Determination of performance limitations for ship's navigating to and from Voisey's Bay; summary report

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W. D. Molyneux

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SUMMARY:
This report presents an overview of the results of model experiments carried out to support CCG's evaluations of shipping related to the proposed Voisey's Bay nickel mine. The tests included resistance, propulsion and manoeuvring experiments in level ice, rubble and pack ice. Two models were tested, an R-Class icebreaker and a bulk carrier. The conclusions were that the observed performance of the icebreaker was predicted by the model experiments and that the techniques used could be applied to other ship types. Predictions of bulk carrier performance were made for different ice conditions and installed horsepower.

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1. Project Summary

Canadian Coast Guard (CCG) is mandated to evaluate the risk to the environment of ships travelling to and from the Voisey's Bay mine site. Voisey's Bay Nickel Company (VBNC) has proposed using 25,000 DWT bulk carriers over a season which includes some winter navigation (References 1 and 2). There is no experience with operating this size of ship in this area during winter months. There was therefore a need for CCG to have techniques in place for evaluating the proposed vessels, voyage schedules, etc. such that the risk to the environment could be assessed.

CCG adopted an approach based on simulating shipping conditions using physical model experiments, combined with practical operating experience. A voyage was carried out into the Voisey's Bay area in March and April 1997 to gain some limited operating experience in the worst ice conditions. The ship used for this trip was C.C.G.S. Henry Larsen, a modern, twin propeller, single rudder icebreaker which is the second most powerful ship in the CCG fleet. CCG also requested the Institute for Marine Dynamics (IMD) to carry out a series of model experiments in their Ice Tank in support of the project. IMD is part of the National Research Council of Canada, and is Canada's leading research organization specialized in ships and offshore structures.

There were two major objectives for the model test program. The first was to test a model of the icebreaker, and validate the modeling techniques used by IMD to simulate the ice conditions for the Labrador Coast. To achieve this objective the results of the model tests were compared with the data obtained from the voyage to Voisey's Bay. The second objective was to apply the same techniques to a typical bulk carrier and predict its performance in the ice conditions encountered during the 1997 voyage.

The candidate ship picked by CCG and IMD was the M. V. Arctic, a Canadian ice class bulk carrier for which there is a lot of existing model and full scale performance data. The nature of the modeling methods was such that power and speed could be extended beyond the capability of the actual ship, so that limiting conditions for a range of engine powers could also be determined.

This report presents an overview of the results of the model test project. The conclusions were that the predictions of icebreaker performance made from model experiments were good and that the modeling techniques could be applied to other ships. The limiting speed of the bulk carrier was estimated for different engine powers and ice conditions. The detailed results for different phases of the project can be obtained from the references given at the end of this report.

2. Ship Probe with C. C. G. S. Henry Larsen

In March and April 1997, Canadian Coast Guard sponsored a voyage into theVoisey's Bay area. The purpose of this voyage was to collect some preliminary baseline data on the amount of wildlife, oceanographic conditions, ice conditions and ship performance. The Institute for Marine Dynamics was invited to participate in this voyage. IMD was given responsibility for measuring ice properties (ice type, thickness, strength, coverage) throughout the voyage, and for recording ship maneuvers when time and conditions were suitable. The measured data are given in detail in References 3 and 4 for the ship maneuvering and ice properties respectively.

Pack ice thickness was found to vary between 1.2 and 1.5 m with an average flexural strength of 420 kPa. Rafted and rubble ice was between 3 and 5 metres thick. Observed ship speeds varied between 2.8 knots in heavy ice to 15 knots in open water. A total of 16 turning maneuvers were completed during the voyage.

A photograph of the C.C.G.S 'Henry Larsen', taken during the probe is shown in Figure 1. This ship has a total power available at the propellers of 12 MW.

3. Model Experiments with R-Class Icebreaker

For this project, IMD refurbished a model of an R-Class Icebreaker, which has a very similar hull shape to the Henry Larsen, but the ship has a total available power of 10 MW. A picture of the IMD Icebreaker model is shown in Figure 2.

The purpose of the experiments with the R-Class Icebreaker was to give confidence to the predictions of ship performance made from model experiments. The experiment program was designed to cover the range of ice type, thickness and strength encountered during the 1997 voyage and compare the performance predicted from model experiments with the observed performance of the ship.

The model experiments focused on predicting the speed and maneuverability of the ship in the following ice conditions:

Heavy pack ice (greater than 9/10 concentration)
Rubble ice (multiple layers of ice)

During the voyage to Voisey's Bay, the ship made extensive use of its bubbler system. When the bubbler system was operating, compressed air was blown into the water from holes in the side of the ship. It is well known that bubbler systems improve the speed of the icebreaker, and this is thought to be due in part to a reduction of the friction coefficient between the ice and the hull. By testing the model with two levels of hull-ice friction coefficient, it was hoped to estimate the difference in performance due to the bubbler system. One value of hull-ice friction coefficient used was typical of a new ship without a bubbler system (0.05). The other was a very low friction coefficient (0.01), to simulate the operation of the bubbler system.

Resistance experiments were carried out to measure the force needed to drag the hull through the ice. Propulsion experiments in ice-free water were carried out to determine the propulsive efficiency of the ship. Experiments in ice with the working propellers were made to predict the loss of propulsive efficiency due to propeller-ice interaction. The results of the three sets of experiments were combined to predict the power needed to drive the ship through the different ice conditions.

