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PRELIMINARY RESULTS OF SHIP MANEUVERING IN ICE EXPERIMENTS USING A PLANAR MOTION MECHANISM

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ABSTRACT

Ship maneuvering experiments in ice are being conducted at the Institute for Ocean Technology (IOT) of the National Research Council of Canada. The aim is to provide a model test database for a subsequent mathematical and numerical modeling of the interaction processes between the ship and ice. The first phase of the experiments was carried out using a 1:21.8 scaled model of the Canadian Icebreaker, Terry Fox. The test program included straight resistance runs and turning circles maneuvers achieved by using a Planar Motion Mechanism (PMM) apparatus. In each experiment tow forces, turning moments, and ship motions were measured.

In this paper, preliminary results of the experimental program are presented. The dominant ice-ship interaction processes are identified. The test results show large influence of ship motions and interaction geometry on the measured yaw moments. The geometrical aspect of the interaction processes is described and its influences on ice loads are discussed. Conclusions are made and recommendations for future works are provided.

INTRODUCTION

Despite a sizeable volume of work, there is not yet a universally accepted analytical method of predicting ship performances in ice. A comprehensive study was initiated at the Institute for Ocean Technology (IOT) of the National Research Council of Canada (www.nrc-cnrc.gc.ca) with the objective to develop a physical representation of the complex interaction processes of a ship maneuvering in ice and to build a mathematical model to satisfactorily predict its performance. In turn, the mathematical model provides a tool to ship designers as part of the assessment of ship navigation in ice infested routes. Also, it can be incorporated into marine simulators to train mariners or into automatic ship control systems for a better ship maneuvering.

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Ship maneuvers and the maneuverability of a ship in various ice conditions is a complex subject. Our present understanding of the nature of ship-ice interactions is still limited. Considering the complexity of the loads imposed by ice during ship maneuvers, a series of ship maneuvering experiments in ice were conducted at IOT. Ultimately, the test results will be used to develop a prediction model for ship's maneuvering in ice.

TEST PROGRAM

The experiments were carried out with a 1:21.8 scaled model of the Canadian Coast Guard's icebreaker, Terry Fox (IOT Model № 417). For these experiments, the test conditions are given in Table 1. The model was mounted to the towing carriage through a PMM (Planar Motion Mechanism, Spencer and Harris, 1997) at the model's center of gravity (see Figure 1). The model was towed at a controlled planar motion through a level ice sheet. In each experiment tow force, turning moment, and ship motions were measured. The transducer for outputs were sampled digitally at 50 Hz, and filtered at 200 Hz. The model surface was finished to a friction coefficient of 0.01 with Dupont's Imron paint. Two video recordings were made of each test: one on the starboard side, manually controlled to follow the model's maneuvers, and the other looking down ahead of the model at the port side.

Fig. 1. Figure showing the Terry Fox model attached to the PMM

Table 1. Model Hydrostatics

IOT Model №417, scale 1/21.8, without appendages	
Displacement (kg)	665.6
Waterline Length (m)	3.739
Waterline Beam at Mid-Ship (m)	0.789
Draught at Mid-Ship (m)	0.368
Center of Buoyancy Forward of Mid-Ship (m)	-0.07
Center of Aft Body Buoyancy Forward of Mid-Ship (m)	0.594
Stem Angle (°)	23.27
Waterline Entrance Angel (°)	32.15

The PMM apparatus consists of two primary components: a sway sub-carriage that is mounted beneath the main towing carriage, and a yaw assembly that is connected to the sway sub-carriage. The apparatus allows the model to yaw and sway in a controlled manner, while measuring the sway and surge forces as well as the yaw moment. The combination of sway and yaw allows a variety of maneuvers to be performed. The specifications for the PMM are given in Table 2.

The test matrix for the experimental program is summarized in Table 3. For the tests described in this program, the ice sheets had a target ice thickness of 40 mm and a target flexural strength of 35 kPa. The following maneuvers were utilized: (1) static drift, in which the model was towed along a straight line at a fixed yaw angle, and (2) pure yaw through a constant radius maneuver so that the heading of the model was always tangential to the path of its center of gravity resulting in zero sway force and a yaw moment. The static drift was performed with three drift angles, and the constant radius maneuver was conducted with two turning radii (50 m and 10 m). All tests were conducted with model velocity ranging from 0.02 to 0.6 m/s. Concurrent to the testing in ice, maneuvers in open water were also conducted.

Table 2. Specifications of the PMM

Max Sway Amplitude (m)	± 4.0
Max Yaw Amplitude (º)	± 175
Max Sway Velocity (m/s)	± 0.70
Max Yaw Rate (º/s)	± 60.0
Max Sway Force (N)	± 2200
Max Yaw Moment (N-m)	± 3000

Table 3. Matrix of the test program

Turning Radius, *R* (m)	∞	50	10
Drift Angle, β (º)	-2	0	
Model Speed, V (m/s)	0.02 ~ 0.6		
Yaw Rate, γ (deg/s)	0.02 ~ 0.34		
Ice Thickness (mm)	40		
Ice Strength (kPa)	35		

The experiments were carried out in CD-EG/AD/S ice (Spencer and Timco, 1990). With inclusions of air bubbles into the growing ice sheet, this model ice significantly improves scaling of ice density, elastic and fracture properties.

The useable model ice area is 12 m x 76 m. For each ice sheet, flexural, compressive and shear strengths were measured frequently throughout the test period. The values reported at test time were interpolated from the strength versus time curves for the ice sheet. Flexural strength, σ_f, was measured using in-situ cantilever beams. Shear strength measurement was performed immediately after the flexural strength test to provide index values for comparison with the measured flexural strengths. The ratio of shear strength to downward breaking flexural strength varied from 1.03 to 3.16. The reported ice thickness, h, is the average over approximately 65 measurements for the ice sheet along the test path. IOT standard and work procedures were followed for producing and characterizing level ice sheets.

TEST RESULT AND DISCUSSIONS

At the time of writing of this paper, the results are still being analyzed, and only limited results are available. As the yaw moment and turning radius are the important indicators of the maneuvering performance, this paper will focus on the interaction processes and the influence of ship motions on the yaw moment exerted on the ship hull.

Icebreaking pattern and channel width

As the ship advances into an unbroken ice field, individual cusps or wedges begin to break off from the level ice at the point of contact at the bow of the advancing side of the hull. These broken cusps and wedges are, then, rotated downward, pushed farther down the hull, and eventually cleared away from the hull at the sides. Once the rest of level ice sheet contacts the hull, the same breaking process continues. This sequential icebreaking creates a channel wide enough for the passage of the hull. Figure 2 shows an idealization of the channel created by the hull. The breaking initiated at the bow creates an initial channel width, W_i, slightly wider than the ship's beam, i.e., about 0.4 times ice characteristic length, l_c, wider (Lau et al, 1999). For a tighter turn, further ice breaking at the leeward side of the hull may be necessary to create a final channel width, W_f, wide enough for its passage. The location of ice ship contacts, and hence the local icebreaking load, can be estimated by considering the geometry of the interaction during turning. The zones for possible contact at different parts of the ship can be defined by a number of concentric circles. For a typical ship, the zone of possible ice contact for outer side is always larger than the inner side, and W_f is greatly dependent of the turning radius as shown in Figure 3. In Figure 3 the theoretical and measured W_f are plotted against the turning radius showing agreement between theory and test data. For the 10 m radius turn, the measured channel width is 4% greater than the theoretical width and for the 50 m radius turn, 6% smaller.

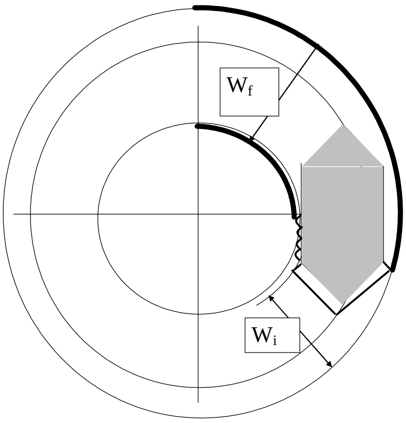

Fig. 2. The influence of turning motion on channel width showing the breaking at the bow and hull

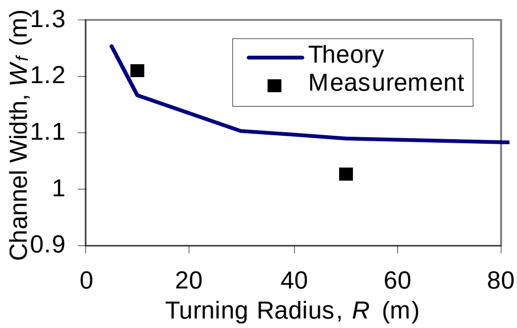

Fig. 3. Figure showing the theoretical and measured channel width as a function of the turning circle

The effect of ship turning on yawing moment

The result for the turning circle runs is given in Figure 4. Two turning circle radii of 50 m and 10 m were tested, each with the velocity ranging from 0.02 to 0.6 m/s. These corresponded to a yaw rate ranging from –0.02 to –3.4 deg/s. The data have been adjusted to 35 kPa ice flexural strength. The data show a bilinear relationship between yaw moment and yaw rate with a moment offset at 12.7 and 43 Nm for the 50 and 10 m turning maneuvers, respectively. The slope change is at a yaw rate of around 0.5 deg/s. Preliminary analysis was performed to understand the observed trend. It is believed that the moment offsets were mainly contributed by velocity independent ice breaking and submergence components, and the initial slope was determined by velocity dependent ice clearing and the open water components.

