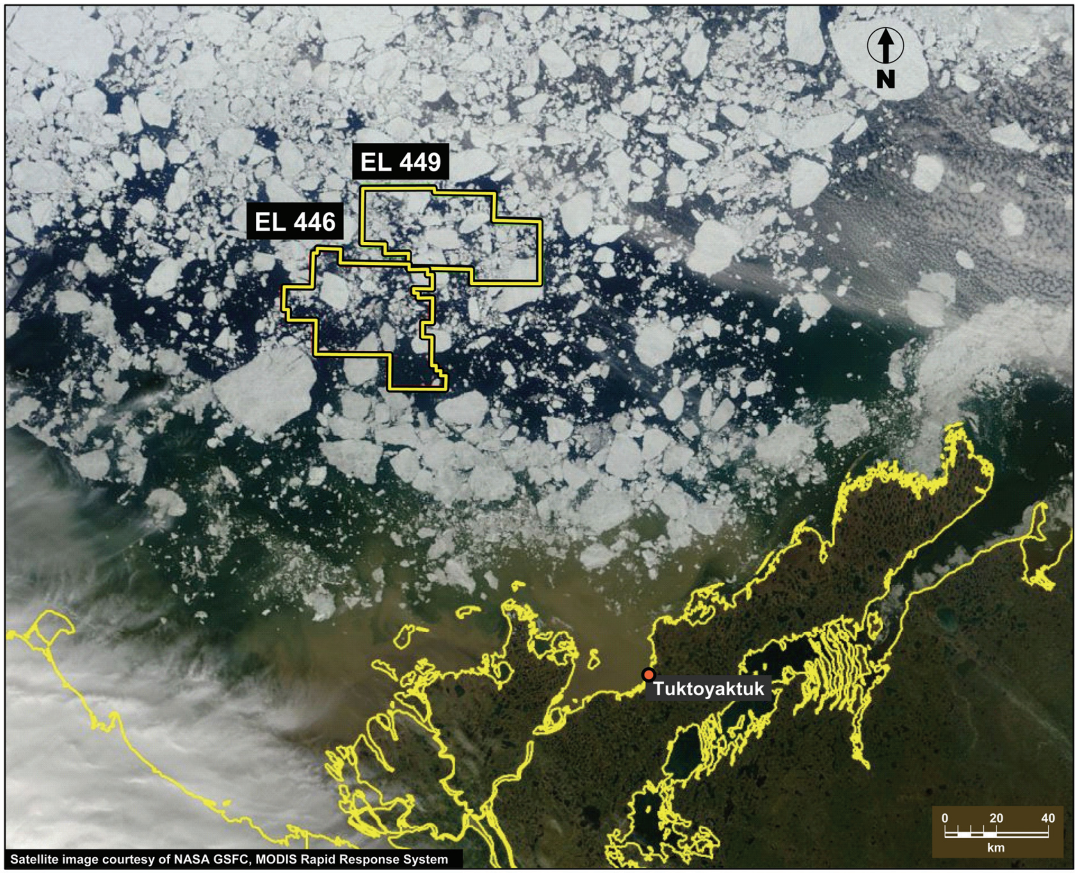

Figure 1. Beaufort Sea Canadian Exploration Licence Areas

During the 1970s and early 1980s, many wells were successfully drilled in the shallow waters of the Beaufort Sea. Bottom-founded platforms were used for winter (landfast ice) operations. The bottom-founded structures included sandbag-retained gravel islands, sacrificial beach gravel islands, spray ice islands, caisson-retained gravel islands and a ballasted drilling barge. These wells were usually completed, tested and abandoned in a single eight-month season (October through May).

In mid-water depths (30 m – 90 m), floating operations were conducted from moored, fixed-heading, non-ice-classed drillships or an inverted cone drilling barge during the summer (open water) seasons. Because the summer season typically lasts only the three months of August, September and October, and is much less predictable than the winter season, those wells often required two to four summer seasons to drill, test and abandon.

In the deeper water and beyond the shelf break, the water depth makes bottom-founded structures (and winter season drilling) impractical, while the more severe ice environment (multi-year ice, and frequent direction and velocity changes) precludes the use of fixed-heading, moored, non-ice-class drillships. Preferred options for this environment include an ice-classed drillship capable of drilling while using dynamic positioning (DP) for stationkeeping, or a turret-moored drillship. In both cases, it is highly desirable to have ice-classed drilling vessels supported by ice management vessels to reduce the operational impact of a difficult ice season and to extend the seasonal window for safe drilling.

Unmanaged sea ice can generate high loads on stationkeeping systems, and active ice management is required to defend floating drilling systems from more severe ice conditions. A recent application of this type of drilling was the scientific expedition to undertake shallow seabed coring programs near the north pole (ACEX), which successfully used active ice management to protect the drilling vessel from more severe old ice conditions, including multi-year ice.

This paper describes a field test program that was undertaken to advance ice management techniques beyond those used in first-year ice and landfast ice in the Beaufort Sea. These techniques are needed to enable seasonal exploration drilling in the more difficult conditions of deep water prone to ice incursions with dynamic multi-year ice (MYI) inclusions. Improving this capability involved developing advanced ice management simulation technology [Hamilton et al. 2010] calibrated with full-scale ice management trials conducted in 2009 by Imperial in the Fram Strait. Results from the trials are being used to develop more advanced ice management strategies for future use in the deepwater Beaufort Sea.

The ice management strategies must include tactics to deal with a range of ice conditions, ice speed and changes in ice drift direction. The Fram Strait trials were undertaken to explore how best to leverage the capabilities of two different vessel types under a range of ice management activities. They provided quantitative information on ice management fleet requirements for defending a stationkeeping vessel in an Arctic environment. The objectives of the Fram Strait trials can be summarized as follows:

- Determine the ability of the icebreakers to operate in thick first-year ice and old ice with adequate performance, to allow a drilling vessel to maintain position against changing ice drift velocities (speed and direction).
- Determine the ability of icebreakers to reduce floe size in thick first-year ice and old ice to the requirements of a stationkeeping vessel.
- Identify the limiting ice conditions for the test fleet.
- Obtain the data necessary to accurately simulate the performance of a future ice management fleet operating in Beaufort Sea conditions.
- Identify the ice forecasting, ice monitoring, control and communications systems needed to maximize an ice management fleet's effectiveness for real-time operations.

