NRC Publications Archive
Archives des publications du CNRC

Model experiments to support the design of large icebreaking tankers
Molyneux, W. D.; Kim, H. S.

This publication could be one of several versions: author's original, accepted manuscript or the publisher's version. / La version de cette publication peut être l'une des suivantes : la version prépublication de l'auteur, la version acceptée du manuscrit ou la version de l'éditeur.

NRC Publications Record / Notice d'Archives des publications de CNRC:
https://nrc-publications.canada.ca/eng/view/object/?id=078fc0d7-3510-41f3-9b7b-0937d297f157
https://publications-cnrc.canada.ca/fra/voir/objet/?id=078fc0d7-3510-41f3-9b7b-0937d297f157

Access and use of this website and the material on it are subject to the Terms and Conditions set forth at
https://nrc-publications.canada.ca/eng/copyright
READ THESE TERMS AND CONDITIONS CAREFULLY BEFORE USING THIS WEBSITE.

L'accès à ce site Web et l'utilisation de son contenu sont assujettis aux conditions présentées dans le site
https://publications-cnrc.canada.ca/fra/droits
LISEZ CES CONDITIONS ATTENTIVEMENT AVANT D'UTILISER CE SITE WEB.

Questions? Contact the NRC Publications Archive team at PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca. If you wish to email the authors directly, please see the first page of the publication for their contact information.

Vous avez des questions? Nous pouvons vous aider. Pour communiquer directement avec un auteur, consultez la première page de la revue dans laquelle son article a été publié afin de trouver ses coordonnées. Si vous n'arrivez pas à les repérer, communiquez avec nous à PublicationsArchive-ArchivesPublications@nrc-cnrc.gc.ca.

National Research Council Canada
Conseil national de recherches Canada

MODEL EXPERIMENTS TO SUPPORT THE DESIGN OF LARGE ICEBREAKING TANKERS

D Molyneux, Institute for Ocean Technology, National Research Council, Canada
H S Kim, Marine Research Institute, Samsung Heavy Industries, Korea

SUMMARY

In 1997, Samsung Heavy Industries became interested in applying its expertise in the design and construction of oil tankers to the specialized construction of ice class vessels for oil transportation in the Arctic Ocean and Baltic Sea. This interest was motivated by the potential development of several offshore and near shore oil and gas reserves together with increased shipping of oil through the Baltic Sea from Russia. Since at that time, Samsung Heavy Industries had little experience with performance prediction for ships in ice, they entered into a collaborative project with the Institute for Ocean Technology to apply and refine the modelling techniques required for predicting the performance of large tankers in ice.

This paper describes the modelling methods used. One important technique is the preparation of the model ice, and the scaling of the ice forces. Equally important is the preparation of the ship model and its propulsion system. The two models are combined to predict the powering and manoeuvring performance for large tankers in a range of ice conditions including level first year ice, pack ice and rubble ice. The results of experiments on four hull designs, with single and twin-screw propulsion arrangements, are presented and discussed and some suggestions are made for refining the modelling techniques for future projects.

NOMENCLATURE

B	Maximum beam of the model, m
C_b	Coefficient of the buoyancy resistance, R_b
C_{br}	Coefficient of the breaking resistance, R_{br}
C_c	Coefficient of the clearing resistance, R_c
C_o	Ice concentration
F_p	Average pack ice force, N
g	Acceleration of gravity (9.808 m.s^{-2})
h_i	Ice thickness, m
R_b	Resistance due to buoyancy of the ice, N
R_{br}	Resistance due to breaking the ice, N
R_c	Resistance due to clearing of the ice, N
R_{ow}	Resistance due to open water, N
R_t	Total resistance in ice, N
T	Maximum draft of the model, m
V_m	Model velocity, m.s^{-1}
$\Delta\rho_i$	Difference in density between ice and water.
λ	Linear scale of the model
μ	Hull-ice friction coefficient
ρ_i	Density of the ice, kg.m^{-1}
σ_f	Flexural strength of the ice, N.m^{-2}

1. INTRODUCTION

In 1997, Samsung Heavy Industries (SHI) became interested in applying its expertise in the design and construction of oil tankers to the specialized construction of ice class vessels for oil transportation in the Arctic Ocean and Baltic Sea. This interest was motivated by the potential development of several offshore and near shore oil and gas reserves together with increased shipping of oil through the Baltic Sea from Russia. Since at that time, Samsung Heavy Industries had little experience with performance prediction for ships in ice, they entered into a collaborative project with the Institute for Ocean Technology (IOT) to apply and refine the modelling techniques required for predicting the performance of large tankers in ice.