The results of resistance, propulsion and maneuvering experiments on the icebreaker model are described in detail in References 5, 8, 9 and 10. A photograph of the IMD icebreaker model during a resistance test is shown in Figure 3. The model was 1/20 scale, with working propellers and a working rudder.

The speed-power relationship for the icebreaker in heavy pack ice, predicted from the model experiments, is given in Figure 4. The prediction covers two ice thicknesses, 1.0m and

1.5m, and shows the total power required at the propeller. It is assumed that both shafts are turning at the same rate of rotation. This figure shows that with 10 MW, the ship will move forward at approximately 8 knots in 1 metre of heavy pack ice and 5.5 knots in 1.5 metres of heavy pack ice. In pack ice, the effect of hull-ice friction coefficient on speed is quite small, approximately 0.25 knots. The power of 10MW was equivalent to the maximum shaft rotation observed during the voyage (165 rpm). This power is equivalent to 13,410 Horsepower. Increasing the delivered power to 12 MW increases the speed in both ice thicknesses by approximately 0.5 knots.

An important element of this test program was to compare the predictions from the model with the observations from the voyage, and preliminary studies show that the agreement is good. Unfortunately a direct comparison of the model and ship data cannot be made. There was insufficient time to fully instrument the ship before the voyage but data were available for shaft rotation and ship speed. For a given ship speed and shaft RPM the available tow force, FD, for the ship was calculated from the self-propulsion experiments in open water. We can reasonably assume that the ship will move forward at a steady speed when the tow force equals the resistance in ice, Ri. Figure 5 shows a comparison of the available tow force against ship speed based on the ship probe (blue diamonds) with the equivalent resistance predictions for 1.0 and 1.5 metres of pack ice, made from the model tests. Whilst not completely conclusive, this figure does show that the tow force balances the resistance in ice over the range of ship speeds and icethicknesses observed on the voyage. From this observation we can conclude that the modelling procedure is effective at predicting the performance of the icebreaker.

The speed of the R-Class Icebreaker for different thicknesses of rubble ice is shown in Figures 6 and 7 for the average and low hull-ice friction coefficients respectively. These figures show resistance in rubble ice, Ri, against speed for average rubble thicknesses (hi) between 1.5 and 4.5 metres. They also show how the tow force, FD, varies with speed. The maximum speed for a given ice thickness is determined from where the force line intersects the resistance line. The limiting speed in each rubble ice thickness is given in Table 1, for a maximum total power of 10MW, representing an R-Class and 12 MW, representing 'Henry Larsen'.

Mean Rubble Ice Thickness Metres	Average Friction Knots	Low Friction Knots
10MW, R-Class		
2.5	4.4	6.0
3.0	3.0	4.7
3.5	1.8	2.2
4.0	1.2	1.4
4.5	0.6	1.0
12MW, Henry Larsen		
2.5	4.6	6.2
3.0	3.4	5.2
3.5	2.0	3.2

Table 1, Effect of Hull-Ice Friction Coefficient on Speed in Rubble Ice, Icebreaker

The other major element of the model program was the maneuverability of the icebreaker. For these experiments, the model was remotely controlled and free to turn under the action of the rudder and propellers. The maneuvering techniques were developed with help from an experienced CCG icebreaker captain. The majority of the work focused on two types of steady turn, with no backing and filling. One method used the rudder alone, and the other used the combination of rudder and differential thrust between the port and starboard propellers. For the results presented in this report, the starboard propeller was turning at full RPM and the port propeller was stopped. Other turning combinations were tested and are described in detail in Reference 9.

The summary results are given in Figure 8, for both hull-ice friction coefficients. Overall, it was found that friction coefficient had little effect on turning radius. For the ship with the rudder only, the typical turning radius in all ice conditions was 1500 metres and with differential thrust the radius was typically 540 metres. These predictions are for steady turns at constant speed, and do not include star turns or any other techniques commonly applied when the limit of steady operation is reached.

There is a high degree of variability in ship maneuvers in ice, as seen in Reference 3. The ship often did not complete a traditional circle, but some other arbitrary shape depending on the specific local ice conditions. This level of variability is also seen in the model data. For example, the model failed to maneuver in rubble approximately 3.75 m thick at the low friction coefficient when it had maneuvered adequately in the same nominal conditions at the average friction coefficient. Also the low friction coefficient had a very low turning radius relative to the average friction coefficient in 1.0metre pack ice. The limitations of the IMD ice tank meant that only partial turns were possible, with heading changes typically no more than 75 degrees.

The model maneuvers are compared with the ship maneuvers in Figures 9 and 10. Figure 9 shows turning radius against rudder angle and Figure 10 shows the turning radius against speed at the start of the turn. In both graphs, the blue diamonds show the ship data and pink squares show the model data. It also identifies which points were for the model with rudder only and which points had differential thrust. The results for differential thrust give good agreement with the ship data. Since we did not have exact ice data for each ship maneuver, all of the turns in broken ice (pack and rubble) have been included from the model experiments.

In conclusion, the predicted performance of the R-Class Icebreaker from model tests gives a good agreement with the data observed on the 1997 voyage to Voisey's Bay.

