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ESTIMATING PERFORMANCE REQUIREMENTS FOR SHIPS NAVIGATING TO AND FROM VOISEY'S BAY

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ABSTRACT

The Voisey's Bay nickel mine is located in Northern Labrador. To reach the mine site in winter requires a ship to navigate through a range of ice conditions. Close to the mine site, in the fjord, the ice is mostly uniform first year ice, up to 1.3 m thick. However, before reaching open water the ship must pass through broken ice, several layers thick, with different amounts of consolidation. The broken ice is often under severe pressure caused by wind and current.

This paper describes research carried out at the Institute for Ocean Technology, in support of the environmental impact assessment, on behalf of Canadian Coast Guard, Newfoundland Region. The work fell into three distinct phases, which were full-scale trials on an icebreaker, model experiments on an icebreaker and model experiments on an ice breaking bulk carrier. The paper then identifies gaps in our knowledge of ship performance in typical Labrador ice conditions and the steps that must be taken to overcome them.

INTRODUCTION

The discovery of large mineral deposits in Northern Labrador has tremendous potential for a positive impact on the economy of Newfoundland and Labrador. The most likely transportation system to support the project will use ships for the link between the mine-mill in Labrador and the off-site smelter. The nature of the mine and the milling process is such that shipping ore out at least once during the winter will be necessary. The approach to Voisey's Bay is an area where there can be severe ice conditions and there is little operational experience with large bulk carriers in winter.

The Institute for Ocean Technology (IOT, formerly the Institute for Marine Dynamics) worked with Canadian Coast Guard to develop a modeling methodology to predict the performance of ships in the ice conditions off the Labrador Coast. Our objective was to correlate the measured performance of a CCG icebreaker in 'typical'

Labrador ice conditions with the performance of a scale model of the ship in a scaled environment. If the methodology gave a good correlation, then it was assumed that it could be used to predict the performance for typical bulk carriers and allow alternative ship designs to be evaluated. The material in this paper is taken from submissions made by IOT and CCG to the Voisey's Bay Environmental Assessment Panel (Molyneux, 1998).

LABRADOR ICE CONDITIONS

In March and April 1997, CCG sponsored an expedition into the approaches of the proposed site for the mine's shipping terminal. The voyage provided essential data on the ice conditions and the performance of the ship *'C.C.G.S. Henry Larsen'*. Three ice conditions, typical for Northern Labrador, were found during the voyage. They were:

1) Level, shore-fast ice between 1 and 1.5 metres thick (not the limiting condition for ship progress).

2) Pack ice, with coverage between 8/10 and 10/10, with ice thickness between 1.2 and 1.5 metres.

3) Rubble or rafted ice between 3 and 5 metres thick (2 or 3 layers of broken ice)

Other types of ice, which may be encountered, are shear ridges, pressure ridges and multi-year ice. These were not studied as part of this project.

During the voyage, measurements were made almost continuously of ship speed, shaft rate of rotation, rudder angle and ship's position as functions of time. Data on ice thickness were obtained from video recordings of the ice being broken at the shoulder of the bow and ice thickness, temperature and salinity were obtained from core samples at selected points during the trip. The salinity and temperature measurements were used to calculate the flexural strength of the ice.

MODELING SHIP PERFORMANCE IN LABRADOR ICE CONDITIONS

In order to predict the forces acting on a ship's hull in pack ice and rubble ice, resistance and overload self-propulsion experiments were carried out on models of an icebreaker and a bulk carrier. These experiments were carried out after the completion of the ship trials, starting in 1997 and completed in 1998. For resistance tests, the fully appended model was fitted with dummy propeller hubs and a single centreline rudder. The model was fixed to the tow carriage, free in pitch, heave, and roll. The model was towed at constant speed for each test. Towing forces were measured, together with carriage speed, pitch angle and heave.

For overload propulsion experiments, the model, fitted with working propellers, was fixed to the carriage in the same manner as for the resistance tests. Each self-propelled test was run at constant model speed for a single propeller speed to obtain a steady state measurement of tow force, shaft torque, thrust, and speed. Rates of rotation were set prior to the testing, based on estimates of resistance and available tow force. Shaft friction torque and thrust were checked on each shaft every day, and the reported results have the friction effects removed.

The prime purpose of the overload experiments in ice was to determine the degree of propeller ice interaction and the subsequent degradation in propulsive efficiency. For this reason it was not necessary to obtain the exact self-propulsion point. The propulsion point was estimated prior to the start of the experiments, and measurements were made of the mean values of carriage speed, model tow force, propeller thrust, torque and rate of rotation. The values measured in ice were compared with the open water values at the same carriage speeds and shaft revolutions. The ratios of thrust and torque in ice relative to thrust and torque in open water were used to correct the open water data (including tow force) and the corrected open water data were used for developing ship predictions.