2. ICE CONDITIONS IN DEEPWATER BEAUFORT SEA

2.1 General Description of Summer-Fall Ice Regime

In the summer and early fall, old pack ice brought to the licence area from the northeast by the Beaufort Gyre creates a major challenge for conducting offshore operations. Analyses of Landsat and Worldview optical satellite images reveal old pack ice typically consisting of conglomerate floes, which are MYI inclusions in a second-year ice matrix. These MYI inclusions could potentially be very difficult or impossible to fragment with icebreakers. Incursions of old ice could occur at any time and last from a few days to a month or longer. Ice floes originating from remnants of the first-year ice, some of which include pressure ridges, are often present after break-up. Such ice is expected to be manageable by icebreakers as their strength and thickness degrades in the summer. Typically, by July, this type of ice has mostly disappeared. Ice conditions in the Ajurak/Pokak area after freeze-up in the fall are governed by how far to the north the edge of old pack ice has retreated. If the old ice is far to the north by the time of freeze-up, newly grown, thin ice reduces the mobility of old late season ice and the probability of old ice intrusions in the area.

2.2 Key Ice Parameters for Ice Management

Ice management effectiveness depends on two groups of parameters characterizing the ice conditions – strength-related parameters (thickness, mechanical strength and deformation) and ice drift patterns, including drift velocity and its variability across the site. An ice monitoring system will have to deliver accurate, near-real-time information on the key ice parameters as input to forecasting models and ice management operations.

Ice Thickness and Ridging

Most of the available information on ice thickness in the southeast Beaufort Sea comes from measurements of ice draft with upward-looking sonar or an ice profiling system (IPS). Figure 2 describes the composite ice thickness and ice drift speed data from IPS measurements over a ten-year period at a site monitored by Fisheries and Oceans Canada (DFO Site 2) [Melling and Riedel, 2004]. Superimposed on the plot are similar measurements from ice encountered during the 2009 Fram Strait trials. Most of the latter are between the 10% and 1% exceedance contours for the Beaufort Sea, but are generally clustered towards the lower end of the drift speed axis. Table 1 summarizes the maximum ice ridge keel depths and daily average ice thicknesses observed at DFO Sites 1 and 2 (Site 1 is about 100 km southeast of Ajurak).

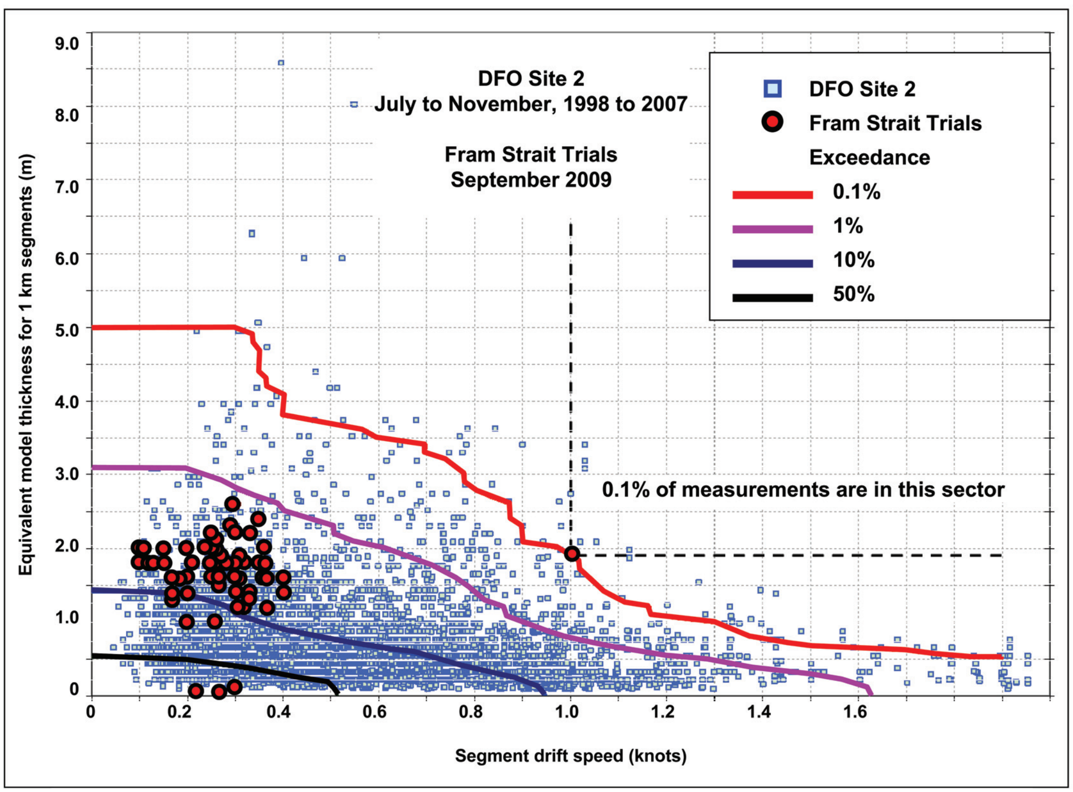

Figure 2. Comparison of Ice Characterization at DFO Site 2 and as Encountered during Fram Strait Trials

Table 1. Characteristic Summer-Fall Ice Thickness Measurements from DFO Sites 1 and 2

Floe Feature	50% Exceedance Probability	10% Exceedance Probability	16-Year Maximum
Daily maximum keel depth (m)	7.5	13	27 - 35
Daily average ice thickness (m)	1.0	3.0	na

Detailed analysis of medium-resolution Landsat images, taken during the 2003 summer-fall season, revealed ice floes containing severe ice features, such as fragments of ice islands, MY ice hummocks and thick MY ice ridges. The areal extent of the identified features ranged from hundreds of meters to several kilometres with potentially large ice thickness. Helicopter electromagnetic induction (EMI) surveys were conducted in July 2009 in the Ajurak area during Imperial's 2009 research collaboration with ArcticNet [Curtin et al. 2010, Prinsenberg, S. 2011]. Thick MYI features with an average EMI-indicated thickness of 3 m to 4 m over several kilometres, embedded into a matrix of first-year ice and second-year ice, were observed and characterized.