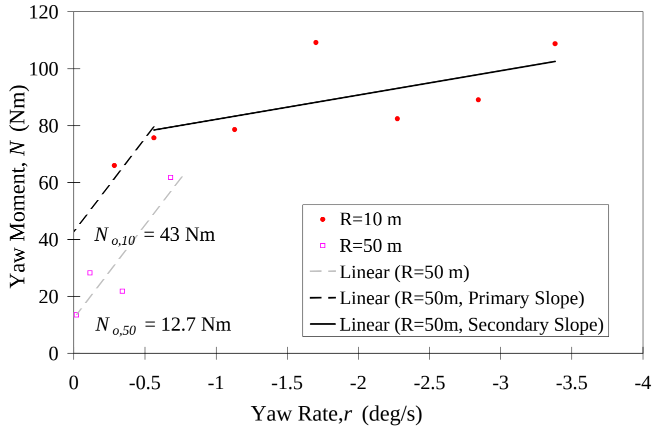

Fig. 4. Moment versus yaw rate for the Terry Fox model turning in ice with 10 and 50 m radii

At this stage, the explanation for the secondary slope needs further analyses. In the following sections, the discussion will be focused on the initial moment offsets, and the effect of the interaction geometry on their values.

MATHEMATICAL MODELING OF ICE BREAKING AND BUOYANCY COMPONENTS DURING SHIP MANEUVERING IN ICE

In the following section, a conceptual model of turning moment imposed on ship hull during a steady turn is presented. This model forms the framework for future mathematical development. Analogous to ice resistance (Spencer, 1992), the expression for total yaw moment, N_{tot}, is divided into the hydrodynamic, N_{ow}, icebreaking, N_{br}, ice submergence (buoyancy component), N_b, and ice clearing, N_{cl}, components:

$$N_{tot} = N_{br} + N_{cl} + N_b + N_{ow}. \tag{1}$$

The fundamental reason for this approach is that different components may not all scale in the same manner to full-scale. The ice breaking term has ice strength and thickness as parameters, and takes into account the effect of channel width and interaction geometry on the zone of application of the ice forces. The ice submergence term calculates the buoyancy forces. These two components are insensitive to model speed, and hence contribute to the moment offset at zero ship speed. The ice clearing and the open water terms include ice added mass and inertial contribution, and hence are velocity dependent.

Breaking component, N_{br}

For the case of a semi-infinite beam on an elastic foundation end loaded by a concentrated transverse force, the maximum vertical load per unit width, P_{Vm}, and the associated end deflection, y_m, is given as follows:

$$P_{Vm} = 0.68\sigma_f (\gamma_w h^5 / E)^{1/4}, \tag{2}$$

$$y_m = \frac{2P_{Vm}}{l_c \gamma_w}. \tag{3}$$

Where σ_f is the flexural strength of ice, γ_w is the specific weight of water, h is the thickness of ice, E is the Young's modulus of ice and l_c is the characteristic length of the ice beam.

Assuming an idealization of ice breaking force-displacement history as shown in Figure 5. The maximum displacement of ship forward, a, before ice failure is related to y_m:

$$a = y_m / \tan\alpha. \tag{4}$$

Where α is the stem angle.

If the average breaking length l_a is taken as $0.2l_c$ (Lau et al, 1999), the average vertical force per unit width, P_{Va}, acting on the ship surface where ice breaking occurs is equal to:

$$P_{Va} = P_{Vm}\frac{a}{2*0.2l_c} = 5.7\frac{\sigma_f^2 h}{E\tan\alpha}. \tag{5}$$

Assume that the ship maneuvers are at a constant yaw rate with a radius, R, as shown in Figure 6. Lets neglect the frictional component, and assume the energy required for ice breaking is proportional to the volume of broken ice created. If the effects of the broken ice pieces sizes are neglected, then the ice will contact the bow and the half side of hull with the three horizontal loads, F_{1h}, F_{2h}, F_{3h}, which can be computed as the following:

$$F_{h1} = P_{Va}(l_1 - l_2)\tan\phi\,, \tag{6}$$

$$F_{h2} = P_{Va}(l_2 - l_3)\tan\phi\,, \tag{7}$$

$$F_{h3} = P_{Va}(l_3 - l_4)\tan\eta\,, \tag{8}$$

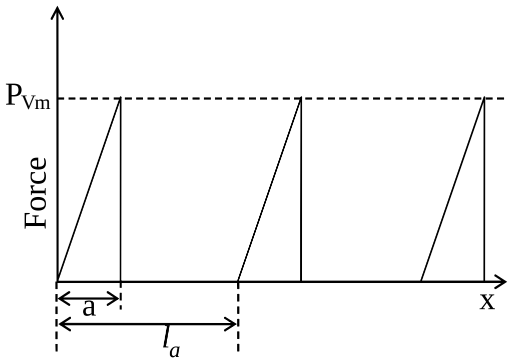

Fig. 5. The idealized force-displacement history when ship advancing

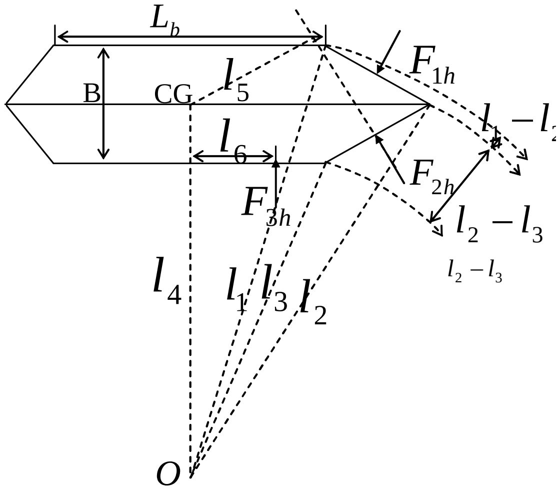

Fig. 6. Geometry of a ship maneuvers at a constant yaw rate

Where l_1, l_2, l_3 and l_4 are the geometric lengths as shown in Figure 6, and the angles ϕ and η are the angles between the normal of the bow and hull side surfaces and the vertical line, respectively. Hence, the yaw moment due to ice breaking from the forward part is given as follow:

$$N_{br} = \left(-F_{h1} + F_{h2}\right)l_5 + F_{h3}l_6\,. \tag{9}$$

Where l_5 and l_6 are the lengths between the respective force centers to the ship's mass center.

We used a 2-dimensional beam-bending model, in which the structure was regarded as having an infinite width. The edge effects should be considered when calculating ice forces. Modification to the above formulation was implemented by considering the ice breaking width adjustments, ∇l_1 and ∇l_2 as shown in Figure 7. By assuming the following proportionality from geometric consideration:

$$\frac{\nabla l_1}{\nabla l_2} = \frac{l_1 - l_2}{l_2 - l_3}\,. \tag{10}$$

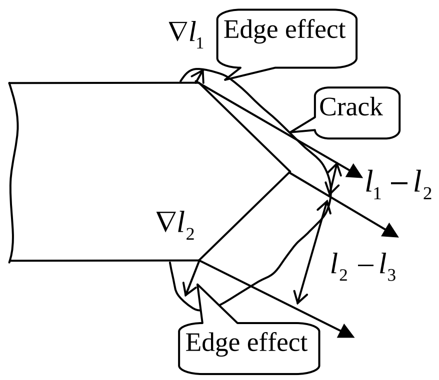

Fig. 7. Figure showing the edge effect on ice broken pattern at the bow

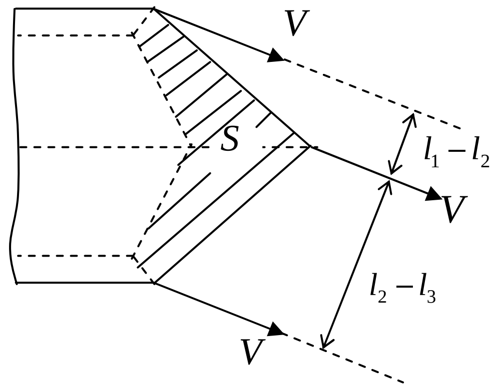

Fig. 8. Bow eometry showing amount of ice sliding on bow surface

The total width W_b of ice broken by the bow is equal to:

$$W_b = \nabla l_1 + \nabla l_2 + l_1 - l_3 . \tag{11}$$

Submergence component, N_b

The buoyancy force on the hull was calculated by considering the amount of ice covering the different parts of the hull. For the bow part as shown in Figure 8, the vertical component, F_{v_1} and F_{v_2} of the buoyant forces acting at the respective side of the bow can be calculated using the following equations:

$$F_{v\_1} = \frac{l_1 - l_2}{l_1 - l_3}(\gamma_w - \gamma_i)hS , \tag{12}$$

$$F_{v\_2} = \frac{l_2 - l_3}{l_1 - l_3}(\gamma_w - \gamma_i)hS . \tag{13}$$

Where γ_i is the specific weight of ice and S is the horizontal projection of the bow surface.

Ignoring the ice/hull friction, the corresponding horizontal forces, F_{h_1} and F_{h_2}, on the respective side of the bow due to buoyancy are given as follows:

$$F_{h\_1} = \frac{l_1 - l_2}{l_1 - l_3}(\gamma_w - \gamma_i)hS \tan(\phi) , \tag{14}$$

$$F_{h\_2} = \frac{l_2 - l_3}{l_1 - l_3}(\gamma_w - \gamma_i)hS \tan(\phi) . \tag{15}$$

And the yaw moment, N_b, due to buoyancy forces from the bow is equal to:

$$N_b = \left(- F_{h\_1} + F_{h\_2}\right) l_5 . \tag{16}$$

The lengths l_1, l_2, l_3 and l_5 are given in Figures 6. Similarly, the buoyant forces on other part of the wetted surface of the hull can also be calculated.

