The Use of Ice Booms to Facilitate the Recovery of Spilled Oil in Ice Infested Waters

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ABSTRACT

Significant potential reserves have been identified in the Beaufort Sea, the Caspian Sea and Offshore Sakhalin Island. As production from these ice-covered fields becomes closer to reality, the need for effective oil-spill countermeasures is brought into focus. This will also lead to increased ship navigation in ice-covered waters initiated by the oil transport to market.

Oil-spill scenarios and appropriate containment and recovery tactics have been investigated, resulting in the production of the Alaska Clean Seas Technical Manual, 1999. The manual provides tactics for oil spill containment for an ice-free situation. However, depending upon the geographical location and the time of year, oil may be released into an environment ranging from open water to broken ice to sheet ice conditions. Mechanical equipment for the efficient recovery of oil in highly packed ice of various concentrations is presently unavailable, despite the fact that a significant amount of research has been conducted.

This paper presents the applicability of ice booms for various scenarios in which oil is released in pack ice. The boom would be deployed to protect the affected areas from oil spills by either providing an ice free zone for conventional oil spill cleanup equipment to be used or by ensuring that any significant ice contaminated area is circled and that the oil is removed before it is let to drift with the pack.

INTRODUCTION

The first step in the development of an effective plan is to define the oil-spill scenarios that are likely to confront the spill cleanup crew.

Conditions at an oil-spill site will be related to the mechanics of oil spreading, the rate and quantity of the discharged oils and the time of year when oil is released into the environment.

Oil may be released by a variety of mechanisms. These include:

- A batch spill resulting from an oil tanker accident.
- Blow-out of an exploration or production well.
- Damage to an underwater pipeline.

Mechanical equipment for the efficient recovery of oil in high pack ice concentrations is presently unavailable, despite the fact that a significant amount of research has been conducted. Purves et al., 1977, proposed a circular net for collecting oil from an Arctic oil well blow-out. At that time, information regarding pack ice pressure and its behaviour was scarce and thus, its effect on an ice boom was also poorly understood. This lack of fundamental knowledge severely hampered the design efforts.

Figure 1: The 22 spans, 2.6 km Lake Erie Upper Niagara River Ice Boom, deployed in the North East end of Lake Erie by the New York Power Authority and Ontario Hydro since 1963.

Fleet Technology Limited (FTL) conducted laboratory tests of an oil-skimming bow, Abdelnour et al, 1985. That study showed that the oil-skimming bow, even with the use of a water jet to herd the oil and move it toward the skimmer, had poor oil recovery efficiency, especially for high ice concentrations of close to 10/10. Loset et al, 1992 investigated the concept of using a flexible boom for collecting ice upstream of a well blow-out. These model test experiments showed that significant research was still required. Field tests were also carried out. No published information was obtained from these tests.

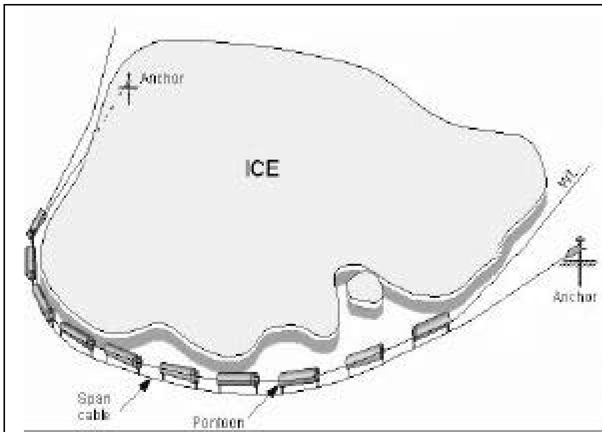

Figure 2: Pictorial view illustrating the ice boom holding an ice cover

RECENT DEVELOPMENTS

Ice booms have been used for more than 40 years upstream of water intakes at hydroelectric power plants to accelerate the formation of a stable ice cover and to protect the intakes from drifting ice. The boom is placed in a site along the river where it can retain the drifting ice and promote the formation of a stable ice cover to rapidly progress upstream. The ice cover acts to insulate the water surface and, depending on the ice cover area, to reduce the volume of ice produced in the river (Figure 1).
An ice boom consists of one span cable (as shown in Figure 2) or more span cables (22 spans is shown in Figure 1). The span cable is attached at each end to an anchor cable or to an anchor placed in the riverbed. Each span has pontoons attached to the cable with chains, one at each end of the pontoon. These chains maintain the cable at about 1 m below the water surface. The pontoons are about 10 m long and the gap between each two pontoons is between 2 and 7 m. When the ice load exceeds the pontoon resistance capacity, it submerges and the ice drifts over the pontoon. This limits the load on the boom, and reduces the probability of ice damage.