4. Model Experiments with Bulk Carrier

Figure 11 shows a photograph of the M. V. Arctic taken during trials in ice. The model experiments with the bulk carrier focused on obtaining preliminary estimates of the speed and maneuverability of the ship in the same range of ice conditions experienced on the voyage to Voisey's Bay. These included

Heavy pack ice (greater than 9/10 concentration)
Rubble ice (multiple layers of ice)

The study also investigated the effect of draft on the speed and maneuverability and the effect of the width of the broken channel on resistance and propulsion. The change in draft was important, since one possibility is for a ship to arrive at Voisey's Bay in ballast (light draft) and return fully loaded. The effect of channel width was included, because there was a proposal for the ship to follow the same track through the fast ice. This track will fill with rubble as the number of ship passages increases.

The model used for this phase of the study was 1/30 scale, with a working propeller and rudder. A photograph of the model of the M. V. Arctic in the IMD ice tank is shown in Figure 12. The model was only tested with one hull-ice friction coefficient, equivalent to the average value. The detailed results of the experiments on this model are given in References 5, 6, 7, 9 and 10.

The speed-power relationship for bulk carrier in heavy pack ice, predicted from the model experiments, is given in Figure 13. The prediction covers two drafts for a single ice thickness of 1.5 metres and shows the total power required at the propeller.

The speed-power relationships for the two drafts are given in Table 2.

Delivered Power, MW	Speed, Knots Load	Speed, Knots Ballast
10	3.2	1.5
15	5.5	3.5
20	7.0	4.5

Table 2, Speed Predictions for Bulk Carrier in Pack Ice, 1.5m

The degradation in performance in the ballast draft is due to two primary factors. One is the increased resistance relative to the load draft. The second is a reduction of propulsive efficiency caused by a greater amount of propeller-ice interaction because the propeller is nearer the ice.

The prediction of the bulk carrier performance in rubble ice (load draft) is shown in Figure 14. This presentation is the same as that used for Figures 5 and 6. This figure shows three power levels for 10, 15 and 20 MW. These data are summarized in Table 3.

Mean Rubble Ice Thickness Metres	Delivered Power 10 MW	Delivered Power 15 MW	Delivered Power 20 MW
2.0	0.9		
2.5	0.4	0.9	
3.0		0.5	0.9
3.5			0.5
4.0			0.4

Table 3, Effect of Delivered Power on Speed in Rubble Ice,
Bulk Carrier, Load Draft

Based on the ice data obtained from the voyage to Voisey's Bay, the model experiments predict 20 MW as the minimum power required to make any reasonable forward progress, without icebreaker assistance and/or a bubbler system.

The degradation in performance between load and ballast drafts discussed above was even more pronounced in the rubble ice experiments. It is interesting to note that the M. V. Arctic always uses a draft close to the load draft when operating in ice.

The maneuverability of the bulk carrier was also studied. Since there was only one propeller, the variable used for controlling turn radius was rudder angle. All turns were carried out with 28.5 degrees of rudder using the shaft power required to initiate a turn in the given ice conditions. The results are summarized in Figure 15. In the ballast draft, the model would not maneuver in level ice or very heavy pack ice (>9/10 concentration). When the pack ice concentration was reduced the model could maneuver. The model could maneuver in all ice conditions tested at the load draft. The average turning radius for the ship at the load draft in pack ice and rubble ice was 1410 m. This is 2.6 times the radius for the icebreaker with differential thrust. However this radius is based on the bulk carrier alone without icebreaker assistance.

Based on the data collected as part of this project, it was concluded that the width of rubble had no effect on ship resistance. Three rubble widths were tested, from the full width of the ice tank (equivalent to 360 metres for the ship) to 1.25 times the ship's beam (equivalent to 28.6 metres).

Another factor to consider for ship operation is the depth of rubble in a channel relative to the thickness of fast ice on either side of it. At some point it will become more efficient to break a new channel than to follow the previously broken one. Based on the results for the M. V. Arctic, when the rubble ice thickness is 3.6 times the level ice thickness, it is less effort to break a new channel. The equivalent ratio for the R-Class icebreaker is also 3.6.

A comparison of the specifications for the M. V. Arctic, the R-Class icebreaker, the SA-15 (another well known icebreaking bulk carrier) and the specifications for the bulk carrier given by VBNC (Reference 2) is given in Table 4.

	Arctic	R-Class Icebreaker	SA-15	VBNC
Length, m	202.4	99.8	164.0	170
Beam, m	22.86	19.8	24.5	25.0
Draft, m	10.98	7.00	9.0	10.6
GRT	20,236	6,166.5	17,910	17,000
NRT	10,849	1,755.3	9,484	9,000
DWT	26,440	2,493	19,943	25,000
Displacement, Tonnes	38,183	7,913	24,255	
Number of Propellers	1	2	1	
Total Power, MW	10.9	10.0	15.4	

Table 4, Comparison of Ship Specifications

5. Limitations of Current Study

All of the work in this study focused on the performance of a single ship, with no assistance from another icebreaker.

The performance estimates given in this report are for steady progress and make no allowance for the backing and filling techniques normally used in ice when the limit of steady progress is reached.

It is well known that pressure in pack ice can have a big effect on the ability of the ship to move forward. During the voyage to Voisey's Bay, there were some conditions for which the icebreaker could not make forward progress. The ship had to wait overnight in a safe place until the weather conditions changed and progress could be resumed the following day.

The effect of pressure was not studied as part of this project. Some earlier work at IMD (Reference 11) has indicated that resistance for the M. V. Arctic in rubble ice at three knots will increase by 17 percent for each 30 kPa of applied lateral pressure. The hull-ice friction coefficient for this ship was 0.1. It is likely that the speed predictions given above can be reduced significantly if there is pressure in the pack ice and rubble. The difficulty in making accurate predictions is caused by lack of field data for pressure measurements.

