POAC'17
Busan, KOREA

Proceedings of the 24th International Conference on
**Port and Ocean Engineering under Arctic Conditions**
June 11-16, 2017, Busan, Korea

# Investigation of Secondary Icebreaker Performance during an Ice Management Operation

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## ABSTRACT

Depending on ice conditions, ice management operations may involve two or more icebreakers, known as primary and secondary icebreakers. Whether developing an ice management strategy, or executing operations, understand the performance of the icebreaker fleet is most important. The Lindqvist model of ice resistance is chosen to predict icebreaker performance in level ice with estimated hydrodynamic resistance. While one may assume that a broken ice regime (following primary icebreaker activity) may have less resistance, ice management operations for a secondary icebreaker will require continuous turning /maneuvering as it interacts with a more complex ice regime. Therefore, it is important to look into secondary icebreaker performance with different operating situations. Recent field observations suggest that existing models may over predict secondary vessel performance. Understanding the influences of the performance reduction for the secondary icebreaker is the key to successful develop of performance model for icebreakers during ice management operations.

This paper presents an overview of the secondary icebreaker performance during an ice management operation and a new analytical model that is compared with field trials data. The resulting model demonstrates reduced icebreaker capabilities with an example.

KEY WORDS: Secondary Icebreaker; Ice Management Operation.

## INTRODUCTION

The increased activity in the high Arctic by industry is driven by the world's remaining undiscovered hydrocarbons. The capability of station-keeping platforms (mooring and hull) in Arctic and subarctic waters is one of the main challenges particularly given the desire and benefit of safely extending the open water season. To reduce/mitigate ice loads on station-keeping platforms, ice management operations are usually involved. The required ice management operations are reviewed by many researchers, such as (Browne et al., 2014; Hamilton, 2011; Hamilton et al., 2016, 2014, 2013, Hamilton et al., 2011, 2011a, 2011b; Wright et al., 2014; Younan et al., 2012). Also, Kubat and Sayed (2014) have a detailed review of station keeping and ice management.

An ice management operation usually involves two or more icebreakers. The leading or primary icebreaker manages unbroken or large ice floes, and the secondary icebreaker further manages these floes into smaller sizes based on broken ice forces on the station-keeping vessel and its mooring/hull structure capacity. In modeling icebreaker performance, this paper focuses on bow breaking technique only. The floe size, thickness, and properties of the ice encountered by the icebreaker influence the icebreaker performance.

Secondary icebreaker performance in broken ice with reduced concentrations will consider open water resistance. It may seem reasonable to model icebreaker performance based on equivalent resistance that considers hydrodynamic resistance and ice resistance. However, it is recognized that the performance of an icebreaker in the water with ice present is much more complicated than a vessel in the open water only, and uncertainty exists.

Modelling secondary icebreaker performance as equivalent resistance would suggest enhanced performance as floe sizes and equivalent concentration of the pre-managed or broken ice field following primary icebreaker activity are reduced. However, recent field observations suggest that current models may over predict secondary vessel performance. Added maneuvering required to maintain course or deviate from a track to smaller floes, which are targeted by the secondary vessel, may lead to reduced performance. The degree of speed reduction for the secondary icebreaker is the main driver of this study.

This study assumes the predicted secondary icebreaker performance will be a function of level ice performance, turning performance, continuous ship-ice interactions with broken floes, and on-demand maneuvering. It is recognized that variability exists (floe size, current and wind conditions, etc.) and modeling performance probabilistically to satisfy some reliability target is desirable. Such analysis allows one to also consider extreme events that may not yet have been observed in the field, but models suggest they may occur.

A balance between system design (more capable and reliable systems cost more but will reduce downtime) and potential downtime must be achieved. For success, the icebreaker must break the ice floes into the target floe size, in a time that is less than the time for the unmanaged ice floes to arrive at the vessel. If this is not satisfied, operations will suspend to make more time available, until either the threat is gone, or the vessel leaves location.

## ICEBREAKER LEVEL ICE PERFORMANCE MODELING

For ships traversing ice covered waters, the main contributing resistances are hydrodynamic (drag) resistance ($R_{ow}$) and ice resistance ($R_{ice}$). Ignoring other minor resistances, such as the resistances from wind and wave effect, the total resistance ($R$) could be represented by:

$$R = R_{ow} + R_{ice} \quad (1)$$

Hydrodynamic hull resistance could be estimated through towing tank tests or full scale sea-trials. The common open water resistance model is represented as

$$R_{ow} = \frac{1}{2} \cdot \rho \cdot V_i^{\;2} \cdot C_D \cdot A \quad (2)$$

where,

$C_D$ = Drag coefficient, estimated through tests or trials,
$\rho$ = Water density,
$A$ = Wetted area = $L \cdot (B + T)$,
$L$ = Length of the ship at waterline,
$B$ = Bean of the ship, and
$T$ = Draft of the ship.

Also, field trial data suggested similar relation with additional coefficient term as shown in Figure 1.