Comparison

According to the present model, the components, N_{br} and N_b, are independent of yaw rate, but greatly influenced by the turning radius R, as shown in Figure 9. As the ship maneuvers in tighter turns, it needs to break more ice at the inner side resulting in increasing yaw moment. As shown in Figure 9, the model predicts a yaw moment of 30.7 Nm and 6.5 Nm for the 10 and 50 m radii, respectively. In comparing with the measured values of 43 and 12.7 Nm, the model under-predicted the moment offset by 29% and 49% for the 10 and 50 m tests, respectively.

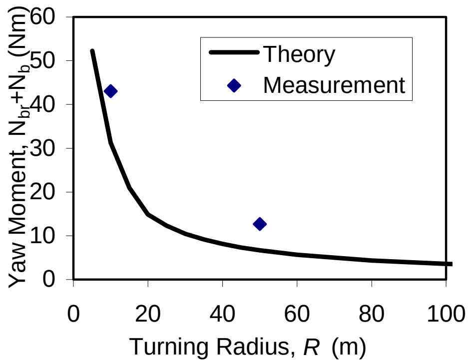

Fig. 9. Predicted moment offset as a function of turning radii

In the present analysis, the friction force and the in-planed ice compression were neglected in order to make the problem simpler. This will tends to underestimate ice load where a steep slope are present, i.e., at the side hull. When calculating the buoyancy force, some assumptions were made for the broken ice motions. All these simplification may introduce uncertainties and errors to the predictions.

FURTHER WORK

At the present, a multifaceted approach would give a more fruitful result. These include deriving the form of prediction equation through analytical means, and performing extensive numerical simulations for a range of hull forms and maneuvers. Fitting data to the analytical model will provide empirical coefficients to a set of semi-empirical equations.

The analysis presented in this paper has been greatly simplified. Efforts are underway to refine the mathematical model by considering the possibility of different failure modes occurring simultaneously along the hull, ice friction, and a refined interaction geometry and ice breaking and clearing processes.

CONCLUSION

In this paper, the preliminary results from a ship maneuvering test series were presented, along with a simple analysis to illustrate the importance of interaction geometry on the interaction processes and the resulting yaw moment. Despite the simplicity of the problem treatment, the analysis gave a favorable prediction. Future work will include a refinement of the problem treatment as well as an extensive series of numerical experiments with the aim of developing a mathematical model to successfully predict a ship's maneuvering performance in various ice conditions.

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FULL-SCALE EXPERIENCE OF DOUBLE ACTING TANKERS (DAT) MASTERA AND TEMPERA

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ABSTRACT

The oil transportation in the icy waters is increasing rapidly and capable tonnage is needed. In the early 1990'ies Kvaerner Masa- Yards together with ABB developed the podded propulsion device Azipod, where the characteristics of a Z-drive and electric propulsion are combined. Combining the new propulsion and old idea of "bow propellers" Kvaerner Masa- Yards has developed a new philosophy to utilize the both ends of the vessel to maximum efficiency. This work has resulted to a design, where the vessel navigates in ice free and mild ice conditions running bow first and in severe ice conditions the vessel runs astern. Finally the ideas materialized to two DAT tankers to be built for Fortum Shipping in Japan at the Sumitomo Yokosuka Shipyard. The vessels were delivered in late 2002 and since then they have trafficed independently between the oil terminal (Fortum refinery) in Porvoo and the Primorsk Oil terminal in Russia some 25 return voyages during the winter in 2003. In March 2003 dedicated ice trials along with a normal voyage were carried out to study the capability of the vessels. This paper describes the conditions where the tests were conducted and test results.

INTRODUCTION

The vessel travels ahead on normal open water conditions using a boulbous bow suitable for open sea, it travels astern when it sails in ice (especially in heavy conditions) using the reinforced stern. The development of the DAT concept is described by Juurmaa & al in references 3 and 4. However The podded azimuthing propulsion is used to obtain large ice breaking capacity and high maneuverability. This concept is been called DAS (Double Acting Ship) and DAT is the Tanker case for DAS. This concept has been developed and patented by Kvaerner Masa-Yards (KMY) and KMY made the conceptual design for the vessel. During the construction of the vessel KMY assisted Sumitomo Heavy Industries Ltd. (SHI) by giving advise in ice related matters.

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Two double acting tankers (DAT) “ Tempera” and “ Mastera” were built by Sumitomo Heavy Industries Ltd. for the Fininish group Fortum Oil and Gas and they were delivered successfully (open water sea trials are described in reference 1 by Sasaki & al.) August 2002 and January 2003 respectively. Full scale ice tests of “Mastera” were conducted in March. 2003 during a regular voyage between Porvoo, Finland to Primorsk, Russia. Ice ice trials were co-ordinated and run by MARC (Kvaerner Masa-yards Arctic Research Center) with the help of experts from CNIIMF (Central Marine Research & Design Institute, St. Petersburg, Russia) and HUT (Helsinki University of Technology). The ice trials of the vessel was the final confirmation of the success of the project.

The main objectives of the full-scale ice tests were to confirm the performance of the vessel in the real wintertime operational conditions. The icebreaking capability was demonstrated mainly in partly ridged level ice but also in ridge, see Figure 1, and different channels. The manoeuvring capability was tested making turning tests enroute.

Fig. 1. MT Mastera in an ice ridge

DOUBLE ACTING TANKER MT MASTERA

This project was started from 1999 as a clean energy project for Baltic Trade in the company of Fortum Oil & Gas Oy. The company decided to realize the DAT concept for next Aframax vessels and ordered Sumitomo to build two double acting tankers. Table 1 shows the main particulars and in Figure 2 there is the side view of the vessel.

Table 1. Main Particulars of MT Mastera

Length pp	230.0	m
Breadth moulded	44.0	m
Draught, max	15.3	m
Power	16.0	MW
Dead weight	106100	ton
Ice Class	1A Super	

The propulsion is provided by an Azipod unit. This contains the electric motor and the fixed pitch propeller. This is pod can rotate at 360° and has a maximum rating of 16 MW.

TEST SCOPE

The ice trials were performed during one regular voyage, which started from Porvoo on March 10, 2003. The ice conditions in the Gulf of Finland (sea area of the voyage is in Figure 2) consisted of different kind of channels, ridges, rubble fields, level ice and rafted ice. The main features of the ice conditions where the following:

- heavy channels to ports and terminals,
- thickness of basic level ice 40 - 60 cm,
- rafted ice 60 - 80 cm,
- small ridges, sail height 0.5 - 1.0 m,
- heavily ridges areas, sail heights up to 2m, with maximum thickness 12 – 15 m.

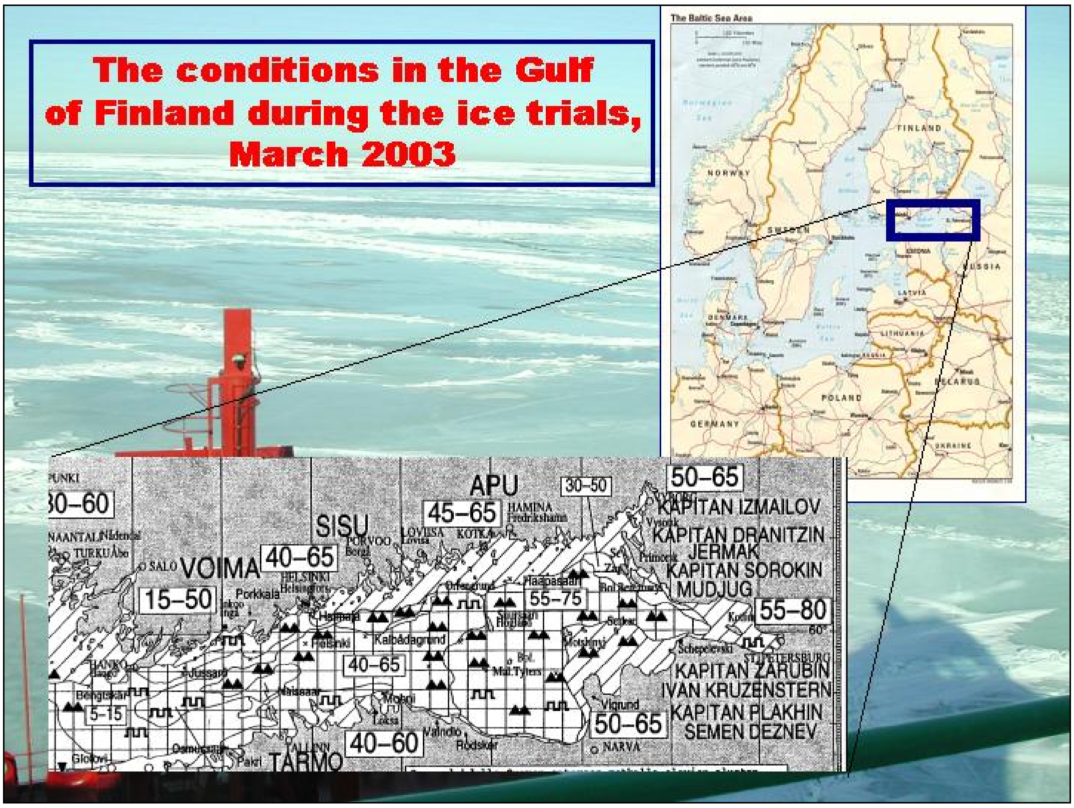

Fig. 3. Gulf of Finland

The route from Porvoo to Primorsk with test sequences is in Figure 4. The return voyge followed mostly the same path. Ridge tests were done at Test 4.