A major portion of the effort for this project was for Naval Architects from Samsung Heavy Industries to become familiar with the challenges associated with designing and building ships for operation in ice covered waters. To achieve this objective, several staff from SHI's Marine Research Institute spent extended periods of time in St. John's, Newfoundland, Canada at the National Research Council's Institute for Ocean Technology (formerly Institute for Marine Dynamics). Staff from IOT explained the modeling processes for ships in ice and provided background literature on ship performance in ice-covered waters to the SHI staff.

The three main types of ice considered for this project were:

- Level first year ice,
- Pack ice in concentrations from 80% to 95%,
- Rubble ice, which consisted of multiple layers of ice, up to three times the initial thickness of the component ice sheet.

Brash ice, to simulate a channel broken by an icebreaker (or other ice capable ships) was also prepared by cutting a channel with straight edges. The ice within the channel was broken into small flows and evenly distributed over the area of the channel to give a nominal concentration between 90 and 100%. This required compacting the ice so that the final length of brash ice was less than the length of the un-broken ice sheet.

This paper presents a summary of the latest methods used by the Institute for Ocean Technology for predicting the performance of large tankers in ice, and presents the results of performance predictions for four ships designed as part of this project. Earlier procedures for model testing at IOT [1] were used as the starting point for developing and refining these techniques. The designs evaluated consisted of two twin screw Aframax sized tankers designed for Arctic ice conditions [2], a twin screw Suezmax sized tanker designed for Arctic ice conditions [3] and a single screw tanker, with bulbous bow, designed for Baltic ice conditions. All five icebreaking tanker designs were compared with a conventional tanker in open water, pack ice and level ice [4].

2. MODELING THE SHIP AND THE ENVIRONMENT

2.1 Ice

The EG/AD/S (CD) model ice prepared in the ice tank at IOT has been developed to provide the kinematic and mechanical characteristics required to model the ship-ice interaction correctly. The ice is grown at a carefully controlled temperature in a mild EG/AD/S (Ethylene Glycol/ Aliphatic Detergent/ Sugar) solution resulting in uniform thickness, with standard deviation normally less than 3%. Fine bubbles are selectively incorporated into the ice to produce the required ice density and plate stiffness. The ice is tempered for a period of time before the test, until the required flexural strength is achieved. Shear strength and compressive failure stresses are established as functions of the flexural strength, similar to the full scale relationships. The ice has a columnar grain structure as is normally found in nature.

Ice flexural strength is measured by sets of cantilever beam tests at different times and locations in the tank. For each ice sheet, flexural strength-time curves are developed, and strength is interpolated to test time and location. Ice thickness is measured every two metres along the ship track after a test. Ice density, shear strength, and compressive failure stress are determined from flexural strength relations, calibrated by measurements in each ice sheet. Pack ice concentration is determined from digitized overhead photographs of each ice sheet.

Additional ice conditions can be prepared from the level ice sheets, after completion of tests in this ice condition. Brash ice is prepared on the centreline of the ice tank, by cutting a channel with straight edges. The width of the channel is determined to be some fraction of the ships beam, and will vary depending on the requirements of a particular project. The ice within the channel is broken into small flows and distributed evenly within the channel. Nominal concentration within the channel should be between 90 and 100%. This requires compacting the ice so that the final length of brash ice is less than the length of the unbroken ice sheet. Photographs of the brash ice are taken and analyzed to estimate the concentration of ice within the channel.

Pack ice can be prepared in a similar manner by breaking the ice sheet into approximately uniform floes, and distributing them evenly over the test area. Photographs of the pack ice are taken and analyzed to estimate the concentration of ice within the test area. Two concentrations of pack ice were used in this project (95% and 75% nominal values).

2.2 Ship Models

A typical scale for a tanker model at IOT is approximately 1:35. This provides an adequate compromise between the size of the model hull and propeller, together with the required ice thickness and flexural strength at model scale. Ice thickness and strength both scale linearly with the scale factor. Model hulls are constructed from a Styrofoam™ Hi 60 polystyrene foam core with a ¾” plywood floor and Renshape™ for areas requiring reinforcement. An internal structure of wooden frames and a deck provide additional strength. The foam is milled, with a 5-axis computer controlled milling machine, to the required shape of the hull. After hand smoothing the foam is covered with 3 layers of 10oz glass fibre cloth and epoxy resin. The internal surfaces of the model are covered with one layer of glass fibre cloth and resin to bond the structure together.