Ice Mechanical Strength

By July-August, temperatures in the area are generally above freezing and ice strength decreases rapidly. First-year ice strength reduces to only about 10% of winter strength, and second-year ice strength is similarly reduced. However, MYI shows much less strength loss, declining to only about 50% of its winter strength, and thus will be a more significant challenge to manage.

Ice Drift

Extreme ice drift speeds measured at DFO Site 2 in the summer-fall season are slightly above 1 m/sec or 2 knots. Characteristic values of ice drift speed for different parts of the summer-fall season are given in Table 2.

Table 2. Characteristic Values of Ice Drift Speed at DFO Site 2

Median Daily Maximum Ice Drift Speed (knots)				
June - early July	Late July - early August	Mid August - late September	October	November
0.3 - 0.4	0.5 - 0.6	0.5	0.7 - 0.9	0.35 - 0.8

The length of ice cover that drifts over a point in the Ajurak/Pokak area, estimated using DFO Site 2 data, ranges from 10 km/day to 25 km/day during the June to October operating window.

Ice drift direction in the area is highly variable. This variability is in large part driven by sudden changes in wind direction and inertial oscillations caused by those changes. Inertial oscillations have a period of slightly more than 12 hours and result in cusps or loops in the ice drift path, as shown in IPS data from DFO Site 1 (illustrated in Figure 3). In extreme situations, ice drift direction can change by more than 100 degrees in an hour. However, drift speed while such changes of direction occur is very low (usually < 0.1 knots).

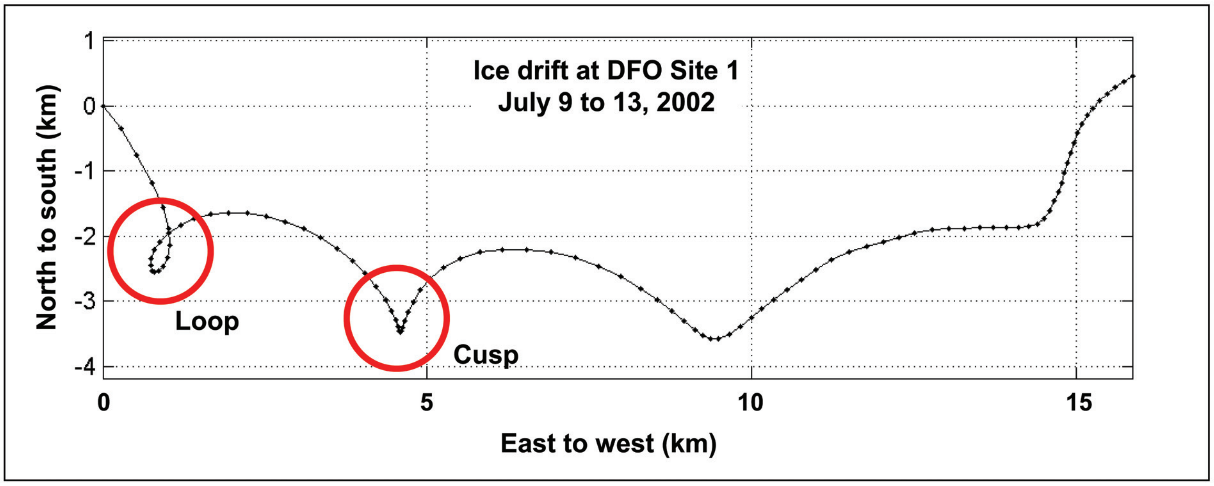

Figure 3. Loops and Cusps at DFO Site 1

3. FRAM STRAIT ICE MANAGEMENT TRIALS

In September 2009, Imperial conducted full-scale ice management trials in the Fram Strait between Svalbard and northeast Greenland. These trials were conducted to establish the foundation for an advanced ice management system, to enable drilling operations in drifting pack ice in deepwater licences.

3.1 Location and Ice Conditions

The Fram Strait between Svalbard and northeast Greenland was selected as the location for the ice management trials because it has ice conditions similar to those expected in the summer-fall season at the Ajurak and Pokak licences. Fram Strait was also an accessible location for the participating icebreakers with home ports in Northern Europe. After review of the ice conditions in the Fram Strait in August 2009, the selected trials were narrowed to an area north of 80^{o}N around the prime meridian. Tests were conducted over a period of eight days (September 13-20, 2009), excluding the open-water transit between Longyearbyen, Svalbard, and the ice edge. The test conditions can be summarized as follows:

- Tests were conducted in an area with second-year and first-year ice. The area included a number of vast (2 to10 km) and giant (>10 km) competent floes. Ice in the trials area had just started regaining strength after the summer melt period by the time the tests started. The air temperature had been below freezing for the two weeks before the trials started.
- Ice drift speed in the area of the trials varied between 0.1 and 0.4 knots. Ice drift direction was fairly constant, but there were some significant changes in ice drift direction during some tests.
- The total ice concentration during the trials was 9+/10^{ths}, which is high compared to summer ice conditions in the Beaufort Sea. However, no pressured ice was experienced during the trials.

Figure 4 is a MODIS satellite image of the area taken during the trials. Ice concentrations were extracted from National Ice Center (NIC) ice charts. The ice characterization was verified through on-site observations. The figure shows the tracks of the icebreakers during the period of the trials, and locations of the individual tests.