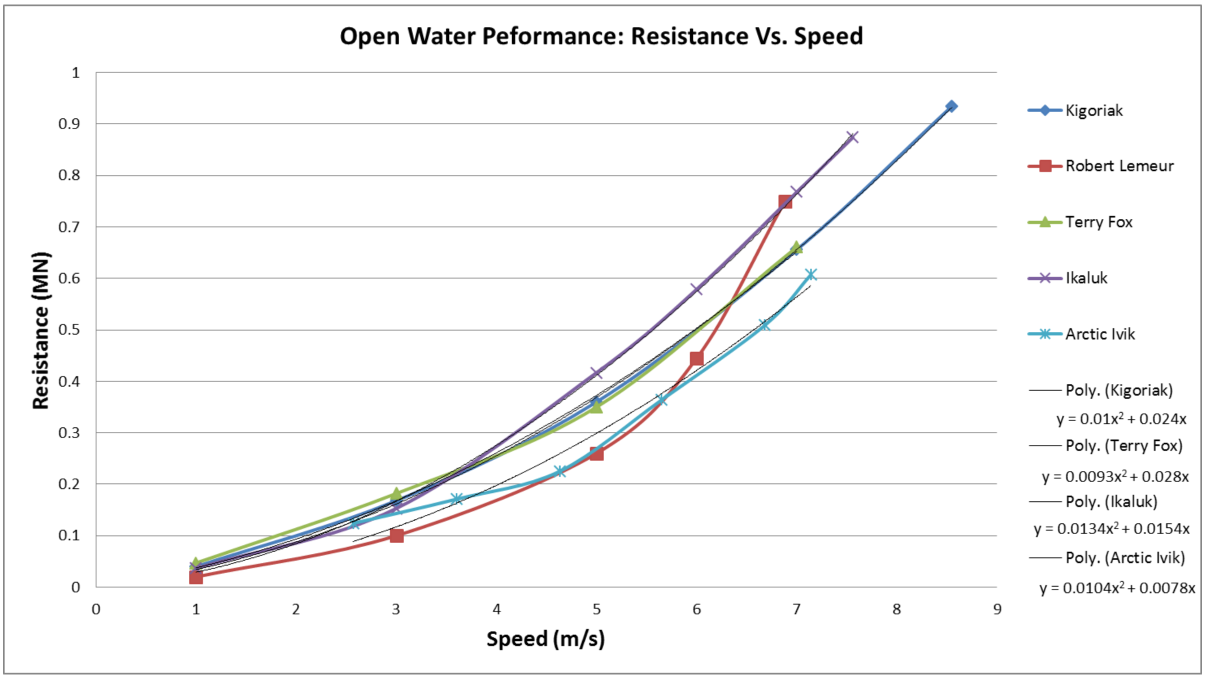



Figure 1. Open water performance (after Keinonen et al., 1989)

Therefore, the open water resistance for these icebreakers could also be estimated as

$$R_{ow} = 0.01 \cdot {V_i}^2 + 0.03 \cdot V_i \quad (3)$$

where,

$V_i$ = Icebreaker initial achieved speed.

There are three common analytical models for ice resistance, including the Riska model (Riska et al., 1998), the Keinonen model (Keinonen et al., 1996, 1991, 1989), and the Lindqvist model (Lindqvist, 1989). To compare, the Riska model only involves ice thickness in its formulas, the Keinonen model considers ice thickness, flexural strength, temperature, and salinity, and the Lindqvist model considers ice thickness, flexural strength, ice friction, shear strength, ice density, Poisson's ratio, and elastic modulus of ice. The Lindqvist model is considered the preferred model to estimate icebreaker ice resistance in level ice due to its comprehensiveness of ice properties.

Lindqvist model is comprised of three resistance components, the crushing resistance ($R_C$), the bending (flexural) resistance ($R_B$), and the submergence resistance ($R_S$), and given as

$$R_{ice} = (R_B + R_C) \cdot \left(1 + 1.4 \cdot \frac{v}{\sqrt{g \cdot H_{ice}}}\right) + R_s \cdot \left(1 + 9.4 \cdot v/\sqrt{g \cdot L}\right) \quad (4)$$

where,

$$R_C = F_v \cdot \frac{\tan\phi + \mu \cdot \cos\phi / \cos\psi}{1 - \mu \cdot \sin\phi / \cos\psi} \quad (4)$$

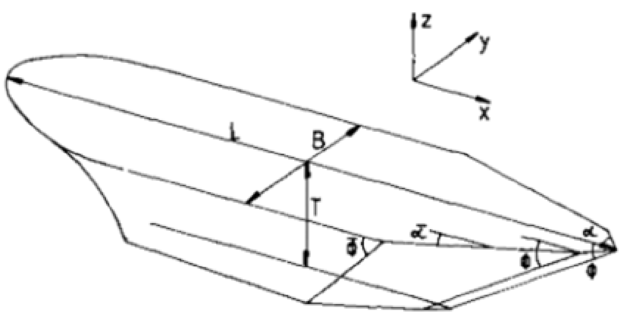
$$F_v = 0.5 \cdot \sigma_f \cdot H_{ice},$$