There is the possibility of estimating the maximum pressure that can be withstood by a single layer of pack ice before it rafts. Similar estimates can be made for two layers and three layers of ice. This will give an estimate of the worst case condition, but the cases should be validated with field data.

All of the results described in this report are for unconsolidated rubble. The closest natural condition to this is when the rubble has been loosened by an icebreaker, or when the air temperature is relatively high. In nature, the top layer of ice will freeze if the rubble is stationary for a period of time and the air temperature is below freezing. Breaking this frozen crust will add to the resistance of the ship. Some experiments were carried out as part of this project to investigate the effect of different degrees of consolidation on ship resistance. The results showed a very high increase in resistance, but they could not be checked against data from the field, and so have been omitted from this report. The detailed results are given in Reference 7.

6. Areas for Further Research

There has been relatively little research into understanding the factors effecting ship resistance in rubble ice. Both models tested as part of this project showed a tendency for the resistance to increase at very low speeds. This can be seen in Figures 5 and 6, at speeds lower than 1 knot. The amount of increase depended on rubble ice thickness relative to ship draft, with the R-Class Icebreaker and the ballast draft on the bulk carrier showing the most noticeable trends. The bulk carrier at the load draft showed the same trend, but only in ice thicknesses outside the practical range for this project. There is some theoretical justification to this observation, as discussed in Reference 3, but this is not a fully understood phenomenon. The implication for the ship is that if the ship stops moving, it will be harder to start, and the ship may become stuck.

The other areas of ship performance in rubble that need more study are the effect of pressure and the effect of consolidation of the top layer. To progress this work further, good measurements from field studies are needed.

The simplification of the bubbler system model to a low hull-ice friction coefficient is feasible over most of the speed range considered for this project. At speeds over 3 knots, there was a significant resistance reduction due to the change in hull-ice friction coefficient. Therefore it is feasible to consider friction coefficient as a simplified alternative to a working bubbler system model. Below this speed there was little effect due to friction coefficient. In reality, the bubbler system is very effective at getting the ship moving after it has stopped. This feature cannot be modeled with a low hull-ice friction coefficient, and so alternative methods must be developed.

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FIGURES

Figure 1, C.C.G.S. Henry Larsen, During Ice probe, March 1997

Figure 2, Model of R-Class Icebreaker in IMD Ice Tank, Maneuvering Experiments

Figure 3, R-Class Model in Rubble Ice, IMD Ice Tank,
Resistance and Propulsion Experiments

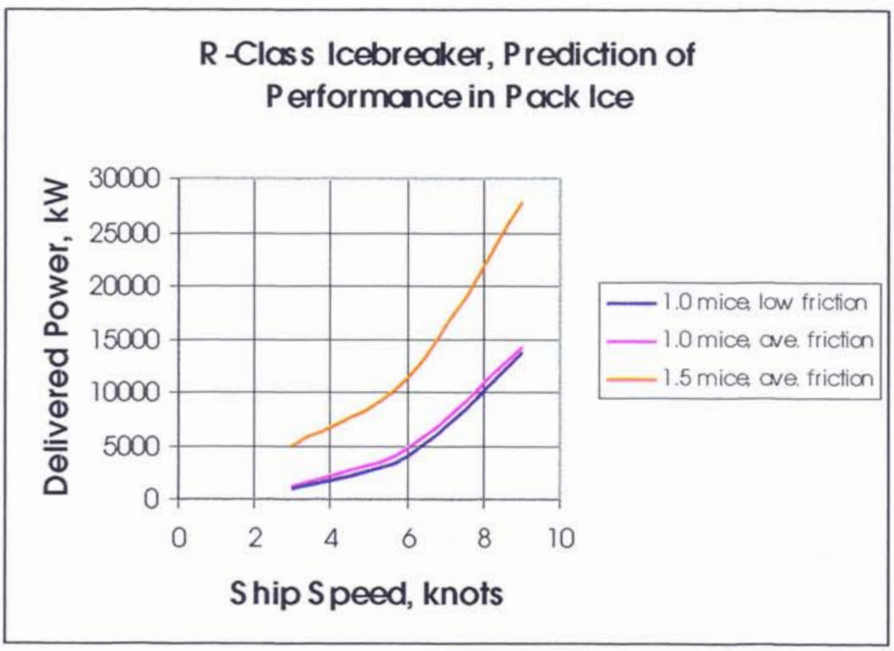

Figure 4, Prediction of Delivered Power against Speed in Pack Ice, R-Class Icebreaker