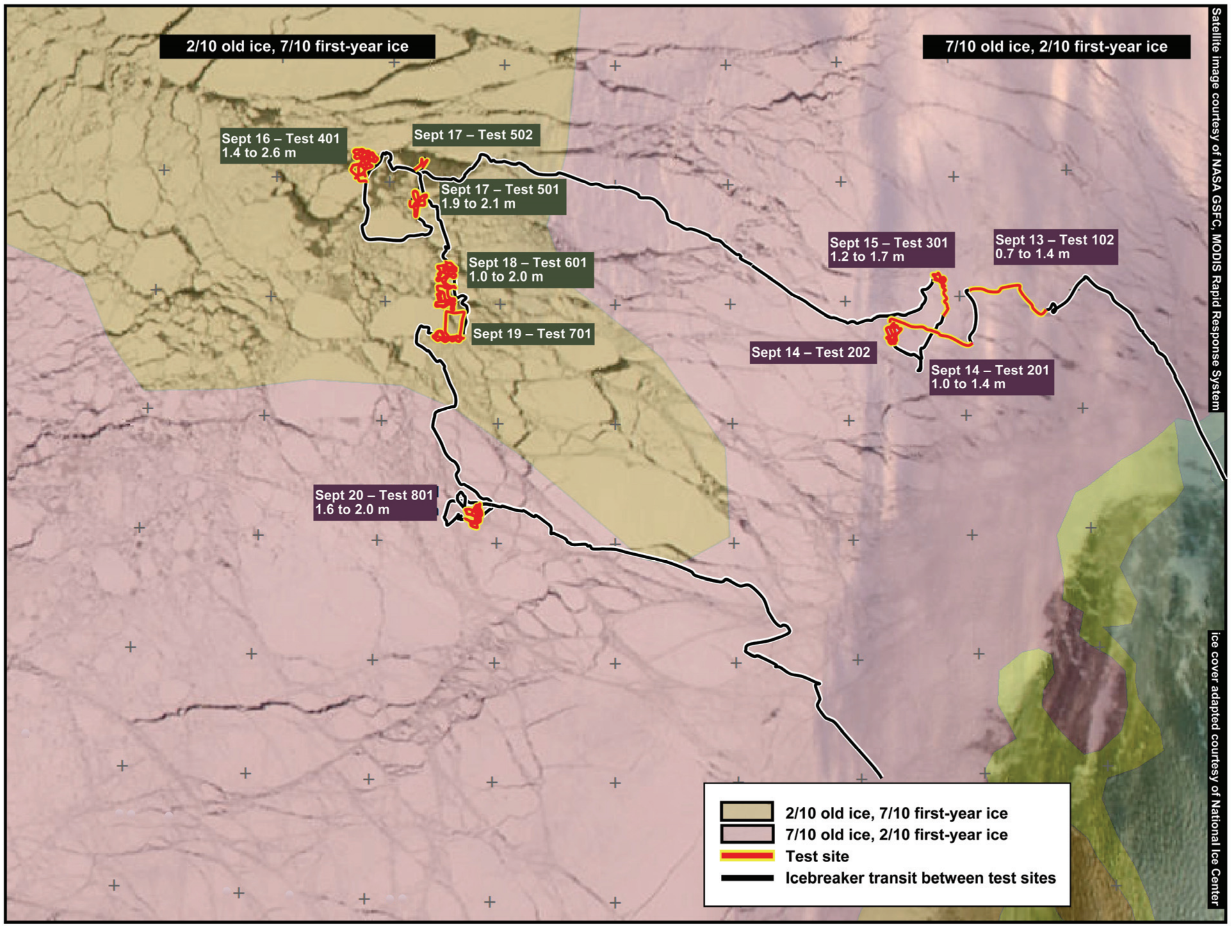

Figure 4. Ice Conditions and Characterization During the 2009
Fram Strait Ice Management Trials

For Test 501 (September 17, 2009), Figure 5 shows the ice thickness profile and histogram from data measured with an electromagnetic instrument suspended over the bow of the icebreaker AHTS *Oden*. This test involved ice management of a vast floe. The maximum thickness in the profile is a little over 7 m, while the histogram exhibits two modes – a mode of 0.2 m, which corresponds to open-water areas and refrozen leads, and a mode of 2.6 m, which would be typical of second-year ice.

3.2 Tests Undertaken and Data Collected

One of the objectives of the Fram Strait trials conducted was to understand how different configurations of ice management vessels could be used to enable a drilling vessel to stationkeep in pack ice in the deepwater Beaufort Sea. One of the configurations could involve the following three main stages of ice management, as shown in Figure 6:

- Stage 1: preliminary floe size reduction by an icebreaker moving in loops in incoming intact ice, furthest updrift of the drillship
- Stage 2: further floe size reduction by an icebreaker moving in loops in ice already managed by the Stage 1 icebreaker

- Stage 3: ice management by an icebreaker working at close quarters to the drillship, splitting some larger floes that might come out of the first two stages, and clearing ice around the drillship using the wake of the azipod propulsion system