The EGADS (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 finely controlled temperature in a mild EGADS solution [Timco, 1986], 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 [Timco & Spencer, 1990]. 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.

Ice flexural strength was measured by sets of cantilever beam tests at different times and locations in the tank. For each ice sheet, flexural strength-time curves were developed, and strength was interpolated to test time and location. Ice density, shear strength, and compressive failure stress were determined from flexural strength relations, calibrated by measurements in each ice sheet.

The pre-sawn ice consisted of a channel cut in the ice, which was as wide as the beam of the ship plus twice the ice thickness. This test gave data on the forces needed to submerge and clear the ice, without breaking it. In this test program, the purpose of the pre-sawn resistance test was to determine the effect of channel width on resistance in pack ice.

Pack ice was created by breaking the ice sheet with the paddles on the ice tank service carriage. First, the ice was broken into a series of approximately parallel fractures across the tank. Then it was broken by hand so that floe shapes were approximately square. Pack ice concentration was determined from digitized overhead photographs of each ice sheet, prior to the start of experiments. The hull-ice friction coefficient was determined using a sample of ice from the tank at test time and a flat horizontal surface finished simultaneously with the ship model final surface.

After completion of the pack ice experiments, the ice was made into a wide rubble field. The pack ice was compressed longitudinally using the paddles on the service carriage. This resulted in rafting of the ice, in a process not unlike that observed in nature, when ice floes move over one another under the action of wind and current. The nominal ice thickness was based on the volume of ice, but this did not take into account the porosity, which results from uneven stacking of the ice floes. Actual rubble thickness was measured by an underwater acoustic array. The measured thickness was approximately 25% thicker than the nominal values.

PREDICTIONS OF SHIP PERFORMANCE IN LABRADOR ICE CONDITIONS

1) ICEBREAKER

The results of experiments with a 1:20 scale model of the R-Class Icebreaker (Type 1200) provided data to correlate the model with the full-scale performance and also to predict the performance of the ship in other ice conditions. The test matrix was developed from the ship and ice data recorded during the voyage. The results of this phase of the project have been presented [Molyneux & Williams, 1999]. It was concluded that the model data showed good agreement with the data obtained from the ship probe. The predictions obtained from the model experiments were consistent with the measured ship performance and the observed ice conditions at the time of the probe. This study showed that the modelling techniques were generally sound. The same techniques applied to other ship types, such as icebreaking bulk carriers, should give realistic predictions.

2) BULK CARRIER

The model experiments with the bulk carrier focused on obtaining estimates of the speed and maneuverability of the ship in the same range of ice conditions experienced on the voyage of *'C.C.G.S. Henry Larsen'* to Voisey's Bay discussed above. 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 of the ship.

IOT had in stock a 1:30 scale model of the icebreaking tanker/bulk carrier '*M. V. Arctic*' with a working propeller and rudder. The *'M. V. Arctic'* was an acceptable choice for this project since the performance of the ship was well established. The ship is operated by Fednav Ltd. and has been successfully used for ore transportation from other northern mines. The ship was a suitable size for navigating to and from Voisey's Bay, but the required level of propulsion power for the expected ice conditions was uncertain. A photograph of the model of the M. V. Arctic in the IOT ice tank is shown in Figure 1. The hull-ice friction coefficient was 0.06, which was typical for new ships in ice.

The speed-power relationship for the bulk carrier in heavy pack ice, predicted from the model experiments, is given in Table 1. The prediction covers two drafts for a single ice floe thickness of 1.5 metres and shows the total power required at the propeller. The speed-power relationships for the two drafts are plotted in Figure 2.The degradation in performance in the ballast draft relative to the heavier load draft was due to two primary factors. One was the increased resistance relative to the load draft. The second was a reduction of propulsive efficiency caused by a greater amount of propeller-ice interaction because the propeller was nearer the ice.