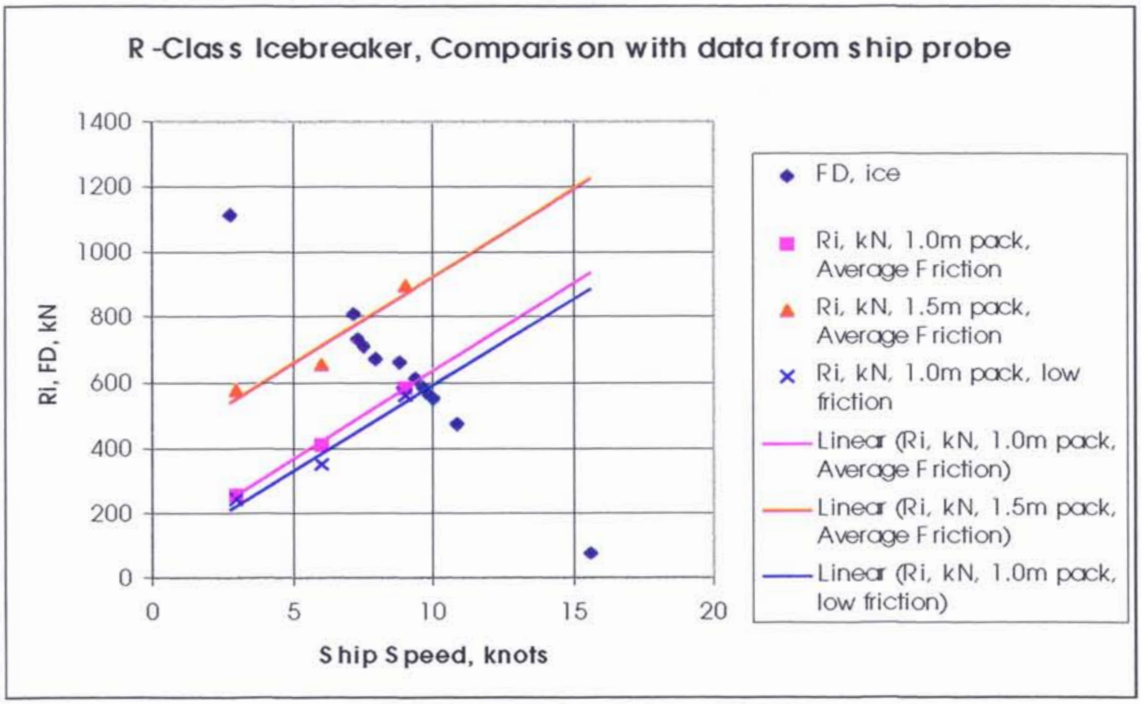

Figure 5, Comparison of Model Resistance Predictions with Observed Performance During Ship Probe

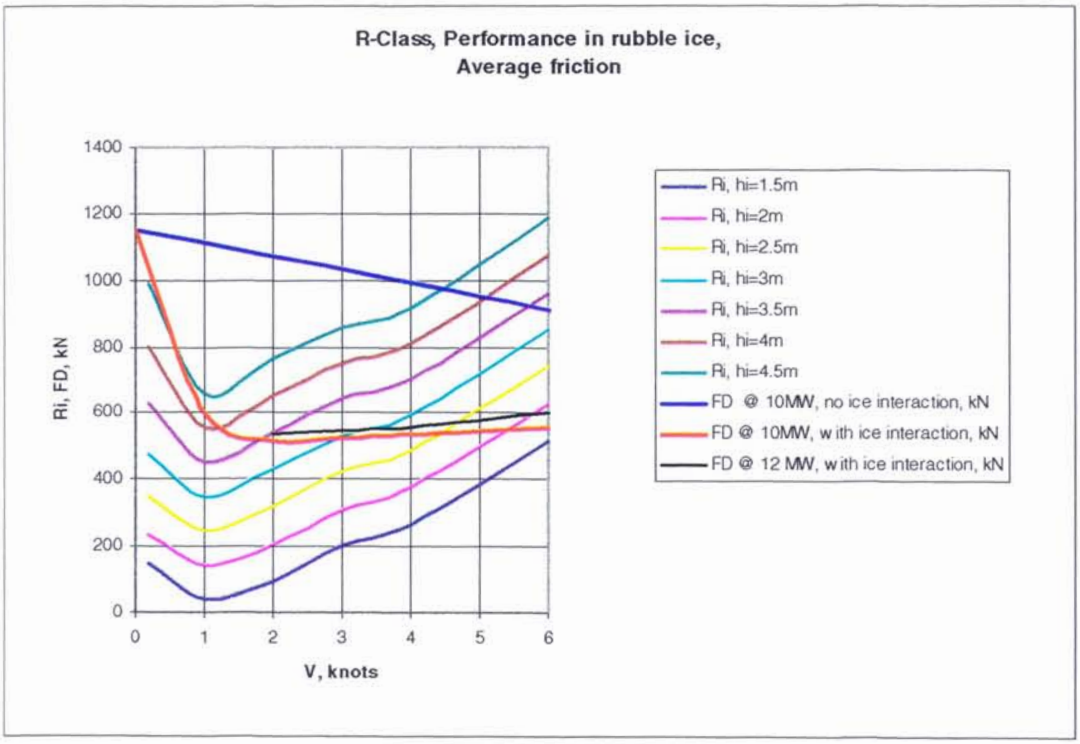

Figure 6, Estimate of Ship Performance in Unconsolidated Rubble, R-Class Icebreaker, Average Hull-Ice Friction Coefficient