$\psi = \arctan(\tan\phi \,/\, \sin\alpha)$,

$$R_B = 0.003 \cdot \sigma_f \cdot B \cdot \frac{H_{ice}^{1.5}}{\sqrt{m}} \cdot \left(\frac{\tan\bar{\psi} + \mu\cos\bar{\phi}}{\sin\bar{\alpha} \cdot \cos\bar{\psi}}\right) \cdot \left(1 + \frac{1}{\cos\bar{\psi}}\right), \quad (5)$$

$$R_s = \delta\rho \cdot g \cdot H_{ice} \cdot B \cdot \left(T\frac{B+T}{B+2T} + \mu(0.7 \cdot L - \frac{T}{tan\bar{\phi}} - \frac{0.25 \cdot B}{tan\bar{\alpha}} + T \cdot cos\bar{\phi} \cdot cos\bar{\psi} \cdot \sqrt{\frac{1}{\sin^2\bar{\phi}} + \frac{1}{\tan^2\bar{\alpha}}}\right), \quad (6)$$

$v$ = Icebreaker speed in level ice = $V_i$ ,
$H_{ice}$ = Ice thickness,
$L$ = Length of the ship at waterline,
$F_v$ = Vertical force needed to fail an ice edge in flexure,
$\mu$ = Friction factor (between ice and ship hull),
$\sigma_f$ = Flexure strength of ice,
$m$ = 1,
$\delta\rho$ = Density difference between ice and water,
$B$ = Beam of the ship,
$T$ = Draft of the ship,
$\phi, \alpha, \psi$ = Refers to the angle at the stem, and
$\bar{\phi}, \bar{\alpha}, \bar{\psi}$ = Average angles over the bow sides.




There are many investigators who have studied ice microstructure and its mechanics. For example, Timco and Weeks (2010) provides a good review of engineering properties for first year sea ice and old ice, including growth and microstructure, thickness, salinity and porosity, density, tensile strength, flexural strength, shear strength, compressive strength, multi-axial loading, borehole strength measurements, creep, elastic and strain modulus, Poisson's ratio, fracture toughness, and friction.

With the purpose to determine ice resistance through analytical modelling, ice engineering properties, including thickness, density, friction, flexural strength, shear strength, Poisson's ratio, and elastic modulus, have been reviewed as illustrated in Table *1*.

Table 1. Ice Property Review

| Ice Property | Literature Review | Assumed Value |
|---|---|---|
| Thickness | Estimated through local in-situ measurements, satellites, marine radar, aircraft, helicopter, or icebreaker reconnaissance, as well as freezing degree day analytical modeling | - |
| Density | Reported to vary in the range 720 kg/m$^3$ to 940 kg/m$^3$. The density is also different for ice above or below waterline. For first year sea ice, an estimated value of 920 kg/m$^3$ is commonly used. | 920 kg/m$^3$ |
| Friction | Liu (2009) summarizes the model tests and full-scale experiments work from IOT-NRC and states the ice-hull friction coefficient is usually between 0.01 and 0.2. Timco and Weeks (2010) reviewed the ice friction as static friction and kinetic friction. | Determined by hull conditions |
| Flexure Strength | (Timco and S. O'Brien, 1994) equation: $\sigma_f = 1.76 \cdot e^{-5.88\sqrt{v_b}}$ Frankenstein and Garner (1967) derived brine volume, from Assur's brine volume table (Assur, 1960), for associated ice salinity and ice temperature between -0.5 °C and -22.9 °C. $v_b = S_i \left[\frac{49.185}{\lvert T_i \rvert} + 0.532\right]$ | Equations with environmental data |
| Shear Strength | Timco and Weeks (2010) listed shear strength for granular ice are ranged from 400 kPa to 700 kPa and for columnar ice are ranged from 550 kPa to 900 kPa. Lindqvist (1989) assumed the shear strength equals to the bending strength (flexural strength). | Lindqvist (1989) assumption |
| Poisson's Ratio | Lindqvist (1989) assumed the Poisson's ratio equal to 0.3 for sea ice. Langleben and Pounder (1963) determined the mean value of Poisson's ratio for ice is 0.295±0.009. (Weeks and Assur, 1968, 1967) proposed $\mu_D = 0.333 + 0.06105 \cdot e^{\frac{T_i}{5.48}}$ | Lindqvist (1989) assumption |
| Elastic Modulus | Timco and Weeks (2010) briefed the effective static elastic modulus of ice is in the range of 1.7 to 5.7 GPa, and the effective dynamic elastic modulus of ice is in the range of 1.7 to 9.1 GPa. Lindqvist (1989) used an elastic modulus equals to 2 GPa for his model. | Lindqvist (1989) value |

## STEADY TURNING PERFORMANCE (SPEED)

The reduction in ship speed while turning depends on many factors, both the ship and the ocean. For example, House (2007) points out that the ship's ability to turn is decreased significantly in shallow water, comparing with deep water. More importantly, he indicates the ship speed during hard over turn is decreased by a considerable amount, 30 to 40 percent from the full speed. In addition, he summarizes other factors which include:

- Ship length and superstructure arrangements;
- Distribution of any cargo or weight;
- Draft, trim, and heel;
- The relationship between power and ship displacement;
- Number and type of propellers;
- Rudder angle; and
- External forces that cause heading drift.