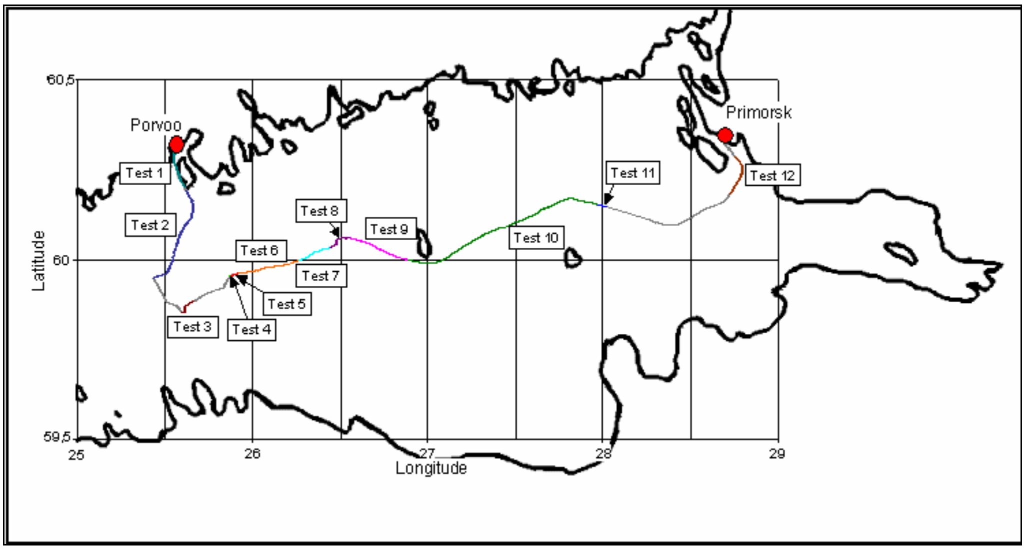

Fig. 4. Route of MT Mastera during ice trials, Porvoo-Primorsk, Ballast

The vessel was run astern both ways from Porvoo to Primorsk in ballast and loaded on return trip. The corresponding draughts were Ballast: T_{aft} = 10.5m, T_{bow}= 7.4m, Loaded: T_{aft} = 15.5 m, T_{bow}= 14.9 m.

Measurements

Machinery Quantities

During the voyage the main propulsion machinery quantities were recorded from systems of the vessel: Propeller RPM, Propeller motor power and Azipod angle. The speed of the vessel was defined with a doppler radar and GPS.

Surface roughness of ice

The roughness of the upper surface (distribution of ridges) of ice encountered by the ship was measured with a laser distance meter (profiler) along the sailing route. Simultaneously with the laser profiler the GPS co-ordinates were recorded on a PC. This portion of the ice trials was on the responsibility of HUT.

On ice measurements

A few days before the voyage an ice party headed on escort tug Ahti to the Porvoo channel to measure the channel cross-sectional profiles at two locations. The the properties of level ice were defined by measuring the salinity and temperature of level ice at two different locations. Firstly, close to the Porvoo pilot station (on level ice off the old channel) and secondly, simultaneously as the ridge measurement session took place, enroute to Primorsk offshore Porvoo. The defined flexural strength values were the following: three days before the trip near Porvoo pilot station the flexural strength σ_F was 551 kPa and during the trip when the ridges were measured the σ_F was 357 kPa. The difference is mainly due to the weather conditions, rain and wet snow.

Offshore Porvoo, east of Kallbådagrundet, two ridge profiles were measured, surveyed and drilled.

Visual observations

During the voyage a 24 hour watch was kept on to visually observe the events happening enroute. Video cameras and still cameras were used to refresh the memory after the voyage. This work was maily on the responsibily of CNIIMF.

Performance in brash ice channels

Old heavily trafficed channels during the voyage were the one out of Porvoo (Tests 1&2) and the one starting from the Island of Gogland (Tests 10-11) leading to St. Petersburg and turning at vicinity of Seskar Island towards Primorsk oil terminal (Test12). The only place where the thickness of channel could be measured was the Porvoo channel, see Figure 5.

Fig. 5. Porvoo channel

MT Mastera is, according to the test results, able to run with the speed of 5 kn (2.57 m/s) in an old 1.0 m thick brash ice channel with a power of 2-3 MW and in a 2 m thick channel with a power of 6-7 MW. These power levels are much lower than the ice class rules define.

Figure 6 illustrates the performance in channel to/from Porvoo where the channel thickness profiles were measures a few days before the test voyage. Figures 7 shows the measured crossection profile at the location near the Porvoo Pilot station (thickness 1 m).

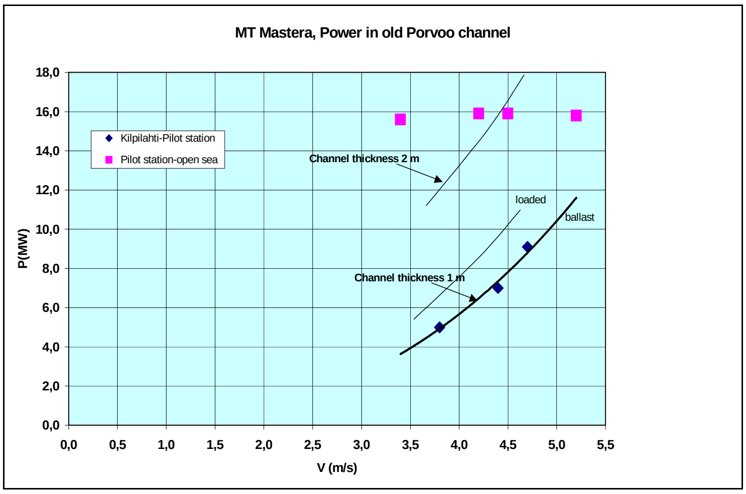

Fig. 6. MT Mastera in Porvoo channel

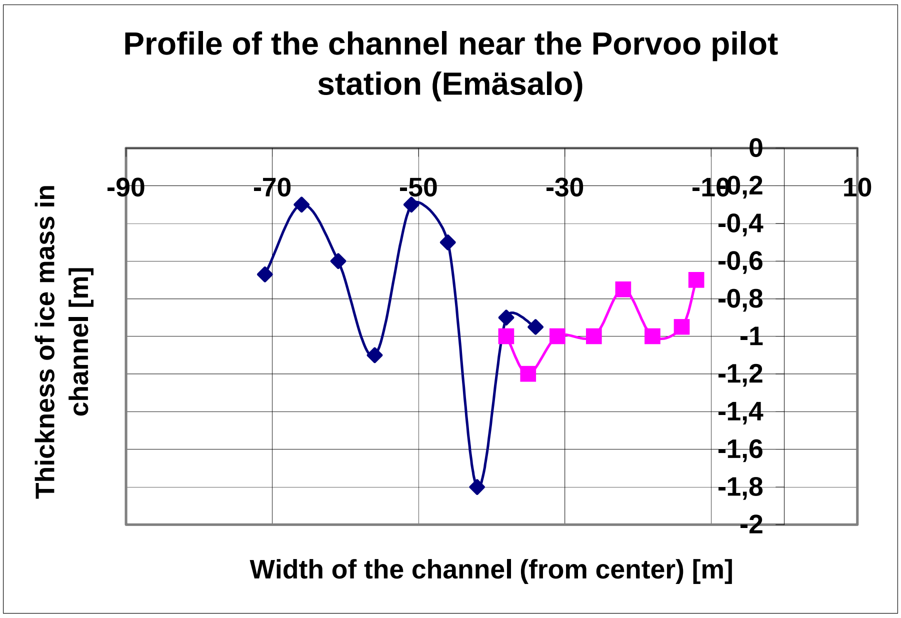

Fig. 7. Measured channel profile at Porvoo Pilot station

Performance in level ice

<u>Straight runs</u>

In general the thickness of level ice was 0.4 – 0.6 m. However, smooth areas of level ice large enough could not be found. Each smooth area was at maximum about one/two ship lengths long and between each "floe" there was typically some either rafted or ridged ice. In these areas the vessel maintained easily a speed of 3 – 4 m/s (6 – 8 kn). The vessel owing a large mass went quite steady with continuous speed without much noticing any of the smaller roughnesses of ice surface. The speed of the vessel vs ice thickness is presented in Figure 8. Figure 9 shows a view of the prevailing level ice conditions.

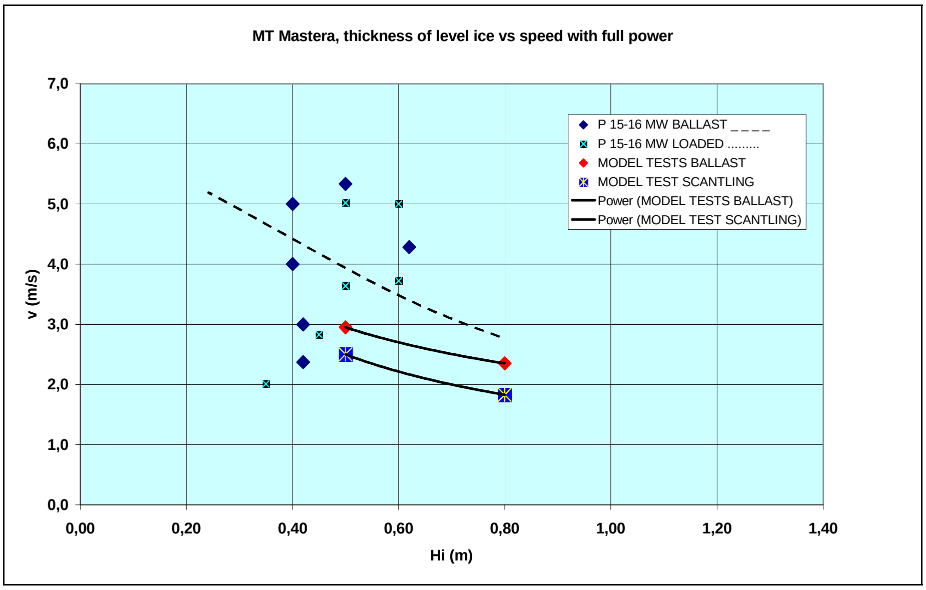

Fig. 8. Icebreaking capability of MT Mastera

Fig. 9. Level ice conditions

Turning tests

On both legs of the voyage turning test were performed in the level ice fields with different Azipod angles. The areas where the tests were performed comprised of large level ice floes with small ridges at the edge of each floe. The size of these floes was 100 – 200 m in diameter in average. The conditions were similar to those in Figure 9. A comparison to other large vessels is in Figure 10. The turning capability of MT Mastera is very good considering the size and length of the parallel midbody.