Figure 1, '*M. V. Arctic*' model in heavy pack ice

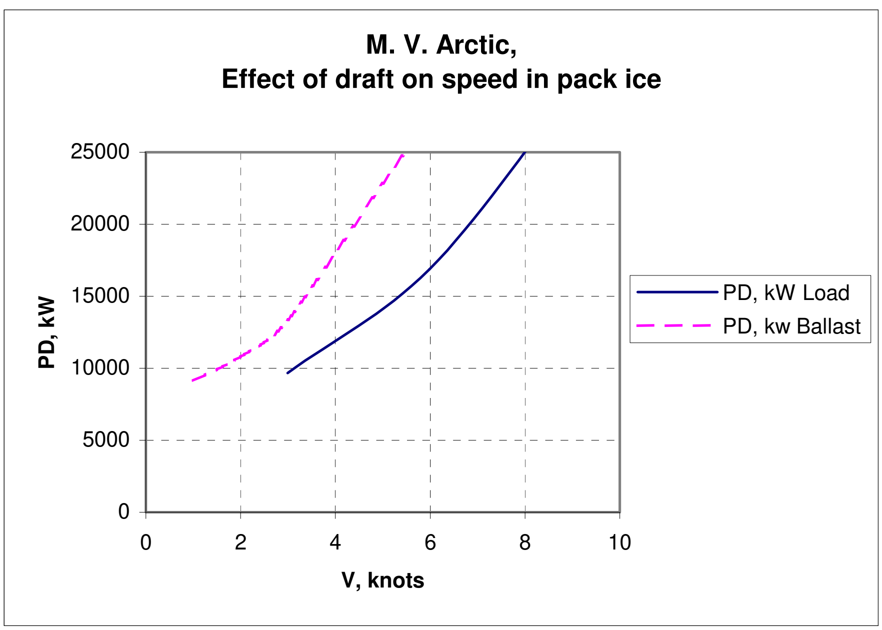

Figure 2, '*M. V. Arctic*', Effect of Draft on Speed in Pack Ice, 1.5 m thick

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 1, Limiting speed (in knots) for bulk carrier in pack ice, 1.5m thick, with different levels of power

The prediction of the bulk carrier performance in rubble ice (load draft) is shown in Figure 3. The figure shows resistance in rubble ice against speed for contours of rubble ice thickness and forward force against speed (developed by the propulsion system) for contours of constant delivered power. The ship will proceed at a steady speed when a power contour intersects a resistance contour. The ice thickness was from 1.5 to 4.5 metres and delivered power levels were 10, 15 and 20 MW. The limiting speeds are summarized in Table 2. Using ice data obtained from the voyage to Voisey's Bay, the model experiments predict 20 MW as the minimum power required to make reasonable forward progress, without icebreaker assistance and/or a bubbler system. The degradation in performance between load and ballast drafts discussed above for pack ice was even more pronounced in the rubble ice experiments.

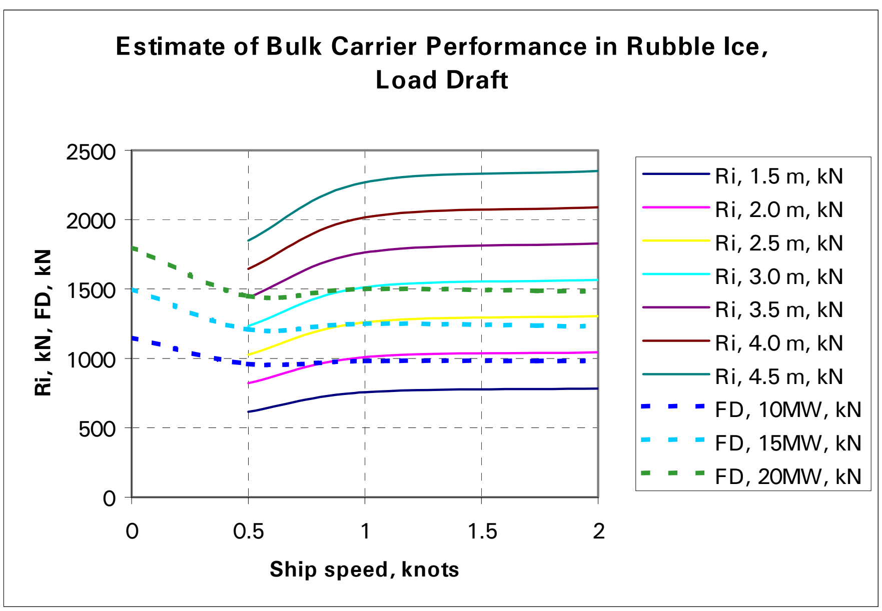

Figure 3, '*M. V. Arctic*', prediction of ship performance in rubble ice, load draft

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 2, Limiting speed (in knots) for bulk carrier in different thickness of rubble ice

The manoeuvrability of the bulk carrier was also studied. All turns were carried out with 28.5 degrees of rudder and using the shaft power required to initiate a turn in the given ice conditions. The results are summarized in Figure 4. At the ballast draft, the model would not manoeuvre in level ice or very heavy pack ice (>9/10 concentration). When the pack ice concentration was reduced the model could manoeuvre. The model could manoeuvre 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 was 2.6 times the smallest radius for the icebreaker in the same ice conditions.