While a general understanding of the factors that influence ship turning exists, data to quantify these influences are limited. Even though all factors listed are significant, this study focuses on ship length, heel, and turning diameter in modeling performance.

### Ship Turning in Relation to Turning Diameters and Ship Length

Among those factors described by (House, 2007), the most significant influence is the speed drop while turning, which is related to the ship length and sharpness of the turn. Shiba, et al. (1959) reports experimental findings of ship turning through three ship models. Their main objective is to model the rudder area effect on ship turning, although application may be limited as the rudder properties are not often published. They do however demonstrate a relationship between steady turning speeding over approaching speed and turning diameters over ship length, as shown in Figure 2. Halpern (2007) compares ship turning by Shiba, et al., (1959) with Davidson, (1944) and finds that they have good agreement, as shown in Figure 3.

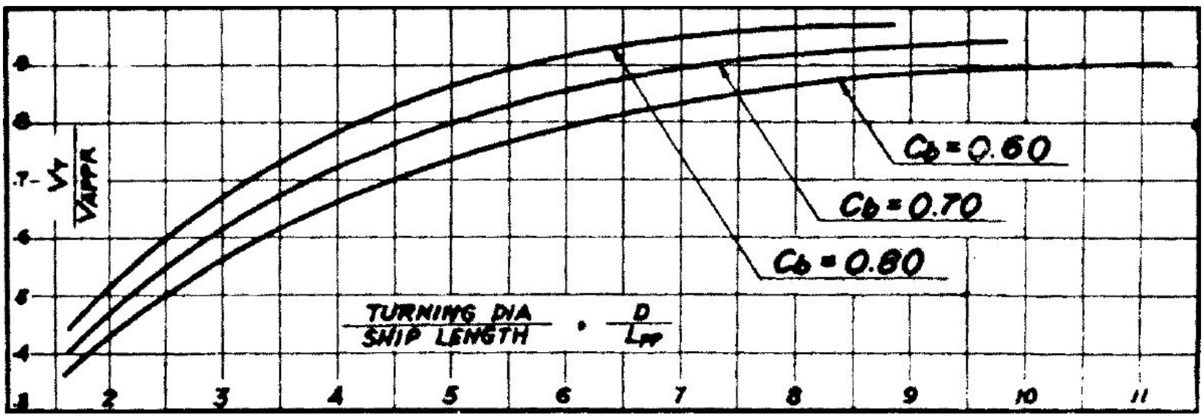



Figure 2. Ship turning performance test (Shiba et al., 1959)

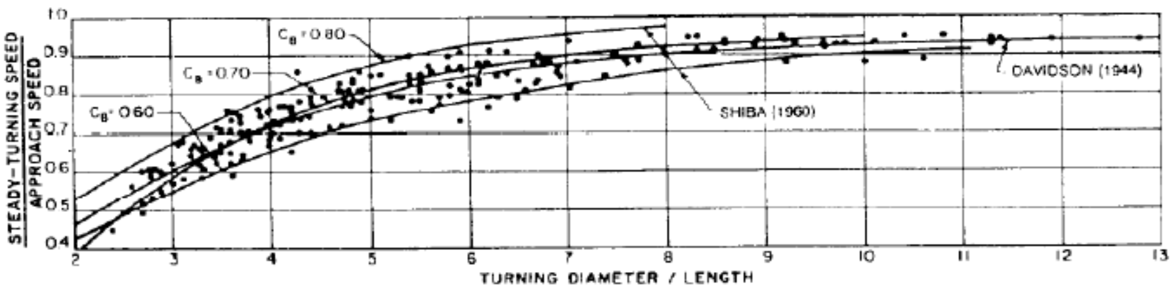



Figure 3. Ship turning performance test: compare (Shiba et al., 1959) with (Davidson 1944)

With this agreement, these curves can be extended to predict turning performance in open water for different conventional propelled ships.

There are many studies on ship turning performance in ice, such as (Brown, 2002; Glen et al., 1991; Lau, 2011; Liu, 2009; Martio, 2007; Quinton and Lau, 2006; Shi, 2002; Zhan et al., 2011; Zhou et al., 2016). Instead of applying a comprehensive model for icebreaker maneuvering, this study takes a simplified approach that models the speed reduction during turning in ice. Assuming the icebreaker turning in ice has a consistent speed reduction as the icebreaker maneuvering in the open water, an icebreaker turning speed coefficient ($C_{Turning}$) for level ice is model as

$$C_{Turning} = \frac{V_{Turning}}{V} \tag{7}$$

where,

$V$ = Icebreaker speed in ice, and

$V_{Turning}$ = Icebreaker turning speed in ice.