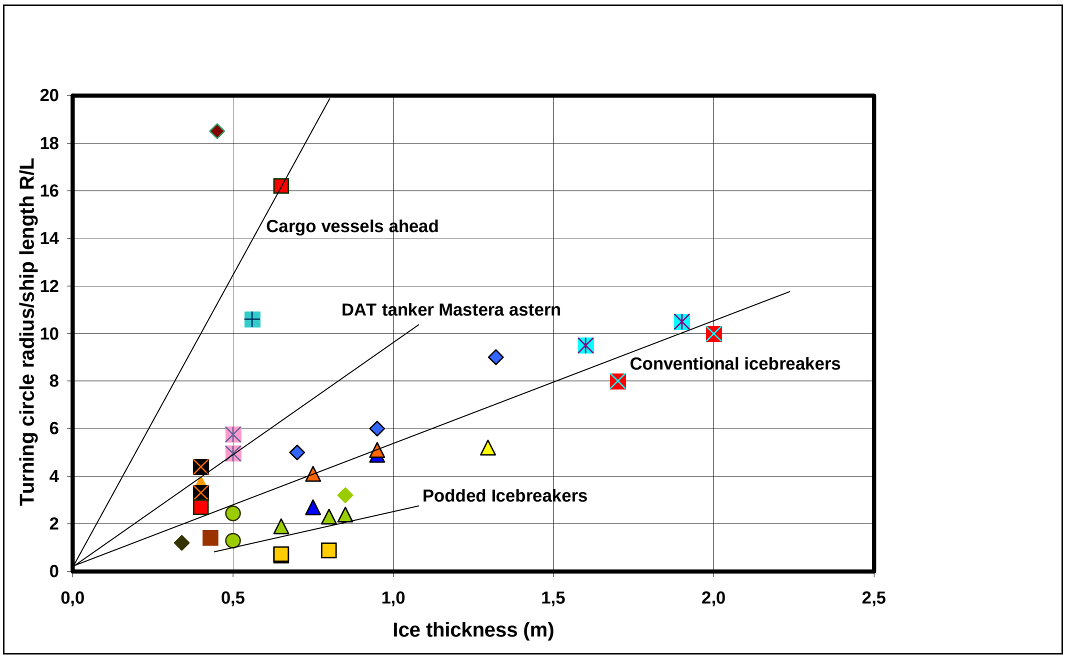

Fig. 10. Turning circle comparison

Performance in ridges

The first ridge was penetrated running the vessel in ballast condition. The vessel started to move from standstill and forced its way over the ridge. The ridge had a maximum thickness of 13.5 m. The average speed to penetrate through the ridge was 0,6 m/s**.** The power used and vessel speed in function of ridge profile is in Figure 11.

Photographs of the ridges and the tests in ballast condition are in Figures 12 – 15.

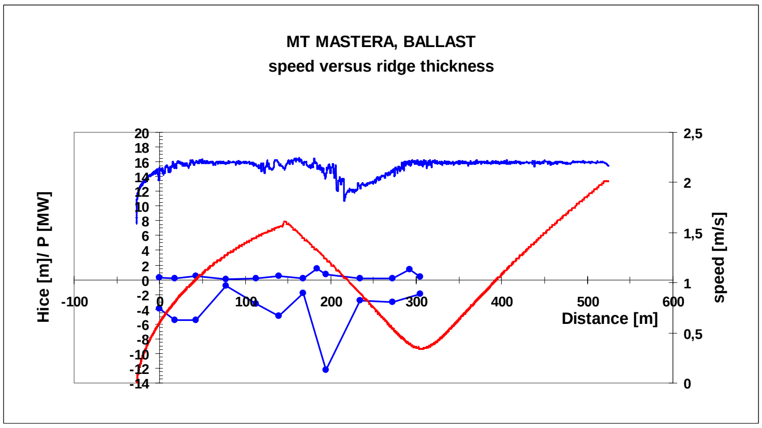

Fig. 11. Performance in measured ridge in ballast condition

Fig. 12. Ridge № 1 Upper surface

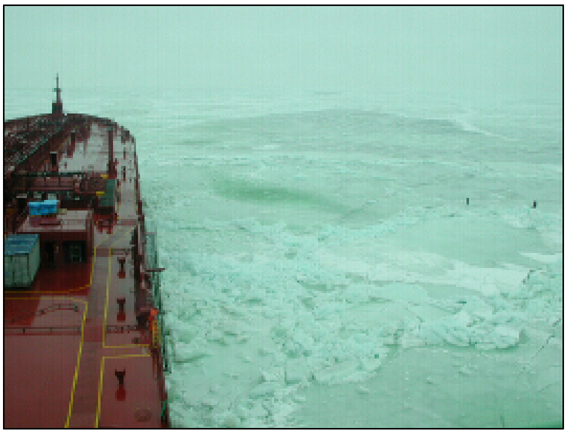

Fig. 13. MT Mastera in ridge

Fig. 14. MT Mastera, ready to attack

Fig. 15. MT Mastera through the ridge

The second ridge was penetrated running the vessel in loaded condition. The vessel started to move from standstill, like in ballast condition, and forced its way over the ridge. The ridge had a maximum thickness of 12.6 m**.** The average speed to penetrate through the ridge was 0,3 m/s.

Figures 16 – 18 show views from the tests.

Fig. 16. Ridge № 2, upper surface

Fig. 17. MT Mastera, ready to attack

Fig. 18. MT Mastera in ridge

CONCLUSIONS

In every respect the vessel performed as expected (based on model tests). The ability to navigate in conditions were some 30 – 40 ships were trapped in ice was overwhelming. MT Mastera and her sistership MT Tempera are the biggest “icebreakers” in the world. In the conditions of Gulf of Finland the two vessels have no problems what so ever.

Fig. 19. Ice rubble, offshore Porvoo

MT Mastera could keep a steady 3-4 m/s speed in the basic ice condition, level ice floes with rubbled edges. In channels the speed increased up to 6 – 6.5 m/s.
The ability of penetrating ridges was proven in individual tests, but also enroute, for instance, when approaching Porvoo from the sea, the vessel was turned to the north near

Kallbådagrundet and crossed a field of ridges, where no ordinary vessel, except an icebreaker, has any business to go. There the speed slowed down a bit, but the vessel never stopped.

Maneuvering is also a major concern. MT Mastera behaves quite well in turning in rough level ice. The results in the ratio turning circle radius/ship length (R/L) are in average around 4 as for vessels equipped with conventional propulsion running ahead the R/L ratio is over 10.

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PROSPECTS OF WINTER NAVIGATION IN SAYANO-SHUSHENSKOYE HPS RESERVOIR

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Sayano-Shushenskoye water reservoir is the deepest one in Russia. Situated in a severe climatic area the reservoir has rather favourable conditions for navigation, because the ice formation on the surface of the reservoir begins on much later term than on u.t. due to the great heat storage which is accumulated in summer.

The main navigable route starts at Shagonar port (the Republic of Tyva) and ends at Sayano-Shushenskoye HPS section (Khakasia) (Fig. 1). The total length of the navigation route is 295 km. Using the reservoir for navigation is realized because of very difficult conditions of transportation support within the Republic of Tuva. At present the transport communication of the republic is supplied by two motor roads only: one connects the capital of the republic – Kyzyl – through Turan and Ermokovskoye with Minusinsk, its length is 400 km. And the other is 513 km of length and it connects Shagonar and Ak-Dovurak with Abaz station. Each of roads has difficult mountain zones, which get covered with snow early, so the republic of Tuva requires more economical and dependable transport communications, one of which could be Sayano-Shushenskoye water reservoir.

The most important problem for the navigable waterway through the reservoir is prolongation of navigation period with the possibility of supplying a year-round navigation.

Sayano-Shushenskoye HPS reservoir has a number of peculiarities which influence on the thermal water rate and of course the ice rate.

The first speciality is an exceptionally big reservoir depth which amount to 200 m at the HPS section (Fig. 2). The second one is a deep drawdown in winter which ammounts to 39 – 40 m.

After the winter drawdown which ends at the turn of April, an intensive filling of the reservoir starts (Fig. 3) until the end of July - the beginning of August. This volume of warm water fills 40 meter reservoir layer and by autumn cold, when average monthly air temperature sinks below zero, the above-zero temperature lasts out in the reservoir, what postpones the time of freezing significantly.

The results of research of the ice formation in the reservoir are given in the Table 1.