In 1992, the New York Power Authority (NYPA) and Ontario Power Generation initiated a study to assess the performance of the Lake Erie-Upper Niagara River Ice Boom, a 2.6 km-long ice boom. This ice boom had relatively poor ice retention capacity and allowed a significant volume of ice to over-run the boom causing power significant losses.
An analytical assessment of the Lake Erie Ice Boom was made and concluded that the ice boom would be much more effective in retaining the ice if the pontoons had more buoyancy to provide more ice resistance. Field instrumentation and prototype testing of the boom during the winters of 1994 and 1996 resulted in the collection of data used in the calibration of numerical models. These models produced the basis for the design of reliable and efficient ice booms that led to overall improved performance. (Abdelnour et al, 1995).
A recommendation was made in July 1994 to replace the timber pontoons with larger and more buoyant steel pontoons. These pontoons increased the boom's ice resistance by up to 5 times, compared to the timber pontoons.
During the same period, the Canadian Coast Guard (CCG) embarked on a plan to improve the reliability of winter transportation through the St. Lawrence River System following an ice-related event that interrupted navigation for a long period of time during the winter of 1993.
Laboratory tests were carried out to compare various ice boom pontoons. This was followed by the use of analytical models to design a boom capable of retaining the ice in 0.8 m/sec currents. A steel pontoon, a pipe with 0.61 m (24") diameter, was proposed to resist the driving forces expected for the Lavaltrie site (Abdelnour et al., 1995, see also Figure 3).

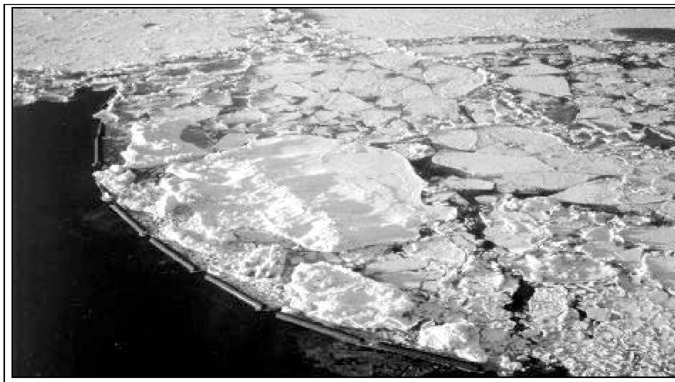

Figure 3: Lavaltrie ice boom. This is a close-up view of one 120 m wide span of the 1 km long Lavaltrie Ice Boom. The current velocity at this location is 0.8 m/sec

Figure 4: Visualization of the prototype tests of the new ice boom pontoon design of the Lake Erie Ice Boom where 25% of the timber pontoons were replaced with steel ones - winter 1997.

The CCG's ice booms near Lavaltrie and Lanoraie on the St. Lawrence River were re-engineered in 1993. As well, a new 2.5 km long ice boom, was constructed in 1994 to retain the ice along the North East side of Lac St. Pierre at Yamachiche.
The results obtained from the Lavaltrie and the Yamachiche ice booms were used to design a new pontoon to replace the timber pontoons of NYPA's Lake Erie Ice Boom. A prototype test was carried out during the winter of 1996/97 where 25% of the timber pontoons were replaced with the new steel pontoons. The new steel pontoons proved to be significantly better in resisting the ice than the timber pontoons (see Figure 4). This prompted the NYPA and Ontario Hydro to proceed with the replacement of all the timber pontoons with steel pontoons during the fall of 1997 (Cowper et al, 1997).
Since 1997, the experience gained from the NYPA study and the feedback obtained from the Canadian Coast Guard ice boom prototype, led the way to the development of a robust ice boom design procedure used for the conceptual design, detailed design, fabrication and

deployment of several new ice booms. One example of these applications is Hull2 ice boom (Abdelnour et al, 1998).