The external surface is primed with Duratec™ Primer Surfacer, sanded to 80 grit, followed by Duratec™ Primer sanded to 220 grit. The model and appendages are painted with 3 coats of Imron™ Caterpillar yellow finish, with the final surface finish having a friction coefficient to match the nominal value between a new ship and sea ice. A wooden board finished with the same surface preparation as the model is made at the time of model construction. This can be used to determine the hull-ice friction coefficient. The model is fitted with a propeller shaft, rudder, ice knife and any other appendages. The model is marked with 11 stations, the centerline and the design waterline.

Power to the propellers is provided by an electric motor fitted to the propeller shaft. A strain gauge dynamometer is used to measure thrust and torque on the shaft. The model is towed with a tow post incorporating a gimbal, which allows the model freedom to sink and trim, but restrained in yaw. Tow force is measured using a load cell built into the gimbal. Rotation rate on the propeller shaft was measured by a tachometer.

3. DESCRIPTION OF MODEL EXPERIMENTS & ANALYSIS METHODS

3.1 Resistance in Level Ice

The method used for carrying out resistance experiments in ice assumes that four different forces occur when a ship moves through ice. These forces are due to the breaking the ice, the movement of the ice pieces around the hull, the friction of the ice against the hull, and the open water resistance (which is itself probably modified by the presence of the ice). These forces all scale differently to full-scale. Therefore, tests are conducted in open water, in level ice, and in pre-sawn ice in order to determine the resistance due to the different processes. Also, by using non-dimensional coefficients, it is easy to extrapolate the results to full-scale.

Therefore, we have,

$$R_t = R_{br} + R_c + R_b + R_{ow} \qquad \cdots\cdots\cdots\cdots\cdots (1)$$

Note that the breaking resistance, R_{br}, is the only term that cannot be measured directly in the ice tank.

The open water term, R_{ow}, is determined by first testing the model in open water at the same speeds as those used in the ice tests.

The theory of the pre-sawn test is that it measures everything except the breaking term, (R_c+R_b+R_{ow}). Since R_{ow} is known, the pre-sawn test determines R_c+ R_b at each speed. By conducting a pre-sawn test at very low speed, V_M=0.02 ms^{-1}, the dynamic forces associated with ice block rotation, ventilation, and acceleration are negligible, leaving only buoyancy, and a sliding friction term which is included in R_b. Having measured R_b, which is independent of velocity, it is subtracted from R_c+R_b to give R_c, which is velocity dependent. R_{ow}, and R_t are also measured for each velocity. Thus R_{br} can be calculated from equation (1) above, and all components can be determined.

In order to scale the model results to full-scale it is convenient to deal with non-dimensional coefficients for the resistance terms. These are defined as:

$$C_{br} = \frac{R_{br}}{\rho_i B h_i V_M{}^2} \qquad \cdots\cdots\cdots\cdots\cdots (2)$$

$$C_c = \frac{R_c}{\rho_i B h_i V_M^2} \qquad \cdots\cdots\cdots\cdots\cdots (3)$$

$$C_b = \frac{R_b}{\Delta\rho_i g B h_i T} \qquad \cdots\cdots\cdots\cdots\cdots (4)$$

A non-dimensional strength number is defined as;

$$S_n = \left[\frac{\rho_i B V_M^2}{\sigma_f h_i}\right]^{1/2} \qquad \cdots\cdots\cdots\cdots\cdots (5)$$

Natural logarithms of C_c are plotted against natural logarithms of Fn_h, where Fn_h is the depth Froude number

$$Fn_h = \frac{V}{\sqrt{g h_i}} \qquad \cdots\cdots\cdots\cdots\cdots (6)$$

and natural logarithms of C_{br} are plotted against natural logarithms of S_n. Linear equations are fitted to both these relationships, and these equations are used to predict the effect of ice strength, thickness, densities of ice and water and ship speed within the range of the data obtained from the experiments.

The resulting force components are scaled from model to full scale by λ^3, except for the open water resistance, which includes a viscous scaling factor, based on the ITTC 1957 line. Figures 1 and 2 show a model in level ice and pre-sawn ice.