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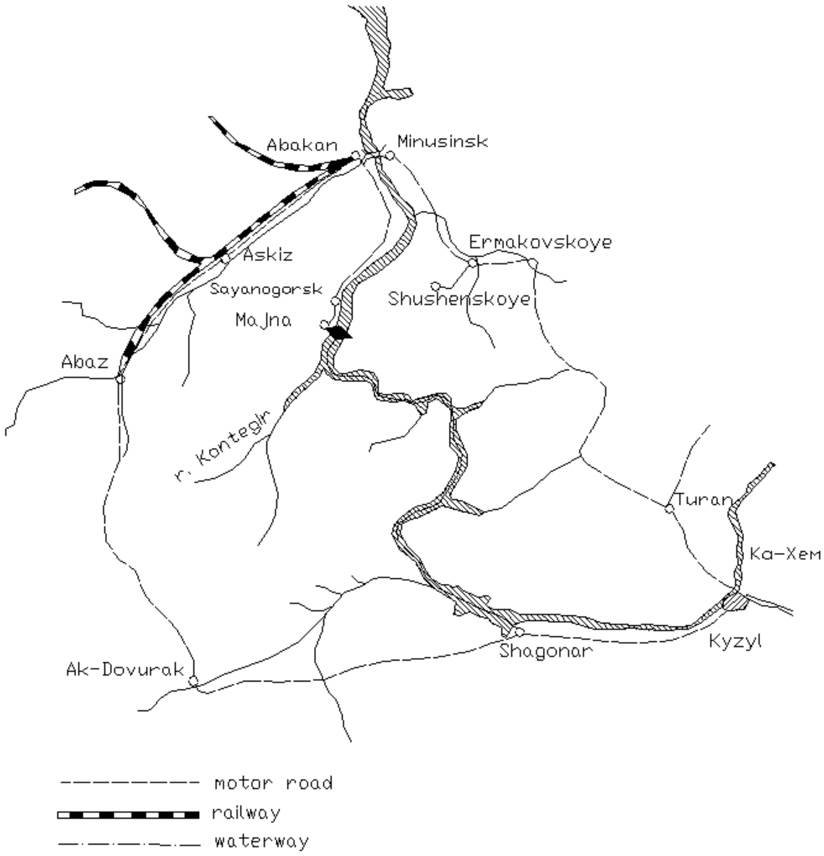


Pic. 1 Scheme of the water route in Kyzyl through Sayano-Shushenskoe HPS reservoir.

Table 1. The beginning of freeze-up in Sayano-Shushenskoye HPS reservoir (observational data 1986 – 2002)

A section of the water way	Mileage from the HPS section, km	Beginning of the ice formation		
		early	medium	late
Lower part of Pashkino-Djoyskaya sosnovka	0-65	25.12	08.01	19.01
Middle part of Kyzyl-Suk	65-190	06.12	08.12	25.12
Upper part of r. Khemchik – Ustj-Usa	190-250	06.11	25.11	01.12
Zone of variable levels N. Shagonar – r. Khemchik	250-295	24.10	02.11	10.11

Taking into account that river opening happens in the same time we can consider the following fixed time of physical navigation, that is when the ice on the surface of the reservoir is broken up (Table 2).

The data of the Table 2 demonstrate that the navigation duration in the reservoir in comparison with common conditions of Enisey river (section Kyzyl-Shagonar) may be prolongated significantly which is written in the Table 3.

Admitting that the average duration on the "natural" river (Kyzyl – Shagonar section) is equal to 169 days we can evaluate the contribution of the reservoir to the navigation prolongation (Table 4).

It follows from the data of the Table 4 that the navigation duration is increased from 1,5 till 2 months at the lower section and on average half a month at the upper section. Therefore the navigation on the part N. Shagonar - river section can be increased by half a month and more without using technical means for ice-fighting.

Table 2. The duration of the physical navigation in Sayano-Shushenskoye water reservoir

Mileage from the HPS section	Duration of navigation		
	Early ice formation	Medium ice formation	Late ice formation
1	2	3	4
0-65	245	235	215
65-190	226	216	205
190-250	217	203	191
250-295	193	177	169

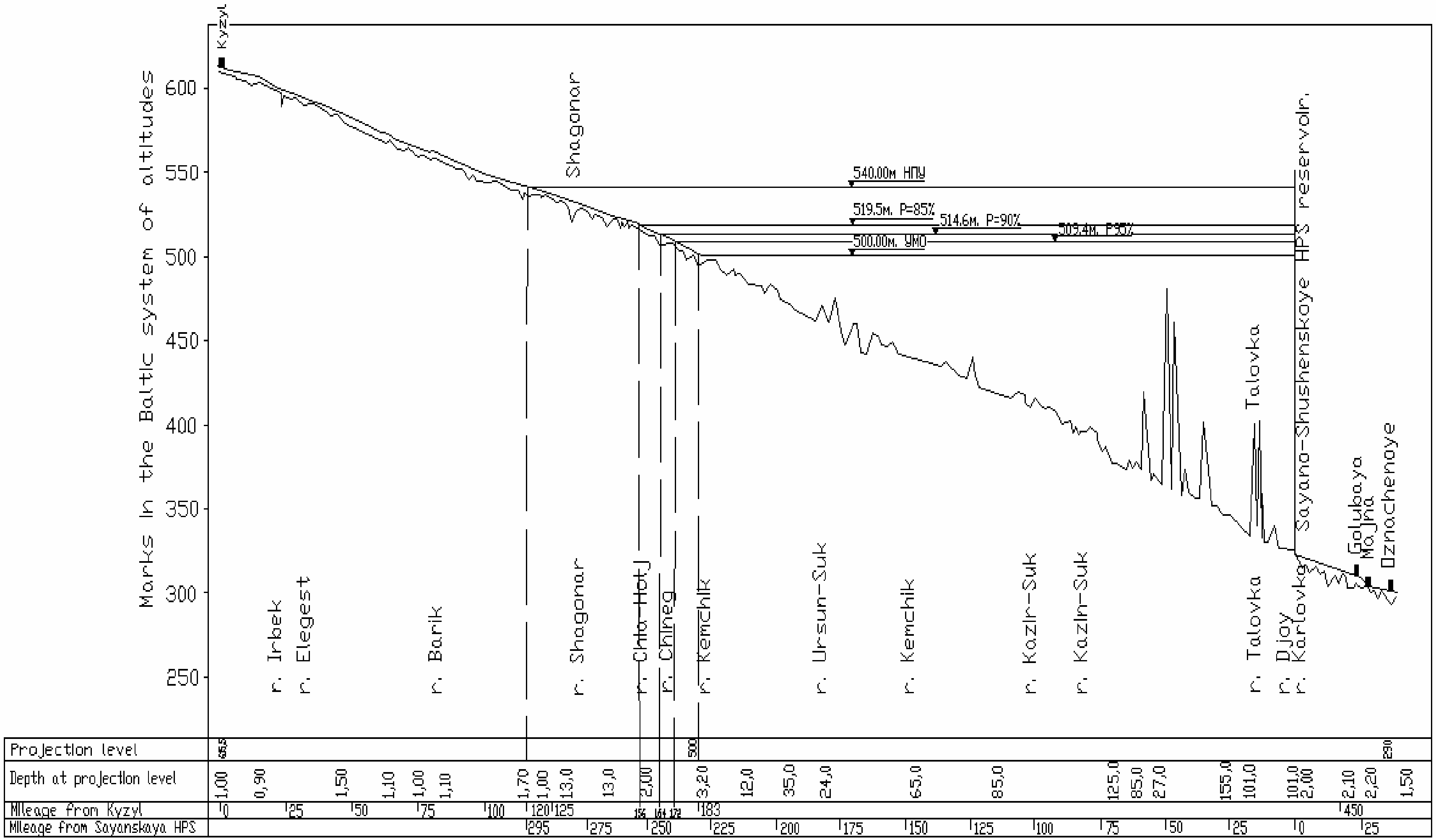
Table 3. The terms of the ice formation beginning and the navigation duration on the section Kyzyl – N. Shagonar

Characteristic	Maximal	Supply, %					Minimal
		10	25	50	75	90	
Date of ice formation	06.11.	13.11	15.11	19.11	25.11	28.11	06.12
Duration of navigation, days	193	180	174	169	165	159	157

Table 4. The prolongation of the navigation duration in Sayano-Shushenskoye HPS reservoir in comparison with the common procedure

Sector of the reservoir, km	0 – 65	65 – 190	190 – 250	250 – 295
Prolongation of navigation, days (numerator – maximum, denominator – minimum)	76/46	57/36	48/22	24/0

Taking into consideration the fact that the minimal level of air temperature is passed by the moment of the ice formation, it is obvious that later terms of the ice formation in the reservoir give a result of a low growth of ice thickness in the residuary cold period. We have no data of the ice growth intensity during winter, but taking in consideration that the maximal ice thickness at N. Shagonar station is 0,8-1,0 m in March and at the lower reservoir section is 0,4-0,5 m, we can regard the task of navigation in winter as quite decidable according to the experience of working in ice, i.e. the possibility of year-round navigation is not ruled out.



Pic. 2 Scheme longitudinal sideview of r.Enisey from Kyzyl till Oznachennoye

Pic. 3 Course of water levels in Sayano-Shushenskoye reservoir for 1996, 1997.