For icebreakers with conventional propellers, the smaller the turning diameter, the slower the icebreaker can advance in certain level ice conditions. The secondary icebreaker in particular, has smaller turning diameter requirement. Given that secondary floes are not aligned with an idealistic path or track of the secondary icebreaker, performance will be degraded as 1) frequent maneuvering will be required (i.e. break floes in half), and 2) interference from bow collisions with small floes.

**Active Heeling System**

Active rapid heeling systems are sometimes used on ships to enhanced maneuvering and improve ship turning performance. Table 2 demonstrates the effectiveness of heeling degrees on icebreaker turning with or without rudder engagement.

Table 2. Study of Heeling Effect for Icebreaker Maneuvering (after Keinonen et al., 1989)

| Vessel | Ice Thickness (m) | Heeling (Deg.) | Rudder | Turning Diameter/ Diameter at Zero Heel, Full Rudder in Same Ice |
|---|---|---|---|---|
| Kigoriak | 1.25 | 6 | Full | 7.9/18.7 = 0.42 |
| | 1.25 | 3 | Full | 13/18.7 = 0.7 |
| | 1.25 | 6 | 0 | 19/18.7 = 1.02 |
| | 1.25 | 3 | 0 | 33/18.7 = 1.76 |
| | 1.25 | 6 | Full Opposite | 63/18.7 = 3.37 |
| | 1.4 | 6 | Full | 5.6/18.7 = 0.32 |
| Robert Lemeur | 0.6 | 6 | Full | 12.8/16 = 0.8 |
| | 0.9 | 3 | Full | 11.6/13 = 0.91 |
| | 0.8 | 4 | Full Opposite | 9.1/14.5 = 0.63 |

## SECONDARY ICEBREAKER IN BROKEN ICE FIELD

For large level ice floes or continuous level ice, the resistance to the primary icebreaker is rather consistent (recognizing that ice thickness has natural variability). However, resistance modeling for the secondary icebreaker is more complex.

Besides breaking larger floes into smaller ones, interactions with small floes in a broken ice channel or regime include floe clearing and floe submergence. These contribute to added resistance and loss of heading control.

### Submerging Floes

Depending on the floe size and bow geometry, one component of resistance influencing the secondary icebreaker performance in broken ice channels is floe submergence. With the water drag resistance, the combined resistance $R_{t\_sub}$ could be estimated as described by Eq. (6) and (2) or (3) as

$$R_{t\_sub} = R_s + R_{ow} \tag{8}$$

### Floe Clearing or Ramming

Due to the geometry of the bow and vessel mass relative to the ice floe mass, ice floes that do not submerge may be cleared to the side. If the ice floes have sufficient mass, the energy used to clear the ice floes could be significant. The vessel may also be pushed off course. The energy transfer can be described as

$$E_{IB\_in} + \sum E_{IF\_in} = E_{IB\_out} + \sum E_{IF\_out} \tag{9}$$

where,

$E_{IB\_in}$ = Energy of the icebreaker before impact,

$\sum E_{IF\_in}$ = Sum of energy of the ice floes before impact,
$E_{IB\_out}$ = Energy of the icebreaker after impact, and
$\sum E_{IF\_out}$ = Sum of energy of the ice floes after impact from the icebreaker.

Combining with icebreaker position, ice drift, and surrounding environment, estimating ice floe energy after any interactions with the icebreaker bow may be challenging. However, it is reasonable that the speed of the ice management icebreaker will be reduced. For modeling the degrees of reduction, different analytical models could be considered with reasonable assumptions, such as the Popov model (Popov et al., 1969). At the initial stage of this study, the reduced icebreaker speed could be represented as

$$\frac{1}{2} \cdot m_{IB} \cdot V_{IB\_in}^2 = \frac{1}{2} \cdot m_{IB} \cdot V_{IB\_out}^2 + \frac{1}{2} \cdot m_{IF} \cdot \left(C_p \cdot V_{IB\_out}\right)^2 \quad (10)$$

where,

$m_{IB}$ = Mass of the icebreaker,
$V_{IB\_in}$= Initial icebreaker speed,
$V_{IB\_out}$ = Speed of the icebreaker after impact,
$m_{IF}$ = Mass of the ice floe, and
$C_p$ = Coefficient of the potential ice floe speed relative to the icebreaker (e.g.$C_p = 1$).

An estimate of floe mass assuming a plan view can be approximated by an equivalent circle as

$$m_{IF} = \rho_{ice} \cdot H_{ice} \cdot \pi \cdot R_{ice}^2 \quad (11)$$

where,

$\rho_{ice}$ = Density of the ice floe,
$\mathrm{H_{ice}}$= Thickness of the ice floe, and
$R_{ice}$ = Radius of the ice floe.

The resulting speed coefficient model ($C_{Broken}$) for an icebreaker in a broken ice field can be estimated as

$$C_{Broken} = \frac{V_{IB\_out}}{V_{IB\_in}} = \sqrt{\frac{m_{IB}}{m_{IB}+m_{IF}}} \quad (12)$$

The total length of the broken ice field is determined by the beam of the icebreaker and number of ice channels encountered. Hamilton et al. (2011) experimentally demonstrated that an icebreaker forms a channel having a width equal to its beam that is filled with brash ice and will break ice between channels with a nominal 1 to 1 aspect ratio as shown in Figure 4. Hisette et al. (2014) suggested the formed ice channel equal to 1.3 times of the beam width during ice management operations. A secondary icebreaker would typically run into broken ice field at each loop of ice management operation. A theoretical example is shown in Figure 5a.