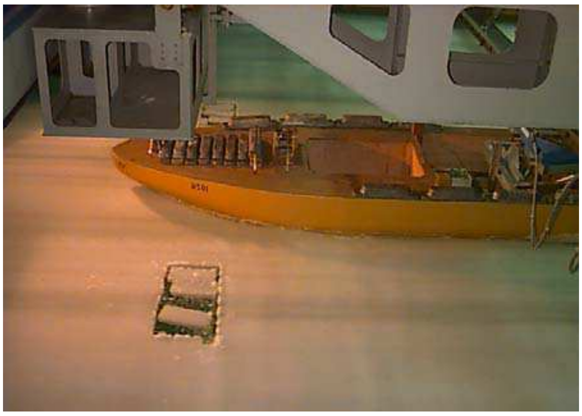

Figure 1, Model tanker in level ice

Figure 2, Model Tanker In Pre-Sawn Ice

3.2 Resistance in Pack Ice

A method for analyzing the results of resistance in pack ice has been presented [6] which considers only the buoyancy and submergence forces caused by the ice on the ship's hull. This method is the same as the analysis of the pre-sawn resistance component used in level ice resistance analysis, with the addition of an ice concentration component. For pre-sawn ice (100% concentration) this factor has a value of 1.0. A model tested in pack ice is shown in Figure 3.

Figure 3, Model Tanker In Pack Ice, 95% Concentration

In the analysis of level ice resistance (presented above) it was assumed that there were four force components, all of which scale separately. In the case of resistance in pack ice, provided that the flow sizes are small and there is very little breaking component, the ice breaking forces can be ignored. Resistance forces on a ship model due to pack ice are determined by subtracting the hydrodynamic resistance, determined from the open water experiments, from the total measured resistance.

The remaining force component can be non-dimensionalized using

$$C_p = \frac{F_p}{1/2\rho_i B h V_i^2 C_o^n} \ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

Velocity can be non-dimensionalized using Pack Ice Froude Number (Fn_p,). The linear function

$$Fn_p = \frac{V_m}{\sqrt{g h_i C_o}} \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots(7)$$

was found to be the most appropriate.

The two coefficients are related by a function derived from the measured data. Experience has shown that Ln(C_p) is a linear function of Ln(Fn_p)

Colbourne [5] recommended a value of 3 for n in equation (6), based on data for speeds appropriate for moored ships or FPSOs, where the only flow component was caused by a current. Analysis of the arctic tanker data for SHI, together with other ships tested in pre-sawn ice and pack ice, suggests a value of 2 collapses pack ice and presawn ice resistance onto a single line, with the smallest error band.

3.3 Delivered Power in Ice

The principle of IOT's method for predicting delivered power in ice is that overload experiments in open water can be used to predict the hydrodynamic torque required to develop a thrust sufficient to move the hull against a force equal to the hull resistance in ice. Because such open water tests cannot take account of any ice-propeller interaction, it is necessary to conduct a corresponding experiment in ice to determine the increase in torque due to propeller-ice interaction. It is assumed in this method that propeller-ice interaction has a negligible effect on the thrust developed by the propulsion system. This has been shown to be true for small values of h_i/D where h_i is the ice thickness and D is the diameter of the propeller. The torque due to ice is considered a function of the ice parameters (thickness, strength etc.) and added to the open water values. This method is applicable to all types of ice, provided overload experiments in are carried out in each ice condition.

This method has the practical advantage that because the towing carriage arrangement for resistance in ice tests and overload propulsion in ice tests are identical, it is possible to change quickly from one to the other. Thus, resistance and propulsion experiments in the same ice sheet are possible.

For overload experiments in open water the model is towed, as in resistance experiments, but the with the propellers operating. The speed range of interest was the ice-breaking condition from zero up to 8 knots. Thrust, torque and revolutions were measured, together with model resistance, which for low speeds and high delivered power was a towrope pull. Five different rates of shaft revolutions up to approximately maximum delivered power for the ship were tested at each forward speed. Measured torques were corrected to the value at the propeller by carrying out experiments before and after the propulsion experiments to determine the mechanical friction in the stern tube bearings.

Self-propulsion experiments in ice using an overload method were conducted in a similar manner to open water experiments. It was not necessary to predict exactly the ship self-propulsion point, but the experiment was carried out at a rate of propeller rotation as close to that point as possible. The required rate of shaft rotation was estimated from the results of the resistance in ice experiments and the open water overload experiments by equating the tow force to the resistance in ice. The shaft revolutions were set and the model was towed through the ice sheet. Values of thrust and torque in ice were measured on each shaft, together with tow force and shaft revolutions. The total torque was analyzed to determine the mean value for each ice condition, relative to the open water value determined above.

Video records of four views of the model were made of all experiments in ice. These views covered underwater, bow and stern, and above water bow and beam views. The underwater views are necessary for observing ice flow around the hull and through the propellers.

3.4 Performance In Other Ice Conditions

Resistance and propulsion experiments in brash ice were carried out in a similar manner to those in level ice and pack ice. Initial concentration of ice floes within the channel was approximately 95%, which was the same nominal value as the heavy pack ice condition. First the model was towed at three speeds through the channel filled with ice floes, and resistance was measured. Friction tests were carried out, the propeller was fitted, and propulsion experiments were carried out to obtain the level of propeller-ice interaction at the same three speeds.