ICE BOOM APPLICABILITY FOR OIL-SPILL CLEANUP IN ICE-INFESTED WATERS

All presently available oil-spill recovery devices cannot operate efficiently in waters containing significant ice concentrations. The ice, and its in-plane pressure, significantly reduces the oil recovery efficiency by preventing conventional skimmers from operating in thick oil pools. Furthermore, the ice prevents the skimmer from accessing the oil easily. Also, the ice exposes the skimmer to potential structural damage.

The overall intent of this paper is to apply the technology developed recently in the design and use of ice booms for recovering oil in ice infested waters.

An ice boom is expected to be useful in two main boom applications to cleanup as follows:

1) Provides the means to prevent the broken ice from drifting into the oil-spill area
   - Allows conventional equipment to operate
   - Allows in-situ burning
   - Maximizes the operating window.

2) Surrounds the contaminated area to separate oil from ice and recover the oil using conventional equipment
   - Prevents/reduces dispersion of the oil from the site.
   - Prevents/reduces ice ingress into the cleanup area so that oil-spill cleanup operations can be effectively carried out.

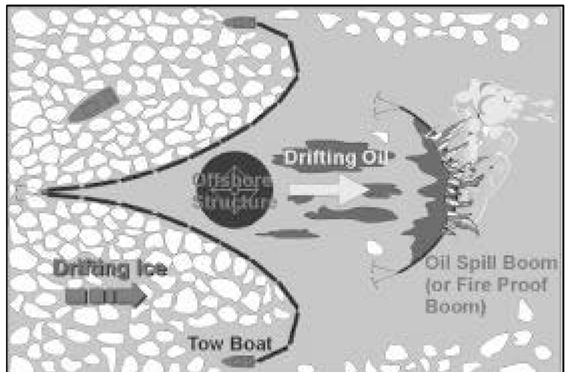

Figure 5: Scenario 1, Oil-Spill from an Offshore Structure

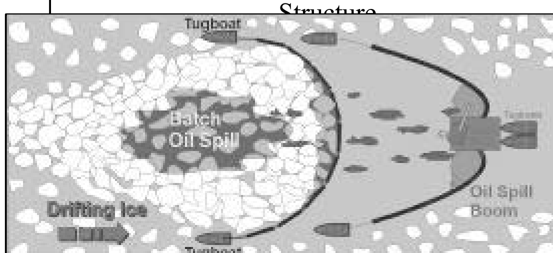

Figure 6: Scenario 2b: A batch spill from a tanker

OIL-SPILL RECOVERY SCENARIOS

The scenarios of oil-spill are well described in the Alaska Clean Sea Technical Manual, 1999, prepared for contingency planning in the event of an oil spill at the exploration sites offshore Alaska. A number of scenarios were defined for which the ice boom could be applied:

Scenario 1: Oil-Spill from an Offshore Structure

Oil spills from an offshore structure can occur in several ways. In this paper one case was depicted. The case is where the wind direction changes are relatively minor and where a continuous oil spill blow up could be involved. In this case, the boom deployment will have to be in continuous realignment with the wind using the tugboats and the distance of the boom upstream from the structure will be significantly more than 100 m upstream (Figure 5).

In either of the above two cases, the drifting oil can either be recovered using conventional oil spill recovery equipment or burned after being contained in a fire proof boom as shown in Figure 5.

Scenario 2: Batch Spill from an oil tanker

A batch spill from a tanker (or a pipeline burst) can cause a large ice cover to be oiled. In this case, a tugboat could tow the boom and surround the contaminated area. (Figure 6) and help separate the oil from the ice in higher ice concentrations. The boom will contain ice pieces, but it will be incapable of containing the oil. Hence, when it is towed through the ice by the ships, it may help to separate the majority of the oil from the ice. Some oil will remain between and on the top of the ice floes.

The relative towing speed should be higher than the required relative current velocity to force the oil droplets to move under and between the ice floes. The oil can either be burned after being contained in a fireproof boom or it can be collected using conventional oil spill recovery equipment as shown in Figure 6.