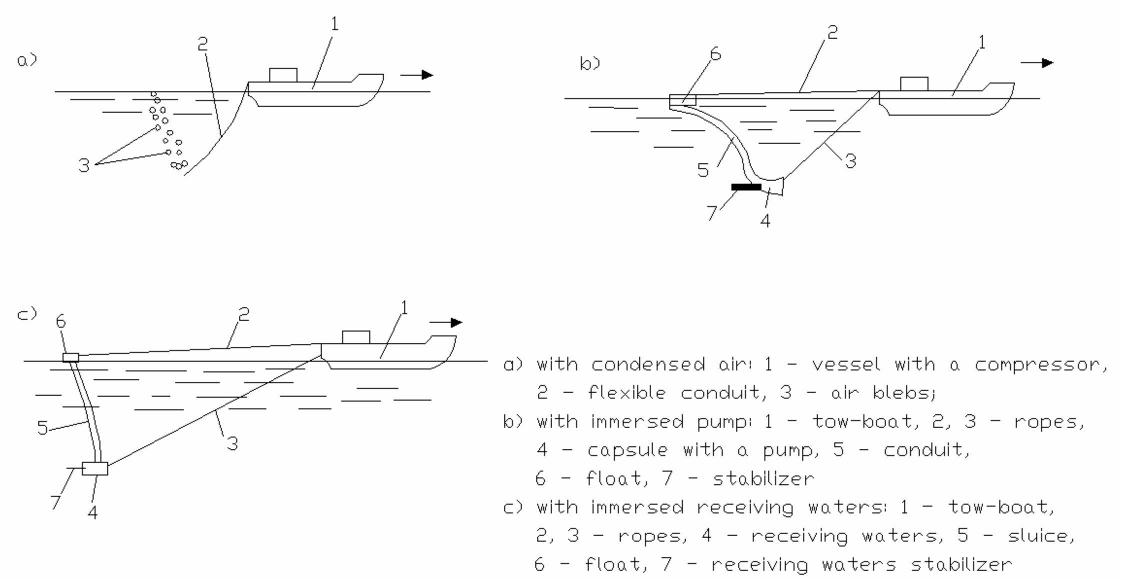
The coal transportation in the volume of 4 million tons a year in road-transport semi-trailers which are loaded on a barge by driving on (method "RO-RO") is provided for in the plan of transport familiarization of Sayano-Shushenskoye water reservoir ("Len-HyproRivTrans", 2003). Both a barge and a tow-boat are of the ice class. It is significant that these vessels can run in autumn-winter navigation for 20-30 days without a special ice-breaker.

It is effective to use the warmth of the hypogene waters for making a navigable and clear of ice route, huge resources of warmth are retained on the depth during the whole winter period.

For this purpose it is effective to use a special floating plant which provides raising warm water from depth to surface (Fig. 4). The plant which is towed by a motor ship can raise water with both a special pump and blebs of condensed air from the conduit which is immersed into the zone of warm water.

The periodicity of plant going along the navigable route is determined by both the quantity of warm water which is raised to the surface and the heat emission from the surface. In this method the ice formation should be allowed for decreasing the heat emission quantity, the thickness of the cover should be that which could be broken by a tow-boat.

The thin ice cover which is formed during the period between tow-boat passings represents as a screen and reduces heat emission from the surface. After tow-boat passing with water-raising plant the broken blocks of ice are melt by raised to the surface warm water.



Pic.4 Schemes of water giving from the depth to the surface of the reservoir

It is necessary to give a quantity of water to the surface for melting the ice and supplying the navigable route. It can be calculated by the formula:

$$Q = BVST/\rho\sigma\left(t_d - t_s\right),$$

where: B – width of a navigable route, m; V – speed of a tow-boat moving with a water-raising plant, m/sec; S – specific heat losses from the surface of the water, W/m^2; ρ – density of the water, kg/m^3; σ – specific heat of the water, J/kg·K; t_d – the water temperature which is taken from the depth by a receiving waters; t_s – the temperature on the water surface at the place of the ice formation; T – the time between a tow-boat passings with the water-raising plant.

The calculations show that technical means (pumps) admit giving the water to the surface with a low energy consumption.

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MODEL TESTS FOR ICE CLASS TANKERS

Göran Wilkman, Kimmo Juurmaa, Tom Mattsson[1]

ABSTRACT
Oil transportation is moving into more challenging waters as new terminals are built in the Baltic and in Far east. The oil export demand requires vessels that need to be designed for harsh environment. From the oil company point of view the oil should be moving not standing for weeks in vessels trapped in ice. One measure is the ice class (classification societies and Finnish Maritime Administration, FMA). Certain ice class requires certain performance (power demand), which is a bit theoretical, in defined conditions. The FMA rules allow also to use model tests to prove the capability of the vessel in required conditions as in some cases the power requirement in the rules is quite high and the project may get into a stop right away. However, ice class does not guarantee the success of the transportation. The whole operation is also dependent on icebreaker service. Big aframax tankers need typically two icebreakers to assist them. In case only one icebreaker is available, what will happen? This paper discusses mainly the utilization of the FMA rules (issued in 2002) in conjunction with model test programmes to check the power needed. Also the general safety and additional requirements depending on the whole level of operation is discussed.

INTRODUCTION
The Finnish-Swedish ice class rules define the conditions for different ice classes as performance in a brash ice channel at a speed of 5 knots (2.57m/s). The prevailing parameter is the thickness of the brash ice in the channel. The basic thickness of brash ice in the middle of the channel for different ice classes is in the following Table 1.

Table 1. Ice classes and brash ice thickness

Ice class	Thickness of brash ice (m) in the center of channel	Thickness of brash ice (m), average value for a 44m wide vessel
1A Super	1.0 and a 0.1 m thick consolidated layer	1.38 and a 0.1 m thick consolidated layer
1A	1.0	1.38
1B	0.8	1.18
1C	0.6	0.98

[1] Kvaerner Masa-Yards Arctic Technology, Helsinki, Finland

However, the thickness in table 1 is not really the one that is to be used when the capability is defined. The brash ice channel has very seldom equal thickness throughout the cross sectional profile. The channel is at its thinnest in the middle and the thickness grows gradually towards the edges. The actual thickness to be used is in equation 1.

$$H_{av} = H_M + 8.73 \cdot 10^{-3} B, \tag{1}$$

where H_{av} = average thickness of brash ice in channel; H_M = thickness of brash ice in the middle of the channel; B = beam of the vessel.

For an aframax size vessel with a beam of 44 m, the values of channel thickness are to be increased by 0.38m, see Table 1.

The rules give in most of the cases and for higher ice classes unrealistic power demands. For instance an aframax tanker of class 1A super may be required to have power levels up to 30-40 MW. This is quite unrealistic. The data base for the rules is from smaller vessels, max beam 30 m and the equations are not considering larger vessels at all Who would build such a ship that would need in ice more than double power than in open water? The schematic presentation of what can be achieved is illustrated in Figure 1.

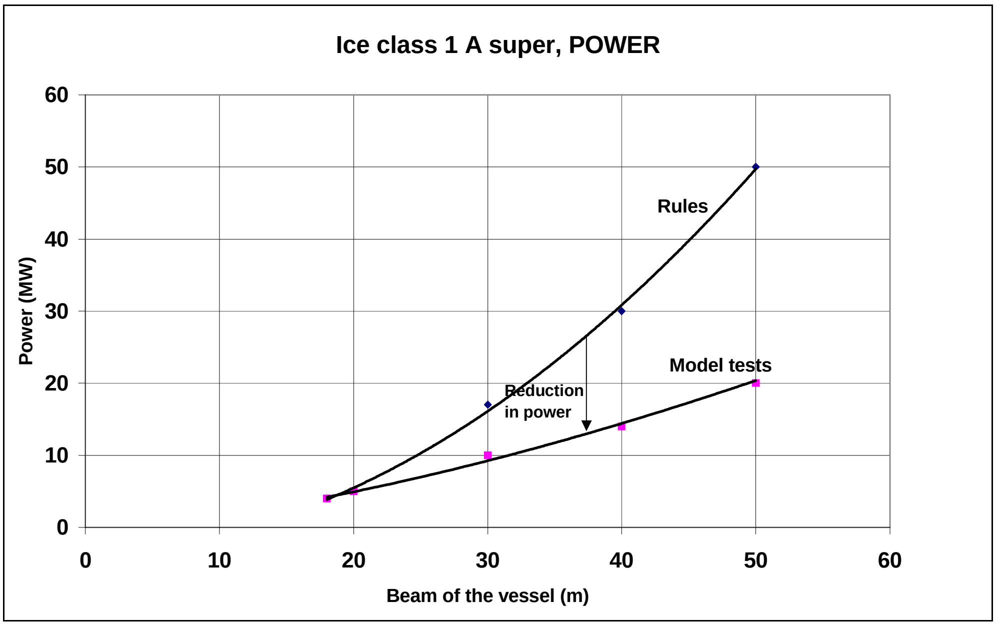

Fig. 1. Ice class rules equation and model test results

CONDITIONS FOR MODEL TESTS

A detailed description of the conditions around the testing can be obtained from the FMA. Here the most important factors are highlighted to get an idea what the conditions for such testing are about.

Brash ice channel

The definition of a brash ice channel is very important. In addition to the ice thickness in the channel the result is affected by the width of the channel and size of ice blocks in the channel.

The width of the channel is dependent on the size of the vessels operating in the area and if there are any restrictions; narrow passages etc.. An example of a regularly trafficked channel, where the vessels are typically between 20000 and 100000 dwt in size, is the channel to Porvoo oil terminal (southern Finland). In normal winter the level ice thickness in the area reaches 0.6m. The channel is in most places c. 100m wide (two way traffic). Most of the channel has quite even thickness of brash ice. The channel may have two series of edges; first that is some 12-15 m from the centre (made by small vessels) and second some 20-30m from the center (big ships). A photograph of the Porvoo channel in March 2003 is in Figure 2.

Fig. 2. Channel to Porvoo

The other typical feature to a brash ice channel is the size of the ice blocks. As seen in Figure 2 the ice blocks are quite small, typically 0.5m times 0.5 - 1.0 m. In model test conditions such a channel looks like the one in Figure 3.