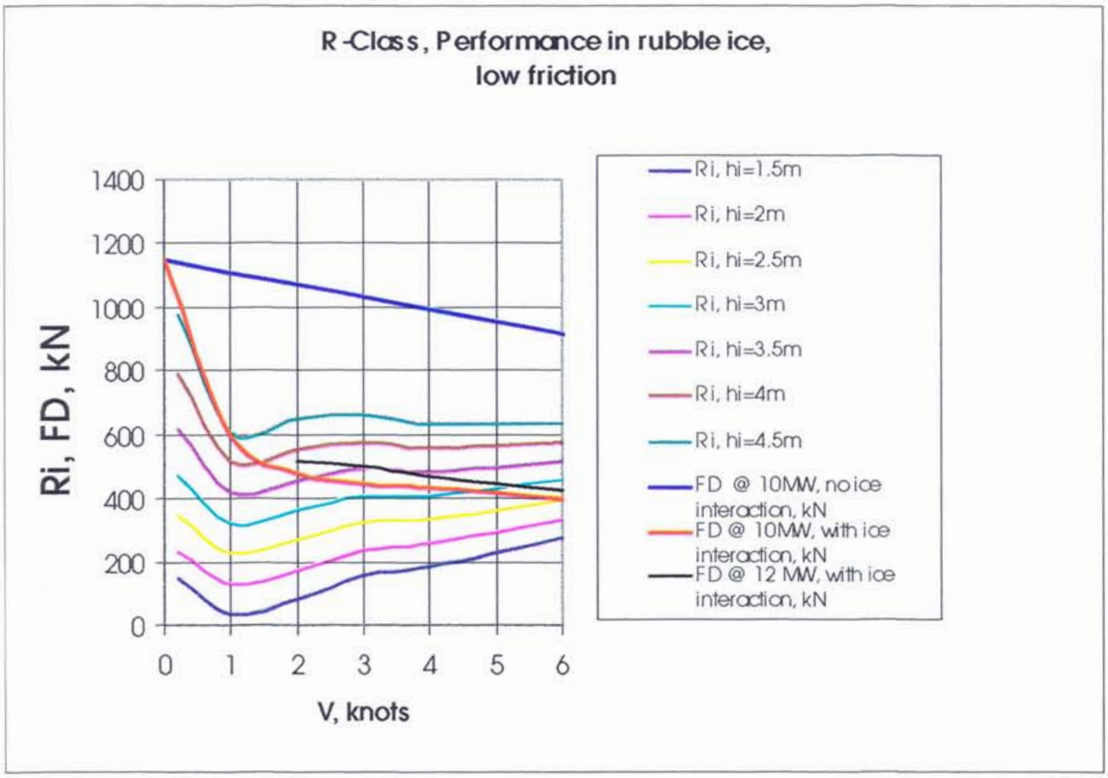

Figure 7, Estimate of Ship Performance in Unconsolidated Rubble, R-Class Icebreaker, Low Hull-Ice Friction Coefficient