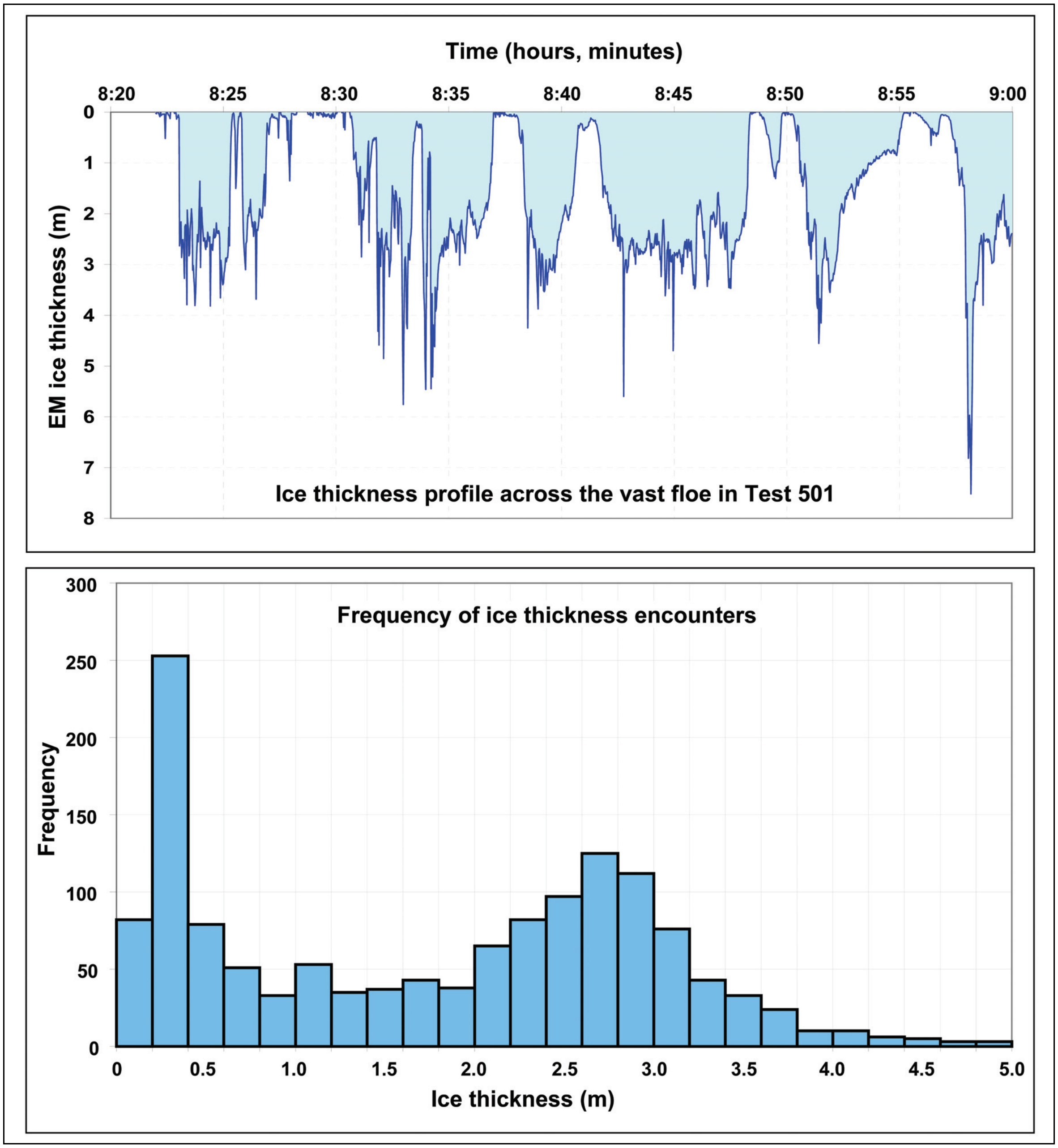

Figure 5. Ice Characterization Test 501 (September 17, 2009)

In addition, another icebreaker might be employed in both a reconnaissance and icebreaking mode to scout and begin breaking vast and giant floes further updrift.

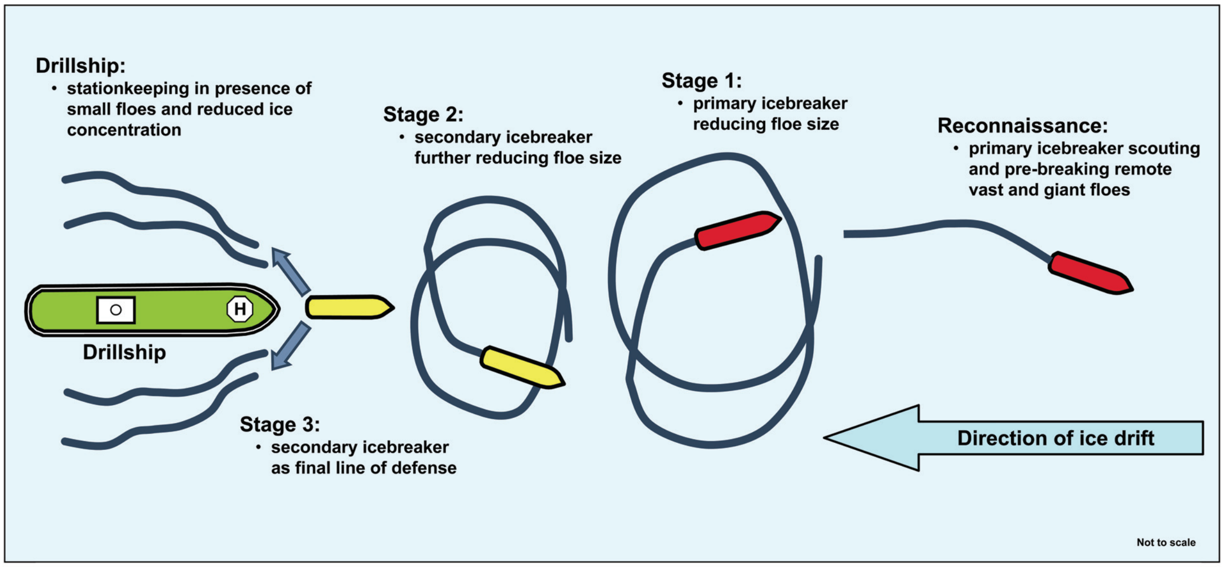

Figure 6. Stages of Ice Management for Deepwater Drilling

During the Fram Strait trials, testing of each of the three main stages was conducted with two existing icebreakers:

- the AHTS *Oden*, operated for the Swedish Polar Research Secretariat by Rederi AB Transatlantic. The AHTS *Oden* was built in 1983, and is classed by DNV as a Polar-20 icebreaker. The icebreaking capability is reported as 1.8 m at 3 knots [Sodhi 1995].
- the MSV *Fennica*, operated for the Finnish Board of Navigation by Arctia, Inc. (previously Finnstaship). The MSV *Fennica* was built in 1993, and is classed by DNV as a Polar-10 icebreaker. The icebreaking capability is reported as 1.8 m at 2 knots [Sodhi 1995].