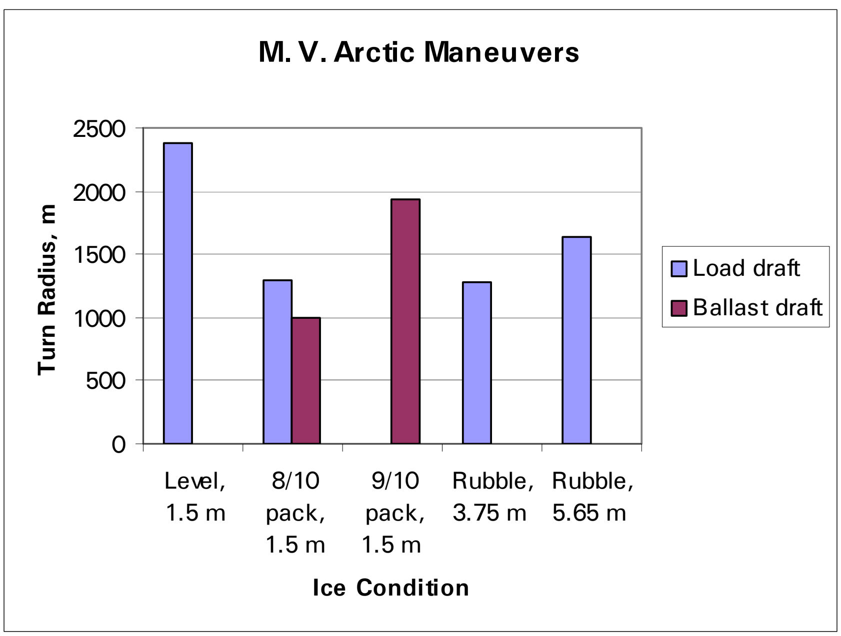

Figure 4, '*M. V. Arctic*', Prediction of manoeuvring performance

A comparison of the specifications for the *'M. V. Arctic'* and the *'C.C.G.S. Henry Larsen'* is given in Table 3.

	M. V. Arctic	*C.C.G.S. Henry Larsen*
Length, m	202.4	99.8
Beam, m	22.86	19.8
Draft, m	10.98	7.00
GRT	20,236	6,166.5
NRT	10,849	1,755.3
DWT	26,440	2,493
Displacement, Tonnes	38,183	7,913
Number of Propellers	1	2
Total Power, MW	10.9	10.0

Table 3, Comparison of Ship Specifications

IMPROVING MODELING METHODS FOR SHIPS IN LABRADOR ICE

Pack ice and rubble ice are subjected to pressure caused by wind and current acting on the ice. The resistance of a ship in ice increases with an increase in the pressure. It has been shown for a model of the '*M. V. Arctic*', that the resistance in rubble ice at three knots will increase by 17 percent for each 30 kPa of applied lateral pressure (Hardiman, 1994). 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 due to the lack of field data for pressure measurements and their effect on ship performance. 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 paper are for unconsolidated pack ice and rubble. The closest natural condition to this is when an icebreaker has loosened the rubble, or when the air temperature is relatively high. In nature, the top layer of ice and open water 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 paper.

For this project, manoeuvring experiments were carried out with free-running models, which reacted to the turning moments created by the rudder (and differential thrust in the case of an icebreaker). This approach gives results that are representative of the behaviour of the ship, but require an experiment for each change in ship parameter. An alternative approach is to use forced manoeuvring methods (Lau, 2004), similar to the ones used in open water, but these methods have not been fully validated.

Finally, there are other factors to consider beyond the powering and manoeuvring requirements for the ship. The amount of ice left in the broken channel behind the ship is very important. When the passage of the ship is a rare event, any disturbance to the ice surface is dangerous to the movement of animals and people. The scaling of broken ice pieces behind the ship and how quickly they freeze together is an area not traditionally considered by naval architects and model testers.

All of these limitations can be addressed by carrying out field measurements on ice properties, and ship trials in appropriate ice conditions. The trials can then be correlated against model experiments, and correction factors can be developed to ensure that the model experiments provide a realistic representation of the physical situation being studied.

CONCLUSIONS

Even though Labrador ice conditions are different from those typically studied in model basins, a good correlation between measured ship performance and a scale model in scaled ice conditions for the Canadian icebreaker *'C.C.G.S. Henry Larsen'* suggests that they can be reproduced in a model basin in a meaningful way. The same methods applied to a typical icebreaking bulk carrier, '*M.V. Arctic*' indicate that it will be possible for a ship to enter and leave Voisey's Bay in winter, provided that the ship has enough power at the propeller, and that the ice is not heavily consolidated or under significant pressure.

Areas where more research is required include methods for obtaining mechanical properties of irregular ice conditions (including consolidation and pressure) and relating these parameters to ship performance. This will require extensive full-scale measurements on ship performance with corresponding measurements of the ice properties and a detailed model-ship correlation study in order to refine prediction methods.

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