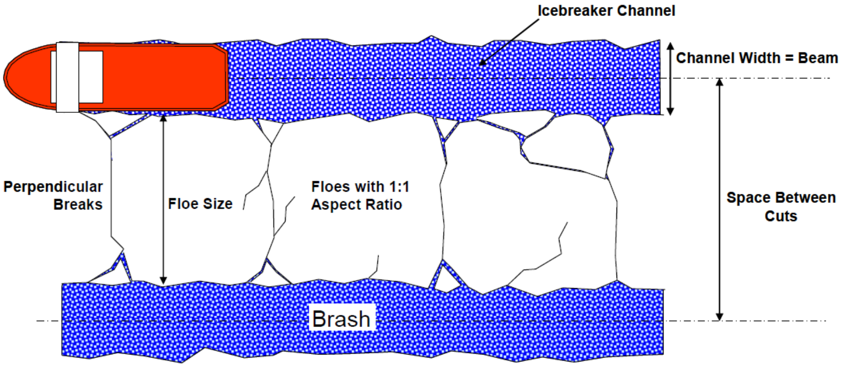



Figure 4. Ice break-up characteristics (Hamilton et al., 2011c)

If the ice floe has sufficient mass and sufficient thickness to prevent flexure failure, the icebreaker may require multiple attempts (i.e. rams) to transect the floe. For scenarios where continuous ramming may be required, comprehensive ship-ice interaction models (e.g. $F_{MAX}$ software by Carter et al. 1995) could be used to estimate required time for the icebreaker to ram through the tough ice field. Field experience from Wright (1999) could also be referenced to estimate time requirement for an icebreaker to break a ridge in general.

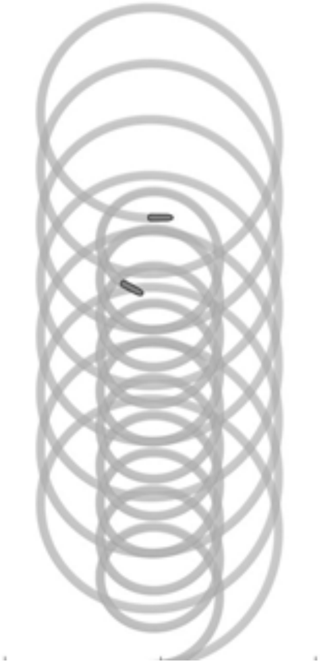
## CONTINUOUS MANOEUVRING

For a drifting large ice field, icebreakers need to adjust speed to achieve advance distance and target managed floe sizes.

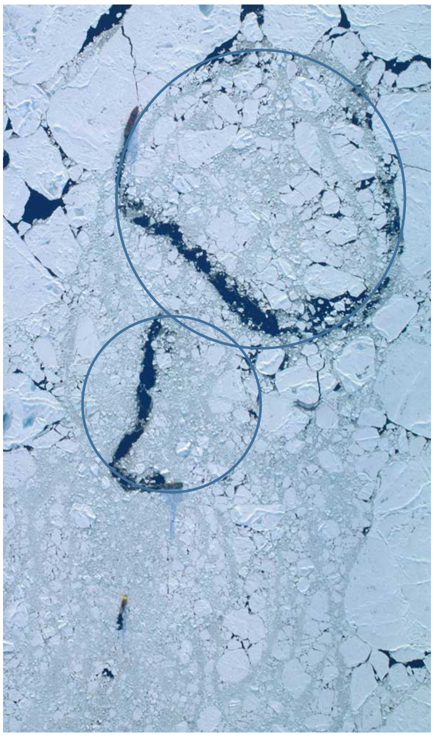
### Deflecting and On-Demand Manoeuvring

Theoretically, idealized icebreaking patterns may be chosen to reduce the size of oncoming ice floes based on a target managed floe size. The actual track however, as illustrated in Figure 5b, may be quite different as the location of the floes will not likely be aligned with the idealized track. The maneuvering associated with this actual track will reduce performance.

If the secondary icebreaker gets deflected off course, the vessel has to continuously maneuver to correct the heading to maintain some target track. The vessel may also have to continually chance course or maneuver to align with an ice floe that is off its track to ensure the floes are managed to achieve the target floe size. These are conceptually illustrated in Figure 6 and each will reduce speed and time required to achieve performance targets.