The types of tests conducted included the following demonstrations:

- Simultaneous Stage 1 and Stage 2 ice management was conducted using the AHTS *Oden* in the Stage 1 role and the MSV *Fennica* in the Stage 2 role.
- In two tests, the MSV *Fennica* performed Stage 3 ice management, clearing an area from ice with her azimuthing propulsion.
- One test simulated a higher ice drift speed by advancing the location of the loops for the AHTS *Oden* and the MSV *Fennica* at a steady rate.
- To assess the maximum ice drift speed that could be managed for a particular set of ice conditions, both the AHTS *Oden* and the MSV *Fennica* advanced at the maximum possible rate.

For all tests, a stationary way point was used as a surrogate position for a virtual drillship conducting stationkeeping.

The data collected during the trials included satellite imagery, navigation and machinery data, ice drift and ice thickness. In particular, continuous ice thickness measurements were made forward of the bow of the AHTS *Oden* using a suspended electromagnetic instrument.

Two Inuvialuit ice and wildlife observers were part of the research team, documenting the reaction of marine mammals to the ice management operations (polar bears were attracted by the open water and were curious, but did not appear to have any adverse reaction.)

3.3 Summary of Trial Outcomes

Floe Size Reduction

Seven floe size reduction tests were conducted, in which the AHTS *Oden* and the MSV *Fennica* worked together to reduce ice floe sizes. The following observations were made:

- When the ice drift was relatively uniform in direction, the two-stage ice management process generally performed as planned.
- When higher variability of the ice drift direction was encountered, the fixed waypoint was occasionally outside the managed ice channel. However, based on post-trial simulations using tools calibrated with trials data [Hamilton et al. 2011], it was confirmed that, with three active icebreakers and continuous real-time monitoring of the ice drift direction, the risk of the drillship being outside the managed ice channel can be reduced to an acceptable level.
- The drift speeds encountered during the trials were lower than the upper end of the range of speeds in the summer-fall expected in the Beaufort Sea. Post-trial simulations have been used to assess the options and vessel performance with higher ice drift speeds.

In one of the tests, a floe was encountered in which the AHTS *Oden* could not make forward progress, even after repeated ramming. Although it was not determined whether this was a MYI fragment embedded in the second-year ice matrix, this test highlighted the challenges presented when encountering ice features that are difficult or impossible to fragment. Effective remote sensing technologies to identify such features far updrift of the drillship will be needed during actual drilling operations.

Clearing

Four clearing tests were performed, in which the MSV *Fennica* used her azimuthing propulsion to open and maintain an area clear of ice. These tests demonstrated that the managed ice channel and the surrounding area beyond it must contain enough brash (broken) ice and open water to allow movement of floes in the ice field. In addition, clearing was much more effective in a fairly homogeneous mix of floes, brash ice and open water, as opposed to strips of floes separated by channels of brash ice and open water. Clearing was effective at the encountered speeds of ice drift (0.2 to 0.4 knots). At higher drift speeds, ice clearing is expected to be less effective.

3.4 Example Test Results

Figure 7 is a photo-mosaic showing the managed ice channel produced by the AHTS *Oden* and the MSV *Fennica* during the two-stage floe size reduction test conducted on September 20, 2009. An oblique photo from the helicopter is shown in Figure 8, in which the MSV *Fennica* can be seen managing ice in a Stage 2 role.

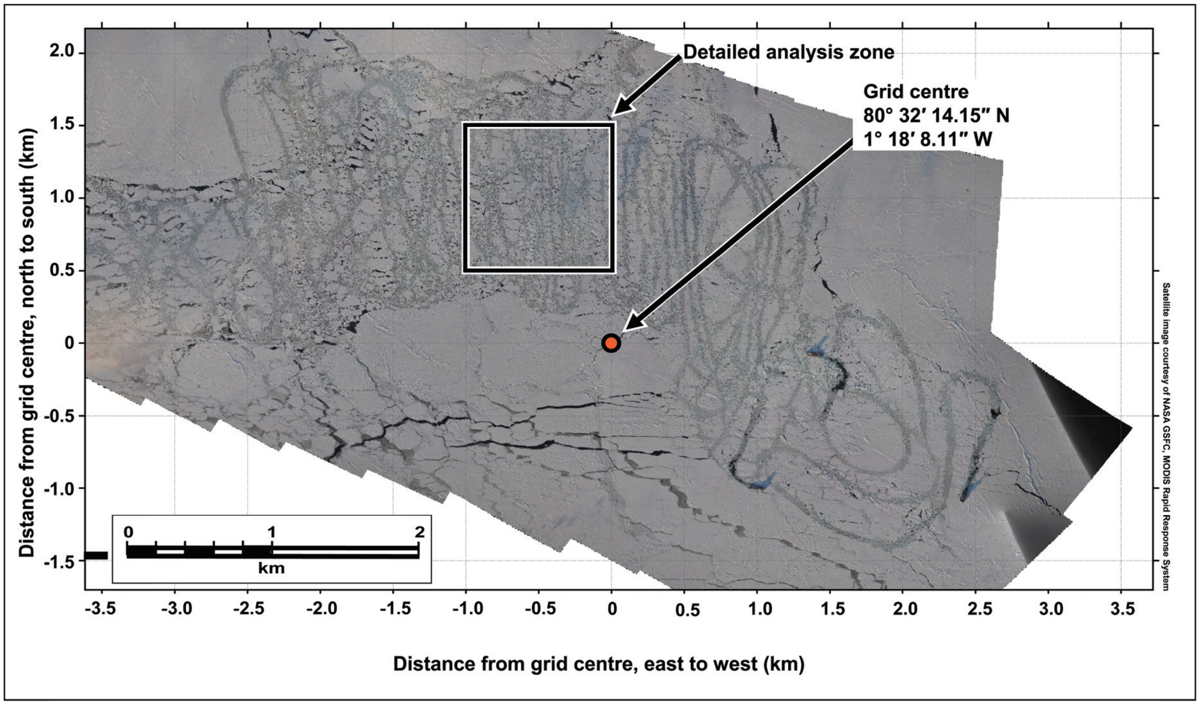

Figure 7. Managed Ice Channel from Floe Size Reduction Test on September 20, 2009

The ice drift speed during the test ranged from 0.1 to 0.4 knots. The drift direction was approximately towards 270 degrees at the beginning of the test and 240 degrees after two hours of testing. The direction then changed slowly to 290 degrees, with a sharp change to 210 degrees at the very end.