Based on laboratory tests by Free et al, 1981, the oil under the ice drifts at a speed of about 15 cm/sec when the current velocity is 30 cm/sec. This is well below the capacity of the ice boom to hold the ice upstream of the boom, which can be as high as 0.8 m/sec.

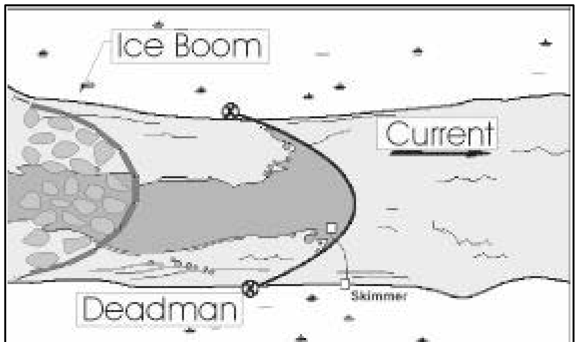

Figure 7: Oil drift in a river

Scenario 3: Oil Drifting in a River

This last scenario is the deployment of ice booms in a river where an oil spill had occurred upstream. The boom can be designed to retain the ice while allowing the oil to drift downstream to be later collected by a conventional ice boom (Figure 7). For this approach to work effectively, the boom deployment site must be carefully selected. The current velocity at the boom site should be higher than the drift velocity of the spilled oil droplets under and between ice floes. The current velocity should also be lower than 0.8 m/sec, which is about the maximum current velocity at which ice can be effectively retained by a boom.

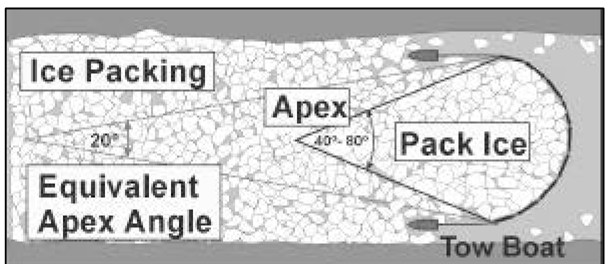

Figure 8: “Dead Wedge” Formed Upstream of a Boom in a Channel or in an Open Sea.

ICE LOADS ON THE BOOM

The expected ice loads are a very important issue, as they will control the operating envelope for the boom, in combination with the capabilities of the available logistical support platforms. It is important to note that because the boom is designed to submerge


Figure 9: Triangular-Shaped Ice Accumulation “Dead Wedge” Upstream of the Yamachiche Boom Placed in Lac St. Pierre (in the St. Lawrence River)

and allow the ice to pass over it when ice forces become too large (described previously), the boom is not expected to be damaged should more severe ice conditions (than the design ones) be encountered. However, this would temporarily render the boom ineffective for oil spill containment or for protecting oil spill cleanup equipment behind the boom.

The ice loads on the boom will depend on the ice conditions in which the boom is deployed. The important issues are whether the boom will be used in "open sea" conditions or in a channel (termed "river ice" conditions). This is an important distinction as the shorelines in a "river ice" condition provide confinement which affect the loads exerted on the boom. See Figure 8.

Although the equivalent apex angle is typically much less for "river ice" situations, which would theoretically result in higher drag loads on the boom, the shorelines provide load relief to the boom as load is transferred to them. The net result, for a 10/10 ice pack, the ice loads tend to be considerably less for "river ice" conditions. However, for 3/10 to 7/10 ice pack, the ice load can be considerably less for a boom in an open sea.

The total force on the boom (F_{tot}) is comprised of two general components, the force due to wind and current drag on the triangular "dead wedge" upstream of the boom, F_{drag} and the pack ice force pushing onto the wedge, F_{ice} (see Figure 9).