(a) Ideal planned



(b) Actual
(Shipboard Scientific Party, 2005)

Figure 5. Comparing (a) ideal planned to (b) actual ice management operation from Arctic Coring Expedition 2004

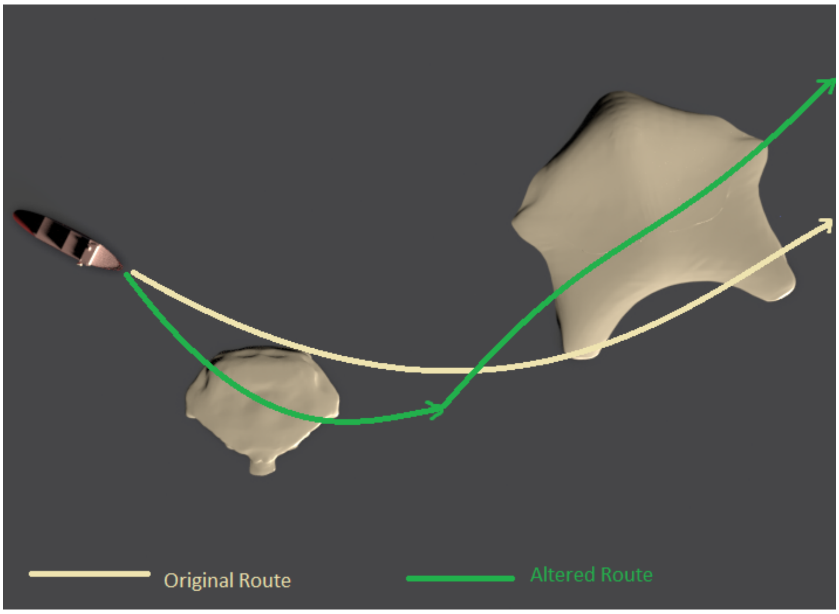



Figure 6. Original route vs. altered route

**Ice Drift**

Ice floes drift based on wind, current, and earth rotation effects. While ultimate management performance will depend on the accuracy of forecasting, the focus here is on performance given ice floes are present.

With respect to ice drift, frequent changes in drift speed and direction will require active changes to maneuvering parameters, which will slow ice management progress requiring more time.

To account for frequent turning requirements relative to planned turning, on-demand maneuvering coefficient $C_{Maneuvering}$ is defined as

$$C_{Maneuvering} = \frac{V_M}{V_{in}} \quad (13)$$

where,

$V_M$ = Icebreaker on-demand maneuvering speed, and
$V_{in}$ = Icebreaker speed before on-demand maneuvering.

## SECONDARY ICEBREAKER PERFORMANCE MODELING

The secondary icebreaker performance model is comprised of icebreaker level ice performance, icebreaker steady turning performance, icebreaker performance in broken ice fields, and icebreaker on-demand maneuvering performance. Assuming an ice management loop to be an idealized circle, the effective secondary icebreaker operational speed ($V_{E\_SIB}$) can be estimated

$$V_{E\_SIB} = \frac{L_{LI}}{\pi \cdot D} \cdot V_{LI\_SIB} \cdot C_{Turning} \cdot C_{Broken} \cdot C_{Maneuvering} + \frac{L_{BI}}{\pi \cdot D} \cdot V_{BI\_SIB} \cdot C_{Turning} \cdot C_{Broken} \cdot C_{Maneuvering} \quad (14)$$

where $L/(\pi \cdot D)$ represents the ratio of advance relative to an idealized planned circle and $V_{LI\_SIB}$ and $V_{BI\_SIB}$ are the secondary icebreaker speeds in level and broken ice respectively.

**Comparison between the Model and Field Trial Data**

Keinonen et al. (1989) reported some field trial data of icebreaker performance for different icebreakers in different ice and environmental conditions (i.e. icebreaker full power performance, and icebreaker turning circle performance at effective turning diameters). Based on the data, the level ice part of the performance model is tested. Since the turning circle trials were carried out with full or close to full power, full rudder, and no heel conditions at continuous turning, coefficients from broken ice and maneuvering ($C_{Broken}$ $and$ $C_{Maneuvering}$) in Eq. (12) and (13) are set to 1 respectively. Estimated turning speeds with recorded turning speeds for given ice and environmental conditions, as shown in Table 3. Due to relative large turning diameters, some estimated turning speeds are close or equal to estimated level ice speed. While comparison data are limited, reasonable consistency is achieved.

Table 3. Comparing Modeled Performance with Data

| Vessel | Ice Thickness (m) | Power (MW) | Hull Condition | Turning Circle Diameter (m) | Recorded Turning Speed (m/s) | *Estimated Level Ice Speed (m/s) | Estimated Speed with $C_{Turning}$ (m/s) |
|---|---|---|---|---|---|---|---|
| Terry Fox | Open Water | 14 | Inerta Coating | 329 | - | 9.0 | 5.00 |
| | 0.22 | | | 366 | 4.98 | 8.03 | 4.88 |
| | 0.75 | | | 2100 | - | 4.94 | 4.94 |
| | 1.5 | 12.8 | | 3744 | - | 1.22 | 1.22 |
| Kigoriak | Open Water | 12 | Bare, smooth, Lube on | 438 | - | 8.70 | 5.28 |
| | 0.35 | | | 455 | - | 7.23 | 4.52 |
| | 0.67 | | | 775 | - | 5.80 | 3.62 |
| | 1.22 | 11.2 | | 1196 | 2.30 | 2.65 | 2.29 |
| | 1.26 | 10.2 | Bare, rough | 1579 | 1.58 | 1.70 | 1.57 |
| | 1.43 | 11.2 | Lube on | 1423 | 1.50 | 1.70 | 1.53 |
| Robert Lemeur | Open Water | 7.1 | Inerta Coating | 198 | - | 7.1 | 2.71 |
| | 0.63 | | | 1369 | - | 4.57 | 4.57 |
| | 0.64 | | | 1266 | - | 4.53 | 4.49 |
| | 1.1 | | | 1543 | - | 2.09 | 2.09 |

*Note: Ice properties are based on average values from the data;
Ice-hull frictions are based on hull condition.