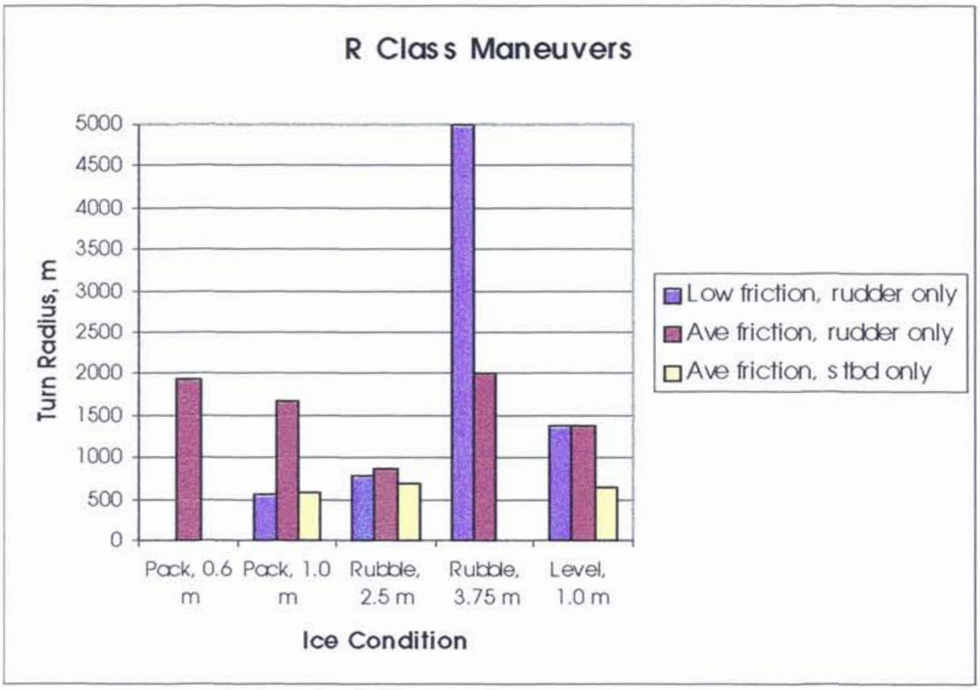

Figure 8, Prediction of Maneuvering Performance, R-Class Icebreaker

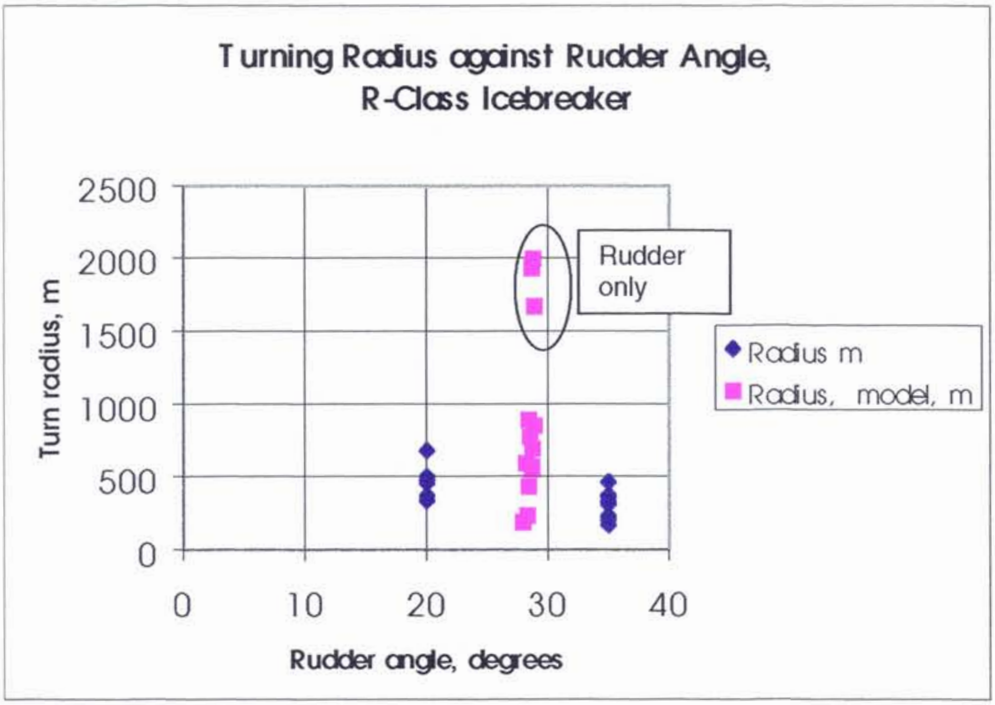

Figure 9, Comparison Between Predictions from Model Tests and Data Obtained on Probe, R-Class Maneuvering

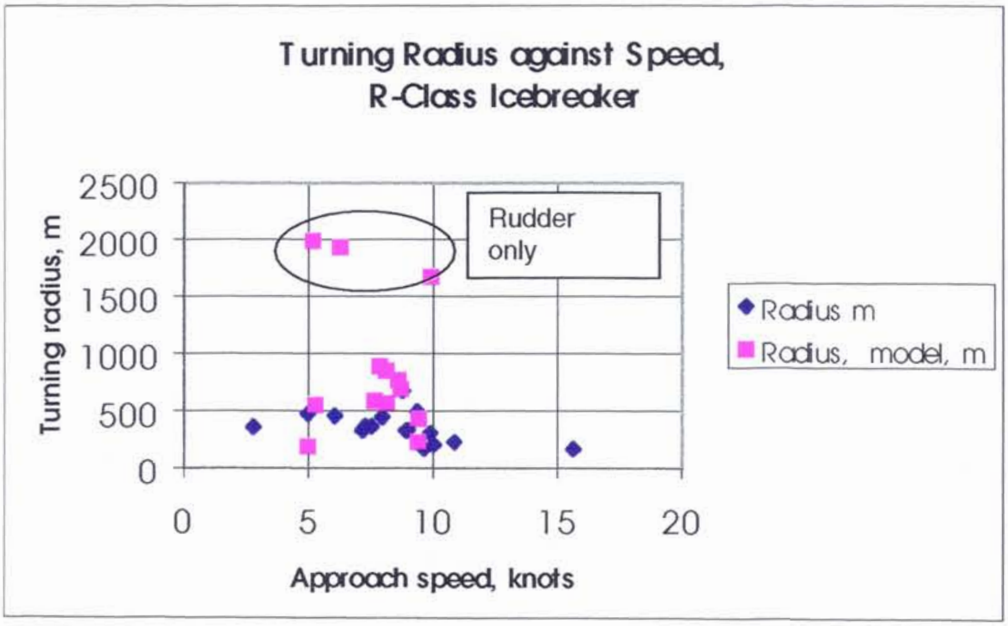

Figure 10, Comparison Between Predictions from Model Tests and Data Obtained on Probe, R-Class Maneuvering