WIND AND CURRENT DRAG FORCES

The total drag forces, F_{drag}, Wind drag shear stress, τ_w and the current drag shear stress, τ_c can be determined as follows:

(1) $F_{drag} = F_{current} + F_{wind} = (t_c + t_w)\,A$

(2) $t_w = r_w\, C_{dw}\, V_w^2$

(3) $t_c = r_c\, C_{dc}\, V_c^2$

	Wind Drag Forces	Current Drag Forces
Ice wedge apex angle	63°	63°
Wind or current speed	100 km/hr	0.30 m/s
Air or water density	1.293 kg/m^3	1000 kg/m^3
Air or water drag coefficient	0.0033	0.0200

Table 1: Drag Force Calculation Inputs

Where:

F_{wind} = wind drag force

$F_{current}$ = current drag force

r = specific gravity of water ρ_c or air ρ_w.

C_d = drag coefficient at air-ice interface C_{dw} or at ice/water interface C_{dc}.

V = wind speed (V_w) or current speed V_c.

A = the effective area of the ice cover affected by the current and wind (termed the "dead wedge", (see Figure 8)

The effective area of the "dead wedge" was defined for the "open sea" conditions analyzed by assuming that a triangular-shaped ice accumulation is formed. This selection is based on past observations, which showed that a wedge would form with an apex angle ranging from about 40° to 80° (see Figure 9). The apex angle will be governed by the frictional properties of the ice fragments in the wedge, and by the lateral confinement. The apex angle will be reduced as the lateral confinement is increased.

Because booms will be most applicable to relatively open pack ice concentrations for the case being analyzed here, the apex angle used for these analyses was determined from analyses of the frictional properties of the ice fragments in the "dead wedge". An investigation of the behavior and properties of pack ice fragments that accumulated in front of the Offshore Structure, the Kulluk was made (Barker et al, 2000). The Kulluk was a moored, 70 m diameter (at the waterline) conical-shaped drilling structure used in the Canadian Beaufort Sea. It was held on station with a mooring system comprised of up to 12, 3.5” diameter mooring lines (Wright, 1999). Barker et al, 2000, found that a value of 27° for φ (the internal friction angle of the pack ice material) produced the best correlation between the measured and predicted ice loads.

Assuming that Coulomb’s friction law is applicable, the apex angle (θ) of the “dead wedge” can be calculated as follows:

(4) $q = 2 * (45 - j /2)$

Equation 4 yields a value of 63° for the apex angle for an internal friction angle of 27°. This value was used for evaluating the area of the “dead wedge” for all subsequent drag force calculations (Figure 10).

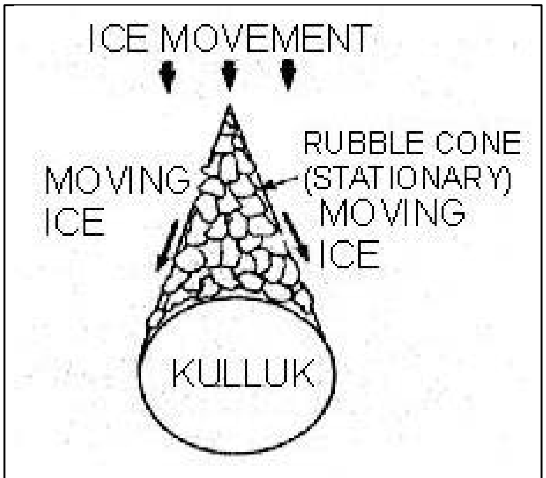

Figure 10: Ice Loading Schematic for the Kulluk (after Wright, 1999)

Values of 0.0033 and 0.020 were used for the air/ice surface drag coefficient (i.e., C_{dw}) and the water/ice surface drag coefficient (i.e., C_{dc}) respectively, as these are typical values for a relatively rough broken ice cover.

Table 1 lists the input values used. Upper range values were used for the wind and current speed to add further conservatism.

Line loads due to drag forces were calculated for boom widths ranging from 230 ft (70 m) to 2500 ft (750 m). As expected, the line loads applied by drag forces increase with the boom width, as a larger boom width results in a larger ice wedge area.

Ice forces were calculated for the case where there was no pressure in the ice as the boom will not be effective in pressured ice.

PACK ICE FORCES

The loads produced by pack ice in an “open sea” condition depend on many factors including the pack ice concentration, the thickness of the pack ice fragments, the type of features in the pack ice (e.g., ridges), whether or not the ice is under pressure or ice management operations are carried out.