Results were presented in non-dimensional form, of C_p against Fn_p, where the coefficients have the same definition as for the analysis of resistance in pack ice, with ice concentrations estimated from photographic records of the brash ice before testing. Power equations were fitted to the data and these equations were used to predict the resistance values at which the open water overload data were interpolated.

4. MODEL-SHIP CORRELATION

The primary objective of carrying out model tests in ice is to make realistic predictions of the performance of the ship in the expected full-scale ice conditions. This requires the measurement of the same ice properties and ship performance data for the ship as were measured for the model. Ship performance parameters can be measured using the same approaches as those used for open water performance measurement [6]. Propeller shaft torque can be measured by either strain gauges on the propeller shaft, or more complex Acurex torsion meters fitted to the shaft. Rotation rate can be measured by tachometers fitted to the propeller shaft. Thrust can be obtained from thrust blocks in the propeller shaft or from strain gauges oriented for thrust rather than torque. Ship speed is commonly measured by differential GPS.

Measured ice properties are an essential part of the model-ship correlation process. Ice thickness can be measured directly by drilling holes along the projected track of the ship, using either a trial party deployed on the ice, or by means of an automated auger system deployed using the ship's crane. The disadvantage of this approach is that ice thickness is only available at the specified measurement points. A continuous record of ice thickness can be obtained from a video view of the ice pieces turned on their side as part of the breaking process. This view must be calibrated using a grid of known dimensions at the level of the unbroken ice sheet. The temperature and salinity profiles of ice core samples are used to obtain the estimated values of flexural strength. An alternative method is direct in-situ measurements of flexural strength using a cantilever beam test, similar to the one used in the model basin, but this is much more time consuming and expensive to use. A photograph of a trials team in action is given in Figure 4.

Figure 4, Trials team making full-scale ice properties measurements

Table 1, Summary of Ship Dimensions in Model-Ship Correlation Studies

	CCGS type 1200, R-Class medium icebreaker	USCGC Healy
Length, O. A (m)	98.2	128.0
Beam (m)	19.1	25.0
Draft (m)	7.2	8.9
Displacement (tonnes)	7,800	16,000
Power (MW, total)	10.14	11.2
No. of propellers	2	2
Diameter[1]	4.12	4.70
P/D	0.775	0.775
Direction of rotation	Outwards	Outwards
Service speed, open water (knots)	16.2	17.0
Model scale	1:20	1:23.7

---

[1] The same propellers were used on both model hulls. The linear scale of each hull was changed to match the required diameter for the ship.

Since there have been relatively few icebreaking ships built in North America in recent years, IOT has attempted to take a rigorous scientific approach to modeling and model-full scale correlation. The most recent studies comparing the results of model tests in ice, using the methods described above, with full scale data are given in [7] and [8].

In both cases, the ships for which full-scale data were available were government owned icebreakers. The principle particulars of each ship are given in Table 1. The advantage of using this type of ship is that there are typically very extensive acceptance trials, including many more data points for ice conditions and ship performance data than would be typically obtained for a commercial merchant ship.

The conclusions from these studies were that a hull-ice friction coefficient of 0.05 gave acceptable correlation between model predictions and full-scale measurements for cases when the hull is in good condition (typically freshly painted) and there is negligible snow cover. In cases where the hull roughness has increased above this level, or when the snow cover is significant this coefficient should be increased to 0.065. At model scale, changing the hull-ice friction coefficient from 0.03 to 0.09 resulted in doubling the delivered power required to propel the ship, and illustrated the importance of maintaining a low value of this coefficient.

The very nature of the material properties of ice (at model and full scale) results in much more uncertainty in measurements compared to traditional hydrodynamic testing. The flexural strength of ice is very sensitive to variations in thickness and tempering temperature, as well structural imperfections within the ice sheet. As a result, uncertainty in full-scale measurements is expected to be within 15% and measurement at model scale within 8% [7].

5. PERFORMANCE PREDICTIONS FOR FIVE TANKER DESIGNS

The detailed descriptions of the development of the hull designs used for illustration have been given [2, 3, 4]. A summary of the ship particulars is given in Table 2. The predictions of ship resistance in level ice against speed are given in Figure 5 for ice 0.75m thick and Figure 6 for ice 1.4m thick. Delivered power predictions are plotted against speed for ice 1.0m thick in Figure 7. Figure 8 shows resistance in pack ice against speed, at 95% coverage, for ice 1.0m thick. Figure 9 shows delivered power in pack ice against speed, for 95% coverage at a thickness of 1.0 m.