Figure 8. Oblique Photo from Fram Strait Test on September 20, 2009

The 1 km x 1 km square area in Figure 7 was analyzed to determine the details of the managed ice conditions in the channel. The analyzed area is shown in greater magnification in Figure 9. Analysis was conducted over the whole 1 km x 1 km square (Area A). More detailed analysis was conducted over the area of the rectangle (Area B, approximately 360 m x 630 m and shown in greater magnification in Figure 10), in which the ice was more highly managed. In Area A:

- floes greater than 50 m long are outlined in yellow. The area contained 127 such floes, covering 27% of Area A. Most had a length of 50 m to 60 m (to a maximum of 148 m) and a width of 30 to 40 m (to a maximum of 79 m).
- brash ice comprised 33% of the area
- open water comprised 2% of the area

The remaining 38% of the area was covered by floes smaller than 50 m across. These floes were too numerous (several hundred) to characterize individually.

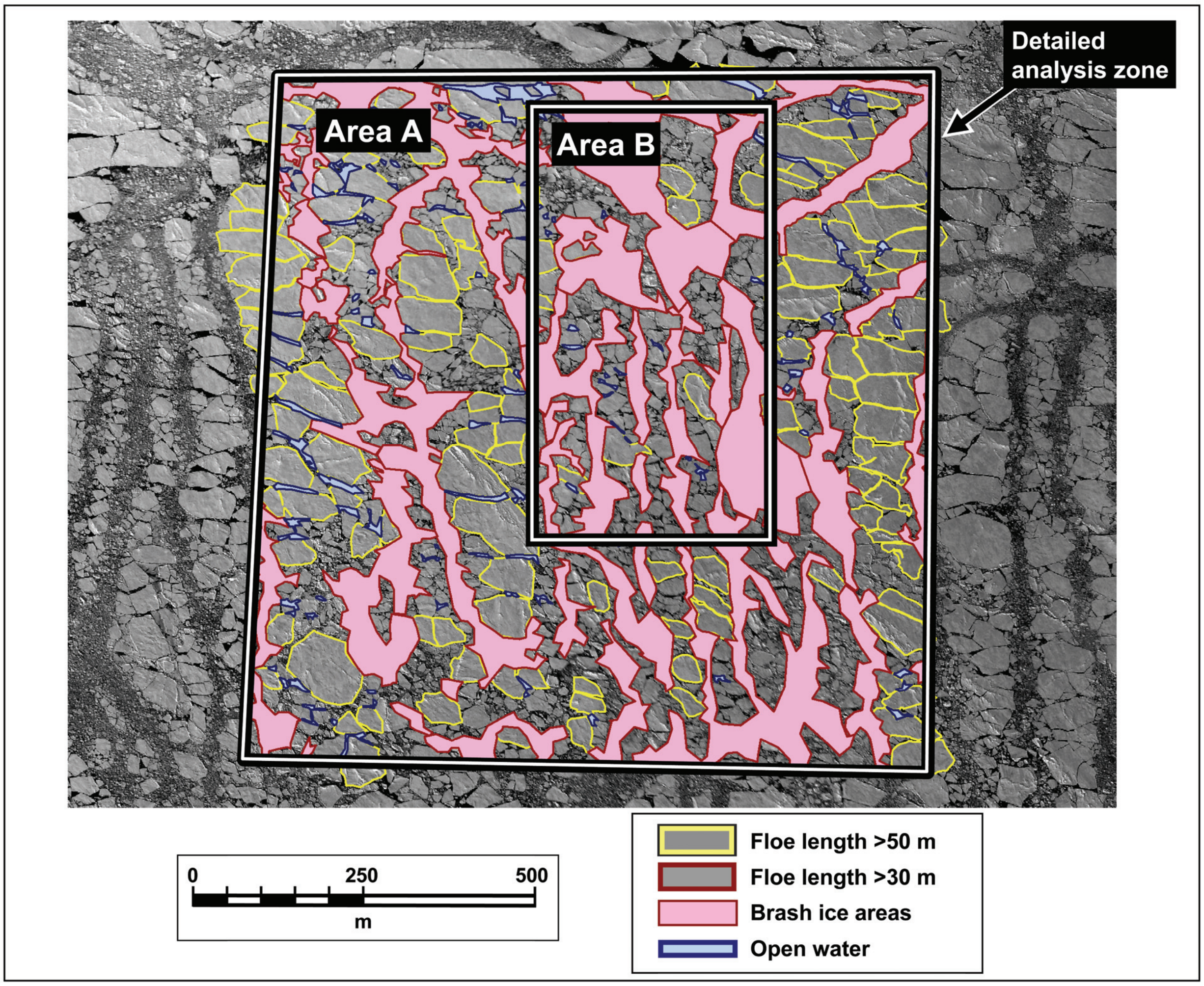

Figure 9. Analysis of Managed Ice Conditions – Areas A and B

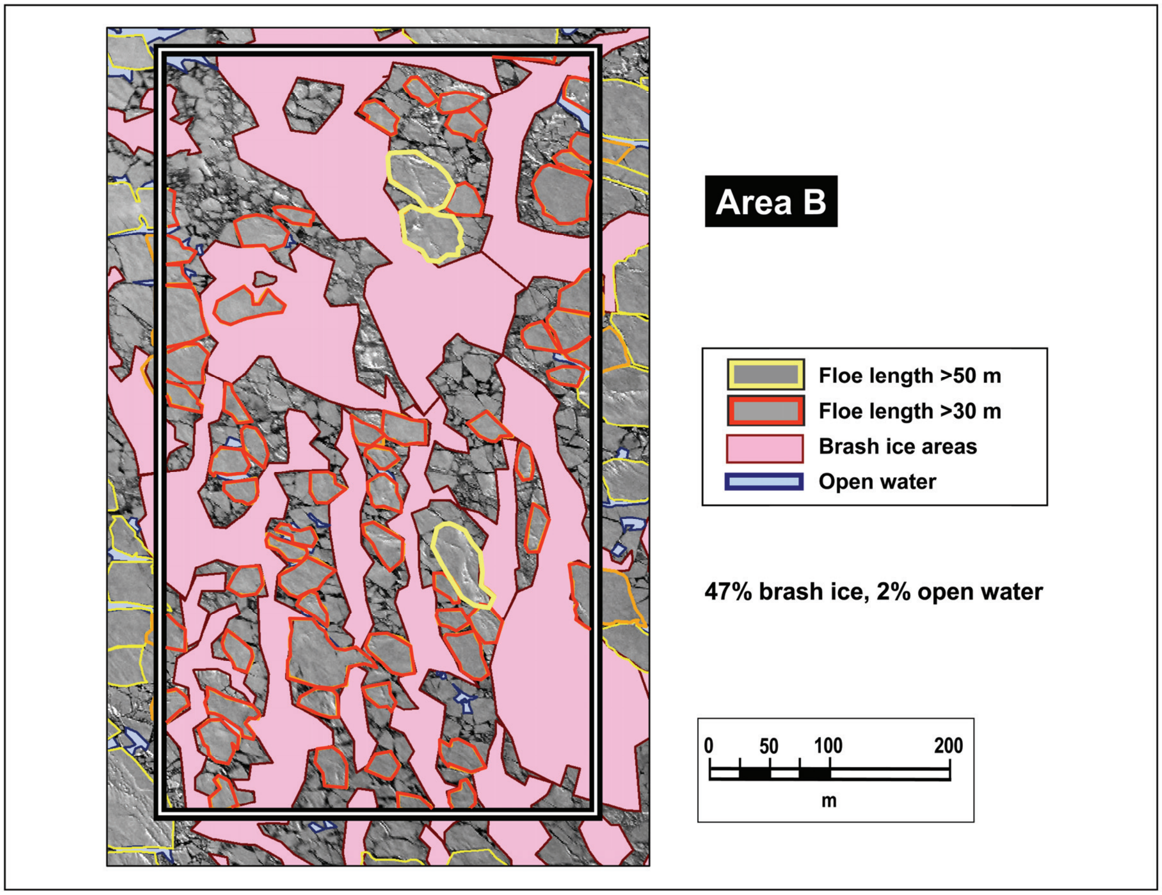

Figure 10. Analysis of Managed Ice Conditions - Area B

Figure 10 shows Area B in greater magnification. Floes longer than 30 m cover about 20% of Area B. Most of them were 30 to 40 m long (to a maximum of 83 m), and 20 to 30 m wide (to a maximum of 48 m). In addition, Area B had about 47% brash ice and 2% open water. The remaining 31% of the area was covered by floes smaller than 30 m across, too numerous to characterize individually.

4. CONCLUSIONS

The full-scale ice management trials conducted in 2009 in the Fram Strait provided both operational insights and quantitative information to plan future ice management operations in the Beaufort Sea. The information includes:

- confirmation of the required icebreaker performance specifications
- limiting ice conditions for conducting reliable ice management operations
- optimum ice management procedures under varying ice drift conditions