The powering problem is mainly for the big vessels, panamax, aframax and suezmax. For such vessels the range of average channel thicknesses is between 1.0 and 1.5 m. The practise is to perform the tests in two channel thicknesses namely 1.0 and 2.0 m. The channel width should be 2 times the beam of the vessel. The channel should be properly recorded; thickness distribution and block size. The basic level ice thickness for the one meter channel is to be 0.5 - 0.6m and for the 2 meter channel respectively 0.8 - 1.0m.

Also tests in narrow brash ice channel can be useful and are actually done prior the wide channels.

Fig. 3. Brash ice channel in model basin

MODEL SHIP

The scale of the model is to be selected to suit the capability of the model basin in question (basin size, model ice thickness). Each model basin has some restrictions.

The model is to be equipped with propulsion and preferably self propulsion is to be used for the tests. However, this is subject to the general practices of the basin. A typical test arrangement at MARC (Kvaerner Masa-Yards Arctic Research Centre) is presented in Figure 4.

The ice rules define that the power is to be defined at two draughts: scantling draught and ballast draught. Sometimes it has been accepted that the maximum draught is not the scantling one but the maximum that the vessel is to use in ice.

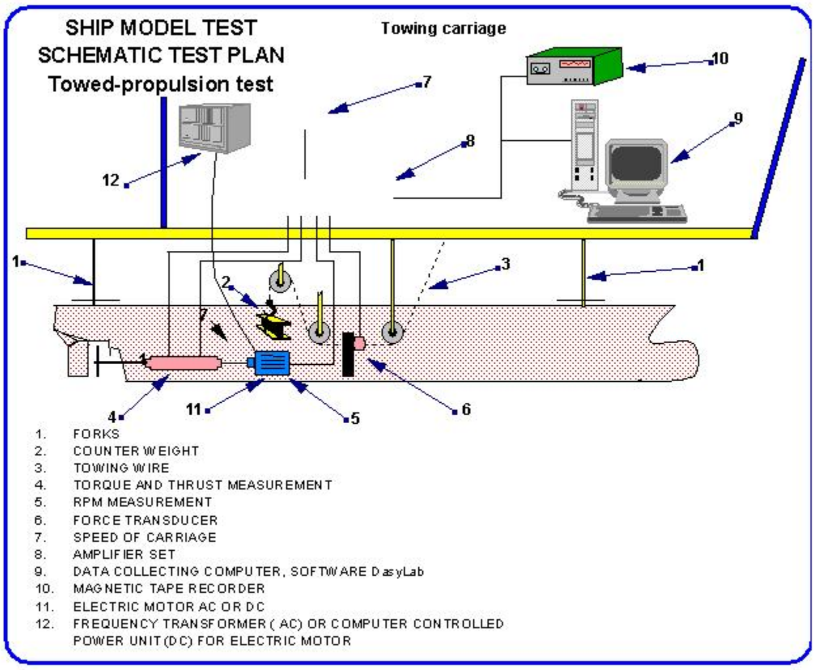

Fig. 4. Test arrangement for propulsion tests

TESTS

An ice sheet in an ice basin is quite expensive and one should utilize it in maximum. Typically tests are done in level ice, narrow channels and wide channels. The range of tests depends also on the hull form. Some vessels are able to proceed in thin level ice but most do not have a chance. A typical test programme is in Table2:

Table 2. Typical test programme

Day 0			
Open water	Bollard pull tests Over power speed tests		
Day 1	Level ice 0.6 m	**Day 3**	Level ice 0.6 m
Scantling draught Ahead	Level ice tests Newly broken channel Narrow channel Wide channel	Ballast draught Ahead	Level ice tests Newly broken channel Narrow channel Wide channel
Day 2	Level ice 1.0 m	**Day 4**	Level ice 1.0 m
Scantling draught Ahead	Level ice tests Newly broken channel Narrow channel Wide channel	Ballast draught Ahead	Level ice tests Newly broken channel Narrow channel Wide channel

In addition to the tests mentioned in Table 2 tests running astern in scantling draught can be considered.

TEST RESULTS

After careful data analysis the ice resistance in the two brash ice conditions is defined (also all other conditions are analysed as well).

The required propeller net thrust to achieve the 5 knot (2.57m/s) speed for the case aframax tanker (beam = 44m) can be interpolated between the two resistance curves, see Figure 5. This result point (v = 2.57m/s, Ri = 1200kN) gives the minimum value for the machinery to fullfill the requirement of ice class 1 A.

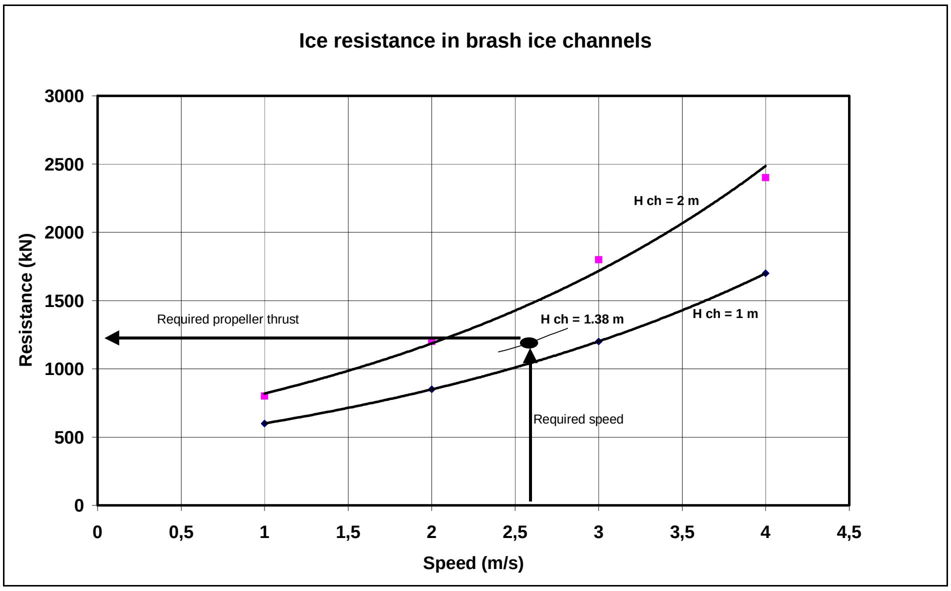

Fig. 5. Model test result; a full scale resistance prediction

MACHINERY SELECTION

The model test result, 1200 kN, sets the required minimum net thrust of the machinery to satisfy the rule requirement. In Figure 6 there are two different propeller net thrust curves added to the resistance curves of Figure 5. The upper thrust curve is for a CPP (controllable pitch propeller) and for a diesel electric machinery with a FPP (fixed pitch propeller). Both these will be able to utilize the full power into the propeller throughout the whole speed range of the vessel. In this case it would be no problem to fullfil the rule requirement. The other thrust curve is for a FPP with direct shaft and a diesel. In this case the output power of the diesel is dependent on the RPM, which will change with the vessel speed and thus under certain point the diesel cannot deliver the installed power anymore and as the RPM and power decreases the thrust that the propeller can deliver will also decrease and the thrust at the point for the classification requirement is under the desired value. This result leads to another round regarding the selection of the diesel and propeller.

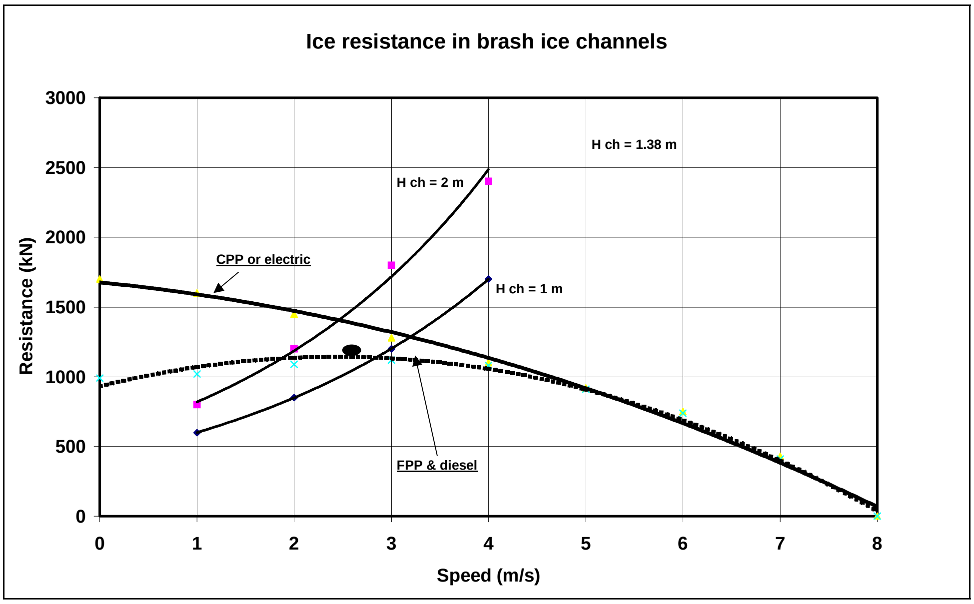

Fig. 6. Propeller thrust with different arrangements

CONCLUSION

Ice classes for cargo vessels are formulated to give adequate hull strength and sufficient power to follow one or two icebreakers. The vessels as such are not to fully navigate independently.

Experience during the last two years has confirmed that it is worthwhile to make model tests to get a reduction in the class requirement. However, it does not happen automatically. One vital part of the game is the machinery. Even the vessel has quite a substantial power at full speed in open water it does not mean necessarily good performance at 5 knots (2.57m/s) speed in overpower condition. This is a function of the selected propulsion, type of engine and propeller.

When the project gets to the final approval by the class, the final engine propeller curves and thus performance must be shown. Even though after the delivery of the vessels the ice class can be lowered in case the authorities find out the performance is not adequate.