These results are helpful to determine which hull features result in the lowest resistance and delivered power. It is particularly important to note that the lowest resistance in ice need not necessarily result in the lowest delivered power. The amount of ice broken by the bow of the ship that interacts with the propellers is a key factor in determining the delivered power. The Aframax tankers were relatively shallow draft, which resulted in the propellers being close to the surface, and as a result, there was a high degree of ice contact with the propellers. The Suezmax tanker for heavy ice had a deeper draft, and as a result the propellers could be further below the water surface, and as a result avoid ice contact. The single screw ship with a bulb, had relatively high ice resistance, but the bow shape was very effective at deflecting the ice away from the propeller.

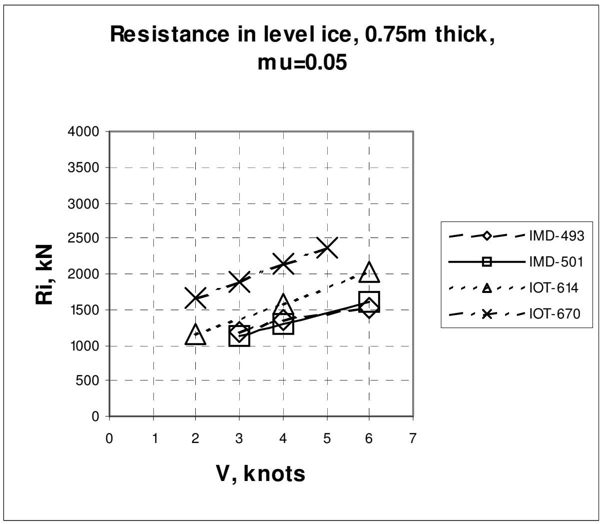

Figure 5, Comparison of resistance in level ice, Hi=0.75 m, μ=0.05

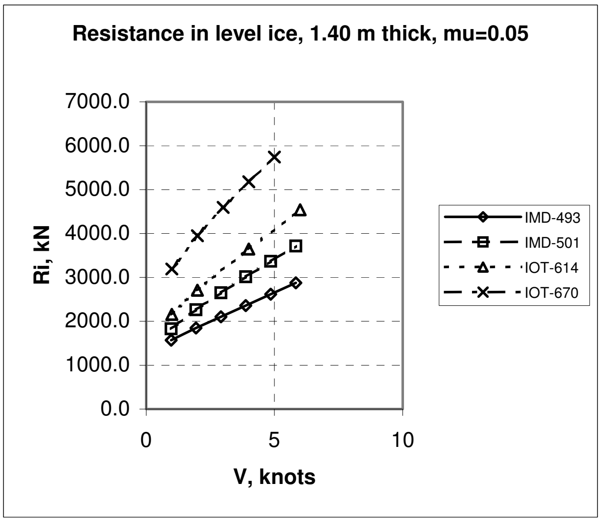

Figure 6, Comparison of resistance in level ice, Hi=1.4 m, μ=0.05

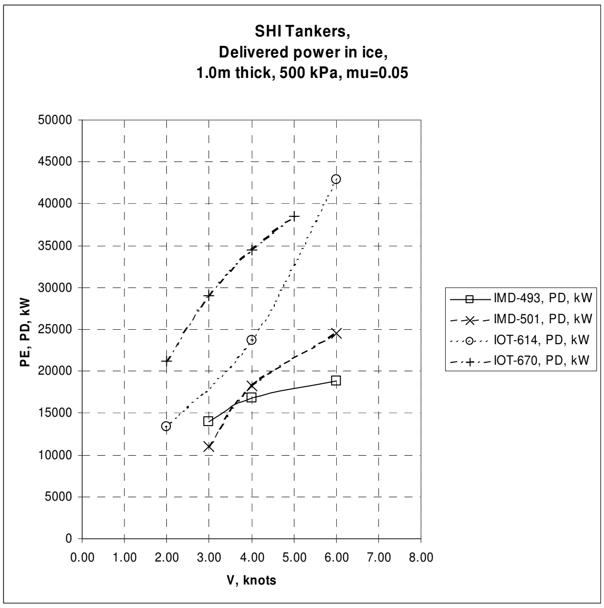

Figure 7, Comparison of delivered power in level ice, *Hi*=1.0 m, μ=0.05

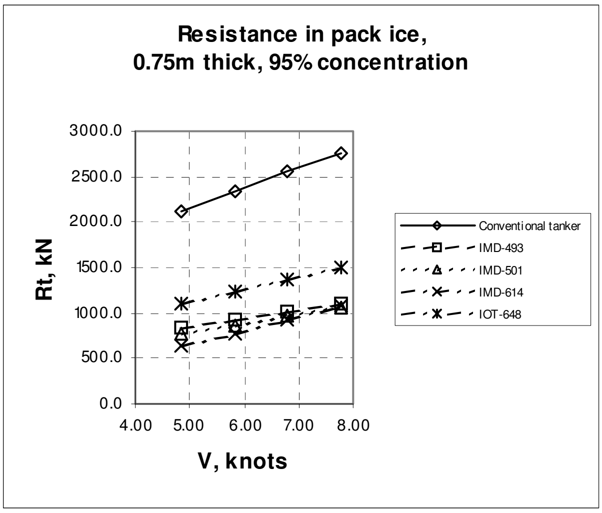

Figure 8, Resistance in 0.75m pack ice, 90% concentration

There are some areas where the modeling process could be improved. The correlation studies discussed above for government icebreakers were based on results for a model scale of approximately 1:22. The tanker models were on average a scale of 1:34. The material structure of model ice does vary with ice thickness. Model ice has a layer of small crystals close to the surface, with longer dendritic crystals growing downwards into the water. The thickness of the layer of small crystals is not a constant proportion of the ice thickness, and tends to be a greater percentage of the total thickness for lower ice thicknesses. This may have some effect on the most appropriate value of the hull-ice friction coefficient. However, obtaining full-scale trial data from an oil tanker is the key element in this evaluation.