- ice monitoring and ice forecasting technology requirements to ensure safe and reliable ice management operations
- control and communications requirements
- opportunities for further technology development

Imperial Oil and ExxonMobil are conducting post-trial simulations using tools calibrated with the trials data, to assess the available options for the site-specific ice conditions in the Beaufort Sea, including both ice thickness and ice drift speeds [Hamilton et al. 2011]. These simulations will further inform decisions regarding:

- the optimal icebreaker fleet for a range of ice conditions and operating seasons
- the floe size distribution targets and the specifications for drillship stationkeeping after ice management operations
- optimizing the size and shape of the loops and patterns used by the icebreakers for varying ice conditions
- optimizing the allocation of icebreaking resources among the ice management stages

REFERENCES

Curtin, M.J., Hall, J.A., Pyć, C.D. and Hawkins, J.R., November 2010. *Collaborative Research to Characterize Biological, Physical and Geotechnical Conditions in Support of Beaufort Sea Drilling Operations*. Presented at the Canada-United States Northern Oil and Gas Research Forum, Calgary, AB, November 30, 2010.

Hamilton J., Holub C. and Blunt J., June 2011. *Simulation of Ice Management Fleet Operations Using Two Decades of Beaufort Sea Ice Drift and Thickness Time Histories*. ISOPE 2011, Maui, Hawaii.

Melling, H. and Riedel, D.A., 2004. *Draft and Movement of Pack Ice in the Beaufort Sea: A Time-Series Presentation, April 1990 – August 1999*. Can. Tech. Rep. Hydrogr. Ocean Science No. 238 (v + 24p).

Prinsenberg, S., March 2011. *NPOL 122-4: Ice and snow statistics for the Beaufort Sea Shelf*. Presented at the 2011 Review Meeting of the Panel on Energy Research and Development (PERD), Calgary, AB, March 15, 2011.

Sodhi, D.S., June 1995. *Northern Sea Route Reconnaissance Study: A Summary of Icebreaking Technology*. CRREL Special Report 95-17.