**Application**

For example, let us assume a Kigoriak type vessel is operating at full power managing 1 m thick ice at 500 m turning diameter ($C_{Turning} = 0.67$) to produce 50 m diameter floes. For each loop (see Figure 5a), it is assumed that:

- the secondary icebreaker encounters broken ice channel an average of 12 times where the width of each channel $L_{BI} = 25\ m$,
- one small floe fragment occurs for each broken channel width that deflect the vessel from its planned course,
- nine tenths of the pre-managed floes are typical level ice with one tenth of the floes having a small diameters approximately one half of the planned ice floe size diameter (i.e. $D_{UB} = 25m$), such compliance of the floe and loss of energy reduces the icebreaking capability; and
- one unexpected maneuvering is required within each planned loop at the vessel's maximum maneuverability (e.g. maneuver back to original route within about 3 ship length).

Based on these assumptions for each loop, the following are considered in modeling the secondary icebreaker performance:

- icebreaker in large ice floes ($V_{LI\_SIB} = 3.3\ m/s, C_{Broken} = 1\ and\ C_{Maneuvering} = 1$),
- icebreaker between two large ice floes with one smaller unbreakable/un-submergible floe fragment ($C_{Broken\_1} = 0.67\ and\ C_{Maneuvering} = 1$),
- icebreaker maneuvering between two large ice floes ( $C_{Broken} = 1\ and\ C_{Maneuvering\_1} = 0.36$),
- and icebreaker in broken ice channel with one smaller unbreakable/un-submergible floe fragment ($V_{BI\_SIB} = 6.5\ m/s, C_{Broken\_2} = 0.67\ and\ C_{Maneuvering} = 1$).

Hence, the effective speed of the second icebreaker can be estimated using Eq. (14) as

$$V_{E\_SIB} = \frac{10}{12} \cdot \frac{L_{LI}}{\pi \cdot D} \cdot V_{LI\_SIB} \cdot C_{Turning} \cdot \left(\frac{9}{10} + \frac{1}{10} \cdot C_{Broken\_1}\right) + \frac{2}{12} \cdot \frac{L_{LI}}{\pi \cdot D} \cdot V_{LI\_SIB} \cdot C_{Turning} \cdot C_{Maneuvering\_1} + \frac{L_{BI}}{\pi \cdot D} \cdot V_{BI\_SIB} \cdot C_{Turning} \cdot C_{Broken\_2} \qquad (15)$$

$$V_{E\_SIB} = 2.1\ m/s$$

The resulting estimated performance illustrates that the vessel could only maintain about 60% of its level ice capability as a secondary icebreaker. The assumptions are considered conservative. If there are more unbreakable/un-submergible/embedded multi-year ice floes, more requirements on maneuvering, or the vessel's maneuverability is over-predicted, the secondary icebreaker might be less than 50% of her level ice capability. Additional test data (field and model) will help clarify these uncertainties.

## CONCLUSIONS

Understanding the factors that influence reduced secondary icebreaker performance are important for ice management operational planning.

Compared with the primary icebreaker, the secondary icebreaker may require increased icebreaking and turning capabilities depending on ice conditions. To model the speed reduction of an icebreaker while turning, a simple approach has been developed and compared with field trial data. With the complexity of secondary icebreaker operations, two extra influence factors are considered, including interactions with smaller ice floes and on-demand maneuvering for unexpected situations.

Consistent with field observations, the resulting model and illustrative example demonstrates the speed reduction in secondary icebreaker performance compared with idealistic modeling. This reduction in performance is important when developing ice management plans and requirements for icebreaker support.

While the performance model compares well with available operational field data, additional verification with more recent field trial data are recommended. The resulting performance model will be implemented in C-CORE's ice management analysis and planning software which has a probabilistic modeling capability to assist with designing an ice management fleet to support station-keeping operations in specific regions having particular ice conditions. Modeling the variability that exists with ice and environmental data, the probabilistic approach allows one to base decisions on a target annual probability of exceedance (e.g. $10^{-2}$).

## ACKNOWLEDGEMENTS

The authors gratefully acknowledge core funding for C-CORE's CARD program by the Hibernia Management and Development Company Ltd. (HMDC), the Terra Nova Development (Suncor Energy Inc. – Operator), and the Research and Development Corporation of Newfoundland and Labrador (RDC).

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