Full-scale data collected with the Kulluk are relevant to this study for a number of reasons: the loading scenario was similar to that expected for the ice control boom, the Kulluk typically operated in the June to December period, the same period a boom can be deployed effectively in Arctic Waters and the width of the structure is within the same order of magnitude as the width of an

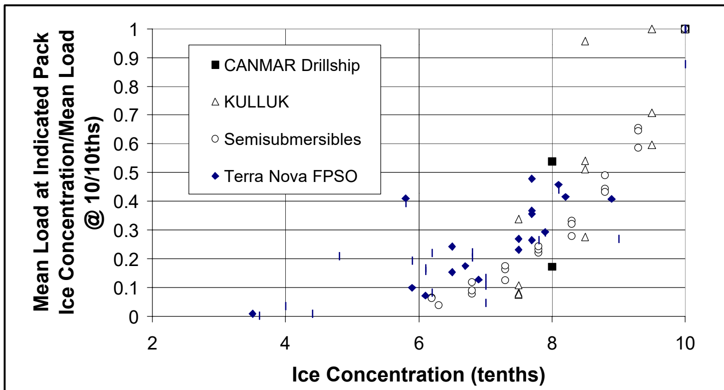

Figure 11: Effect of Pack Ice Concentration on Pack Ice Loads (See Comfort et al, 1999 for supporting information)

ice boom.

Effect of Pack Ice Concentration

Previous studies (e.g., Wright, 1999; Comfort et al, 1999) have shown that this is a very important factor. A wide range of model test data in broken ice have shown that the ice loads are relatively low at ice concentrations below about 8/10ths and that they rise substantially at greater concentrations (Figure 11). The best-fit equation to the model test data is as follows:

(5) $\quad Load\ Ratio = 1.13\ .\ 10^{-5}\ .\ C^{4.94}$

Where:
Load Ratio = mean load at a given concentration/mean load at 10/10 concentration
C = ice concentration, in tenths
This trend has been generally confirmed by full scale data for the Kulluk (Wright, 1999), which was a moored conical-shaped drilling structure used in the Beaufort Sea. When the ice concentration reaches 10/10, the ice may become pressurized. For the Alaskan Beaufort Sea, wind stress is the mechanism most likely to induce pressure in the ice.

Effect of Pack Ice Thickness

Full scale data for the Kulluk (Figure 12) and model test data for a wide range of floating structures (Comfort et al, 1999) both show that the loads increase with the ice thickness.
It is also known that pack ice is highly non-uniform. The significance of the different ice feature and interaction types that may occur is illustrated in Table 2.

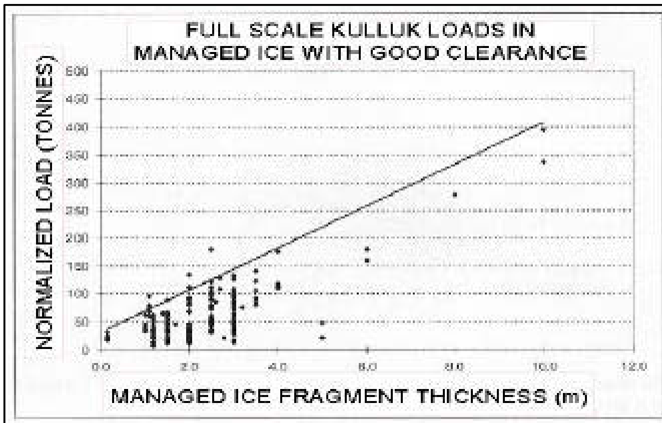

Figure 12: Ice Loads on the Kulluk in Managed Ice Conditions with Good Ice Clearance and No Pressure (after Wright, 1999)

Table 2: Maximum Ice Loads on the Kulluk (Wright, 1999)

Case - Ice condition and thickness	**Maximum Load**		**Maximum Line Load**	
	(tonnes)	**(lbs)**	**(kN/m)**	**(lbs/ft)**
Level unbroken ice to 1.2 m	250	551000	35	2400
Small unmanaged ridges: approx. maximum thickness = 8 m	400	882000	56	3800
Managed ice with good clearance: maximum floe fragment thickness = 10 m	400	882000	56	3800
Floe fragment impacts	600	1323000	84	5700
Tight managed ice with poor clearance: maximum floe fragment thickness = 10 m	350	772000	49	3400
Tight managed ice with poor clearance and pressure: maximum floe fragment thickness = 4m	550	1213000	77	5300

Calculated Line Loads Acting on the Boom

Pack ice forces were calculated and the drag forces were added to determine the total force and line load across the projected width of the boom. The calculated line loads is shown in Figure 13 for pack ice concentration of 70%.