Further study of the concept of the pre-sawn resistance experiment is also required for unconventional icebreaking hull forms. In the pre-sawn experiment, it is assumed that the ice has zero strength, and that no breaking of the ice occurs. In the case of the bulbous bow, the pre-sawn ice floes were clearly breaking on the upper surface of the bulbous bow. The magnitude of this effect may be reduced if the size of the ice floes is reduced.

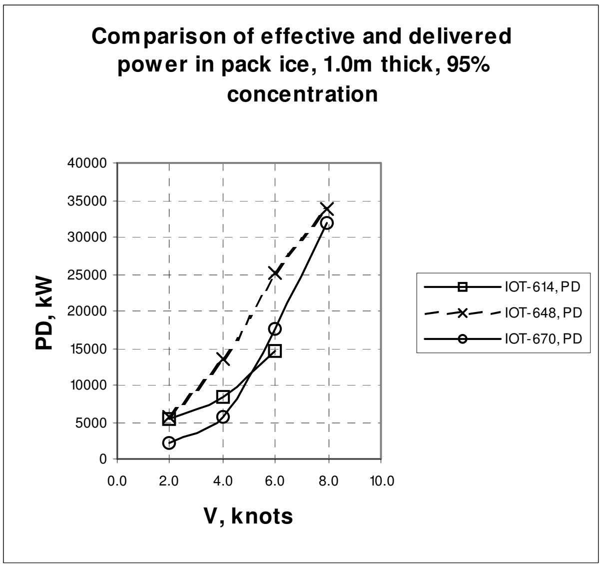

Figure 9, Delivered power in pack ice

6. CONCLUSIONS

The results of this research have been extremely important to SHI's strategy to become the world leader in the construction of large icebreaking merchant ships. Model testing has been an essential element of this strategy, since it is the opinion of the authors that at the present time analytical methods are not sufficiently well developed for accurate performance predictions.

The results of the research have shown that for large tankers in ice:

i) Quite different bow shapes can result in similar resistance in ice, once allowances for hull-ice friction coefficient and ice thickness have been included.

ii) Icebreaker designs have the lowest resistance in level ice and pack ice. Such a design is characterized by a raked bow with a long overhang. This type of bow is effective at breaking the ice, and directing the broken pieces around the hull. However, this type of bow has relatively poor performance in open water.

iii) Bulbous bows in ice have distinctive properties, compared to conventional icebreaker bows. The bow shape results in a lot of secondary breaking where the ice floes come into contact with the upper surface of the bulb. When the ice is already broken before it comes into contact with the ship, this penalty is removed.

iv) It is possible for a ship with a bulbous bow to be effective in light ice conditions, especially pack ice. The ice breaking performance is clearly much worse than a bow designed for heavy ice, but the improvement in open water performance compensates for this. It may be particularly effective in an area with extensive icebreaker support.