Figure 11, M. V. Arctic, Bulk Carrier

Figure 12, M. V. Arctic Model in IMD Ice Tank

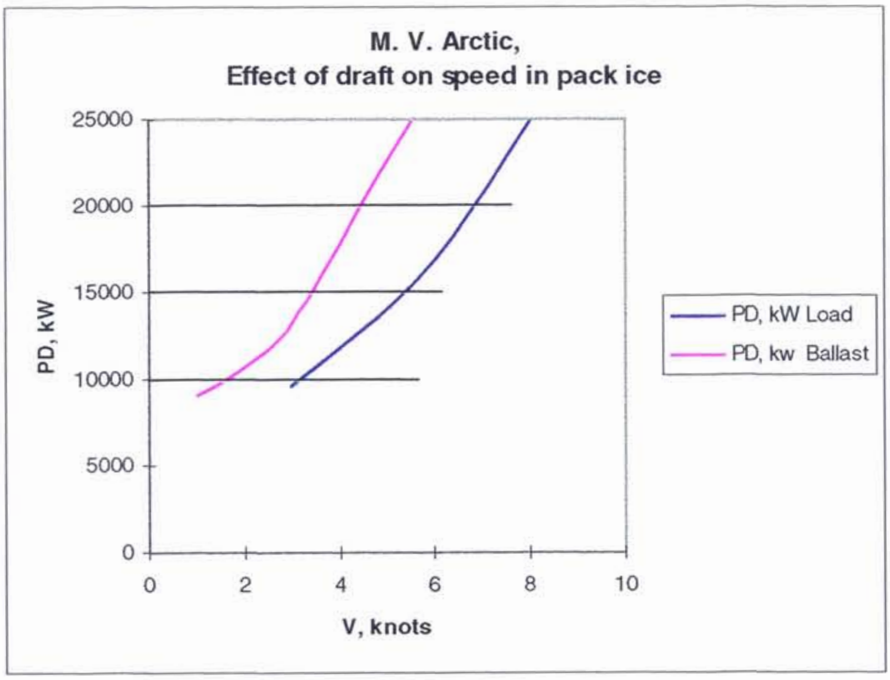

Figure 13, M. V. Arctic, Effect of Draft on Speed in Pack Ice, 1.5 m thick

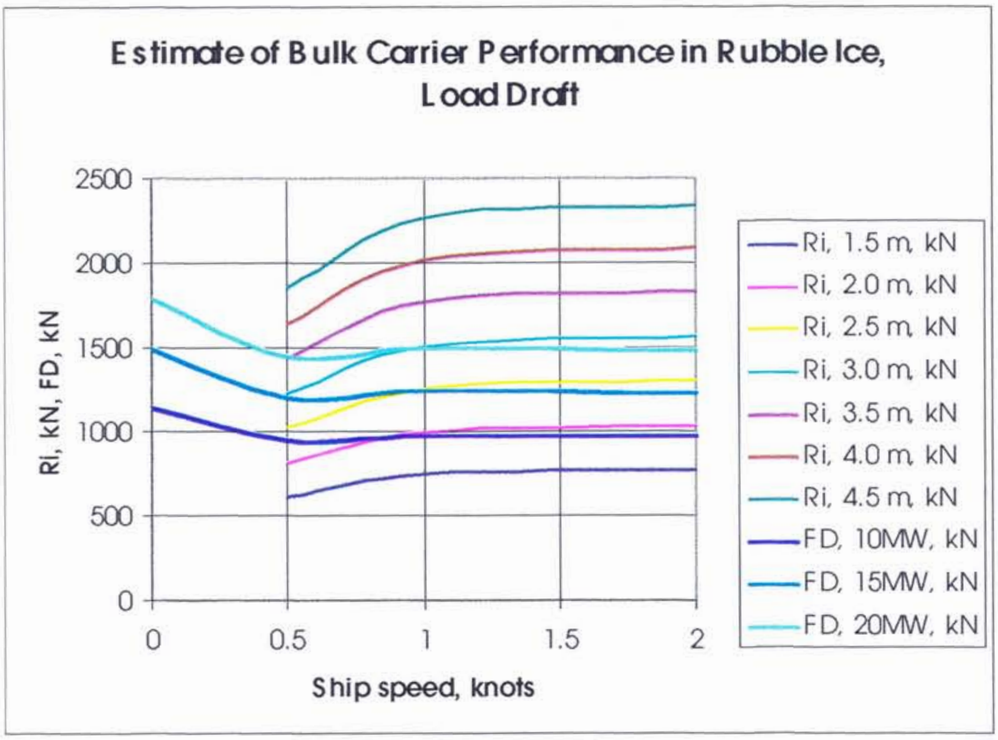

Figure 14, M. V. Arctic, Prediction of Ship Performance in Rubble Ice, Load Draft

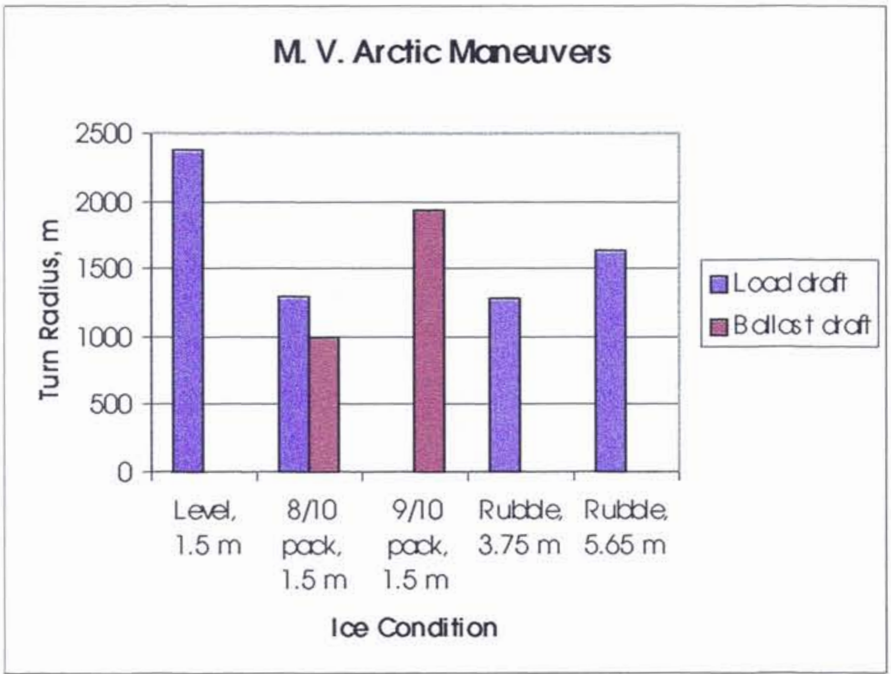

Figure 15, Prediction of Maneuvering Performance, M. V. Arctic