The effect of the ice thickness depends on the pack ice concentration. At low concentrations (i.e., 30% and 50%), the line load is insensitive to the pack ice thickness. This reflects the fact that ice forces are a small proportion of the total force in these cases. At 70% ice concentration, the loads increase with the pack ice thickness (Figure 13) indicating that ice forces are becoming more significant. For the ice thickness and boom widths considered, the line loads range from 160 to 680 lb/ft for pack ice concentrations of 70%.

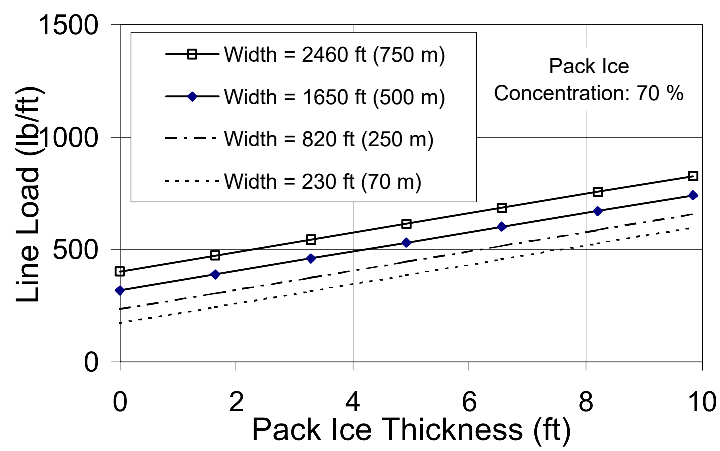

Figure 13: Line loads for a pack ice concentration of 70% with no pressure

ANCHORING OR SHIP THRUST REQUIREMENTS FOR THE BOOM

The total anchoring requirements for a 70% pack ice concentration is shown in Figure 14. It should be noted that the individual anchor requirements will depend on the number of boom spans across the boom width.

As expected, the anchoring requirements increase greatly with the pack ice concentration, and the projected width of the boom.

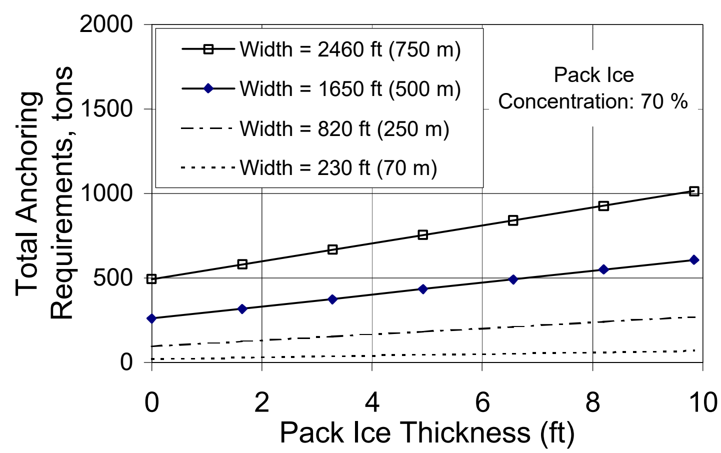

Figure 14: Total Anchoring Requirements for a Pack Ice Concentration of 70% with no Pressure

Pack Ice Concentration and Maximum Line Load for Range of Inputs Considered (Section 4)	**Type of Deployment** 3 Ships– the Pt. Barrow, the Pt. Thompson, and the Arctic River	**Type of Deployment** 2 Ships– the Pt. Barrow and the Pt. Thompson
30 % ; 115 lb/ft (1.7 kN/m)	Maximum Boom Width Allowed: 1260 ft	Maximum Boom Width Allowed: 820 ft
50 % ; 215 lb/ ft (3.1 kN/m)	Maximum Boom Width Allowed: 670 ft	Maximum Boom Width Allowed: 440 ft
70 % ; 680 lb/ft (9.9 kN/m)	Maximum Boom Width Allowed: 210 ft	Maximum Boom Width Allowed: 140 ft

Table 3: Stationkeeping Capabilities of the Largest Vessels on the North Slope for Boom Deployments

For the ice thickness and boom widths considered, the total anchoring requirements range from 1 to 142 tons, 4 to 265 tons, and 18 to 836 tons for pack ice concentrations of 30%, 50%, and 70 %, respectively. Figure 14 shows the anchoring requirement for the 70% ice concentration.