7. ACKNOWLEDGEMENTS

The methods of model testing in ice that are described in this paper have been developed at IOT over the last 25 years. Many people have contributed to this work over the years, but some deserve a special mention. Dr. Bruce Colbourne, Dr. Stephen Jones, Dr. Bruce Parsons, Mr. Don Spencer and Dr. Mary Williams have all made extensive theoretical and experimental contributions to the understanding of ice mechanics and ship-ice interaction at model scale and full scale. The technical staff at IOT have developed and refined the methods for modelling the ice and the ship. Mr. Brian Hill is singled out for his expertise in the management of IOT's model ice making capability and Mr. Craig Kirby for his expertise in making full-scale measurements.

8. REFERENCES

1. Molyneux, W. D., Simoes-Re, A-J, Spencer, D. and Reynolds, A. 'Recent Developments in Model Experiment Techniques for Large Icebreakers', Icetech 90, Paper E, Calgary, SNAME, 1990.

2. Ha, M-K, Kim, H-S, Ahn, D., Williams, F-M and Molyneux, D. 'Development of an Arctic Tanker Design', Proceedings, 18th Offshore Mechanics and Arctic Engineering Conference, St. John's, 1999.

3. Kim, H-S, Ha, M-K, Ahn, D., Molyneux, D. and Chun, H-H. 'Hull Forms for Icebreaking Tankers', Proceedings, 23rd Offshore Mechanics and Arctic Engineering Conference, Vancouver, 2004.

4. Kim, H-S, Ha, M-K., Ahn, D and Molyneux, D. 'Hull Form Designs for Icebreaking Tankers', Proceedings Icetech 2006, Banff, Alberta, July 16-19th, SNAME, 2006.

5. Colbourne, D. B. 'Scaling Pack Ice and Iceberg Loads on Moored Ship shapes', Oceanic Engineering International, Vol. 4, No. 1, pp 39-45, 2000.

6. Williams, F. M., Spencer, D., Mathews, S. T. and Bayly, I. 'Full Scale Trials in Level Ice with Canadian R-Class Icebreaker', Trans. SNAME, Vol. 100, pp 293-313. 1992.

7. Jones, S. J. and Spencer, D. 'Model-Scale/Full-Scale Correlation in Open Water and Ice for Canadian Coast Guard "R-Class" Icebreakers', *Journal of Ship Research*, Vol. 45, No. 4, pp 249-261, 2001.

8. Jones, S. J. and Lau, M. 'Propulsion and Maneuvering Tests of the USCGC Healy in Ice and Correlation with Full-Scale', Proceedings, Icetech 2006, Banff, Alberta, July 16-19th, SNAME, 2006.

9. AUTHORS' BIOGRAPHIES

David Molyneux is a Senior Research Officer at the Institute for Ocean Technology in St. John's, Newfoundland, Canada. He obtained his Master of Applied Science Degree from University of British Columbia, and his Bachelor of Science Degree in Naval Architecture for University of Newcastle-Upon-Tyne. Since 1987, he has carried out research into ship performance in ice, for private and public sector organizations from Canada, United States, Germany and Korea. All of these projects have included model experiments as part of the performance prediction process. During the course of carrying out these projects, scientific ship modelling techniques for predicting powering and manoeuvring performance in a range of ice conditions have been developed and refined.

Hyun Soo Kim is a Senior Engineer at the Marine Research Institute of Samsung Heavy Industries Co. Ltd., Korea. He obtained his Ph. D. of Naval Architecture from Pusan National University, and his Master and Bachelor Degrees in Naval Architecture for the University of Inha. Since 1991, he has performed research on ship hydrodynamics. His major research fields included sloshing analysis, the prediction of ship maneuvering performance, sea trial measurement and analysis and ice technology to predict power of the icebreaking vessels. Recently his interest has included the subject of risk management.

10. APPENDIX

Table 2, Summary of Principal Dimensions, Tanker Designs

Design		Aframax Arctic 1	Aframax Arctic 2	Suezmax, Arctic	Suezmax No ice	Suezmax Baltic
Bow shape		R-Class #1	R-Class #2	Spoon	Bulb	Ice bulb
Propulsion		Twin gondola	Twin gondola	Twin shafts	Single	Single
Model number		IMD-493	IMD-501	IMD-614	SM 173	IOT-648/ IOT-670
Length, wl	m	273.5	274.9	284.0	258.3	271.48
B, wl	m	43.6	43.6	42.8	46.2	44.0
T, midships	m	11.5	11.5	16.5	16.6	15.0
Displacement	tonnes, SW	100144	102145	161935	162001	145699
Wetted area	sq. m.	14720	14502	17689	17492	16746
Propeller Diameter	m	6.60	6.60	6.72	9.80	8.10
Model scale		31.94	31.94	33.87	44.5	36.82