REQUIRED SHIP PERFORMANCE

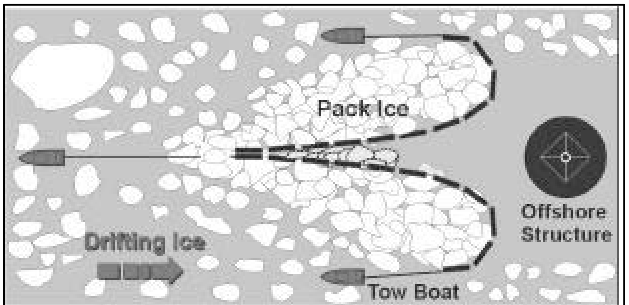

Figure 15: Example Of Ship Maneuvering For Maintaining The Ice Boom In Position

The required ship performance depends on the type of operation, dynamic positioning or transit toward the spill location.
In the dynamic positioning type of operation, the boom would be held on station by two to three supply vessels or icebreakers operating under their own power, as illustrated in Figure 15. This arrangement has the advantage that the boom's orientation can easily be changed should the ice drift direction.
The success of this operation will depend greatly on the powering characteristics of the ship, and the experience of the ship captain in maneuvering in similar situations. The ship bow and its hull geometry are less important for this application particularly since the ice concentration is less than 7/10ths. The ship resistance in broken ice is relatively small when compared with the total load on the ice boom.
The stationkeeping capabilities of the three largest vessels on the North Slope for boom deployments are further investigated in Table 3. It is clear that the available vessels on the North Slope would provide adequate stationkeeping capabilities for a useful range of boom widths in ice concentrations of 30% and 50%. The allowable boom width in 70% ice concentration is much lower because the ice loads are increased significantly. This shows that the available vessels on the North Slope would have limited capabilities for keeping the boom on station in this ice concentration. Larger vessels, such as icebreakers would be required in this case.
Transit to and from the site will not likely impose the design requirement as these loads (in ice concentrations of less than 50%) are expected to be less than those during stationkeeping.
Although more severe cases could arise, they are expected to occur relatively infrequently. These would need to be evaluated on a case-by-case basis, and have not been considered here because this is beyond the scope of the project.

CONCLUSIONS

Improved ice boom technology has been developed and used successfully at several locations. Ice booms have the potential to aid or extend oil spill cleanup capabilities in broken ice in a number of ways, such as:

(a) preventing ice ingress into the spill area, thereby providing an ice-free area where conventional oil spill equipment can operate; and,
(b) providing a means to assist in separating the oil from the ice.

Ice booms have the potential to assist in many of the scenarios defined in the Alaska Clean Seas Technical Manual.
Ice booms, in combination with the available support vessels on the North Slope, are expected to be applicable to oil cleanup in moderate broken ice conditions of up to about

50%. Booms are also expected to be applicable for some cases in higher ice concentrations of up to 70%. However, larger vessels with more power such as icebreakers would be required for a wide operating envelope.

ACKNOWLEDGMENT

The research and development funds provided by the NYPA, Ontario Power Generation (OPG), Hydro-Quebec, and the Canadian Coast Guard, for the development of efficient booms accelerated the rate of ice boom development significantly. These programs produced an extensive knowledge base to define boom performance and they led to the development of numerical models to design an ice boom. The oil spill boom design benefits from this development work as the designs produced were used directly for applications defined by the Alaska Clean Seas Technical Manual, 1999. Particular thanks to Mr. Joseph Mullin of the MMS for providing the necessary funds to investigate the applicability of ice booms for oil spill recovery in ice infested waters.

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