STYRELSEN FÖR

VINTERSJÖFARTSFORSKNING

WINTER NAVIGATION RESEARCH BOARD

Research Report No 52

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PERFORMANCE OF MERCHANT VESSELS IN ICE IN THE BALTIC

Sjöfartsverket
Finland

Finnish Maritime Administration

Sjöfartsverket
Sverige

Swedish Administration of
Shipping and Navigation

PERFORMANCE OF MERCHANT VESSELS IN ICE IN THE BALTIC

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Espoo, December 1997

ISBN 951-49-0880-5
Oy EDITA Ab,Helsinki 1998

FOREWORD

In its report no 52 The Winter Navigation Research Board presents the outcome of a study aimed at a better understanding of the factors influencing the resistance of a ship in a broken lead in the Northern Baltic. The study was carried out by a team from the Technical University of Helsinki, who begun with observing the performance of a number of ships in the ice during several winters. These observations were then verified by model tests. The study ends up with a proposal for a new method for determining the powering requirements in the Finnish-Swedish Ice Class Rules.

The Winter Navigation Research Board warmly thanks professor Riska and his assistants for this report as well as the crew of the ice breakers and cargo ships visited by members of the team.

Helsinki and Norrköping

February 1998

Kyösti Vesterinen

Anders Lindström

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ABSTRACT

The aim of the present report is to analyse the background and develop a proposal for the powering requirements for merchant vessels in the Baltic. This requirement is to be included in the Finnish-Swedish Ice Class Rules. The work reported herein consists of results obtained during a five year effort supported by the Finnish and Swedish Maritime Administrations.

The work towards the powering requirements was decided to commence with an extensive fact collecting campaign. The target here was to gain an insight on the factors influencing the quality of an ice-going merchant vessel. The campaign was started by observing the ship navigation in the Northern Baltic, especially vessels bound to and from harbours of Oulu and Kemi were used. The observations concentrated on the encountered ice conditions and used operation modes. An extensive data bank was collected even if some of the winters included in the five years long (1990-94) observation period were mild. The main conclusions from the observations were that the most common ice condition where the merchant vessels navigate in is an old navigation channel. Further, the most common operation mode is when the ship is assisted by an icebreaker. These observations were supplemented by measuring the old navigation channels to Oulu and Kemi. These were found to be about 1 m thick in the middle part of the channel.

The ship observations were analysed in order to obtain some parameters which describe the whole winter navigation system. Especially the possibility to use the quantity transport efficiency (the ratio between cargo transported times the speed used divided by the power consumed) was investigated. Even tough this quantity gave promising results it was deemed that too little knowledge about it exists in order to base the powering requirements on it.

The reason for the powering requirement for merchant vessels in the Baltic is to make sea transportation in the winter quick and continuous without excessive waiting times. The powering requirement must be seen together with icebreaker assistance and traffic restrictions. A decision was made that the powering requirement is to be based on navigation in old channels. Further it was decided that the powering requirement starts from ship resistance in the channel dimensions valid for the Northern Baltic. This

decision led to an investigation of ship resistance in level ice and in old navigation channels.

The formulation of the ship resistance in level ice which was developed is based on earlier Finnish and Russian formulations. It was calibrated with some full scale data obtained from Finnish vessels. More research was done on channel resistance. It was investigated with an extensive series of model scale tests. A formulation for the channel resistance was developed based on the test results and an earlier formulation. This was calibrated versus full scale observations.

The final proposal for powering requirement consists of ice resistance in an old channel of a thickness of 1 m for vessels in ice class IA. For ice class IA Super the resistance is taken in an old channel of 1 m thickness on top of which is a 10 cm thick newly frozen layer of ice. The resistance formulation provides a somewhat lengthy formula but once the resistance is known, the propulsion power requirement is calculated using a formula adopted from power consumed in bollard pull condition.

The decision to base the power requirement on channel resistance means that icebreakers assist vessels to the beginning of the old navigation channels and then IAS vessels are able to reach the harbour independently. IA vessels require that the channel has not been allowed to consolidate and thus either the temperatures are not freezing or a vessel has broken the consolidated layer some time earlier. Navigation in the open sea where the ice is ridged was not taken as the starting point for power requirements as this would have lead to far too stringent and thus uneconomical requirements.

The final part of the study consists of an analysis of the impact that the proposed power requirement may have on the present Finnish merchant fleet. For the purpose of this, a data bank of Finnish vessels was collected and the proposed power level was compared with the existing requirement. Overall, an increase in the power requirement was noticed, especially for smaller vessels. When, however, the proposed power requirement was compared with the installed power of the vessels it was noticed that practically only for the vessels smaller than about 4000 dwt, the requirement exceeds the installed power. This is well in line with the observations made by the icebreaker crews. These have resulted in a limit in vessel size in the traffic restrictions which is just this 4000 dwt.

The present formulation of ice resistance, both in level ice and in channels, is based on some basic assumptions. The main ones of these are the superposition of open water and ice resistance and the use of the formulation from soil mechanics as the base for channel resistance. These form the starting point of the continuation of the present research. Research should also be directed on the analysis of the transport efficiency and its use in describing the winter navigation system. Finally the ship navigation in a ridged ice field should be analysed in order to gain insight on the requirements stemming from the ice conditions encountered on the open sea. Here especially the question of how much more power is needed in order to navigate in ice ridges either independently or escorted by an icebreaker compared to navigation in channels is interesting.

1. INTRODUCTION

The subject of this report is the formulation of the ice trafficability requirements that may be placed on merchant vessels navigating in the Baltic. The Baltic is partially covered with ice every winter. This has to be accounted for in the seaborne trade. The merchant vessels must be designed in view of the ice conditions encountered and the infrastructure offered by the authorities like icebreaker and port services must be adequate also during wintertime. The efficient utilisation of these services require some kind of traffic control. The overall aim of the traffic control is to ensure as continuous and quick ship transportation as possible using a minimum number of icebreakers escorting the vessels and using as economical merchant vessel fleet as possible. Especially delays due to ships getting stuck in ice should be avoided. The traffic control in the Baltic is enforced by restrictions to navigation which include a limiting ice class and deadweight for each harbour. Ships falling outside the limits are not escorted by icebreakers. These limits are updated as the winter proceeds by the Finnish Maritime Administration. The Finnish-Swedish ice classes include a requirement for minimum propulsion power and thus an ability to proceed in ice will ensure the possession of an ice class. The ice classes have different abilities to proceed in ice. How these abilities should be defined is the specific purpose of this report.

The ice cover influences ships in two ways. Ice causes loads on the ship hull and propulsion and thus proper design of structures must be followed. Ice also increases the motion resistance of ships considerably and in worst cases causes ships to get beset. The aim of the report is to present a basis for the traffic control by analysing the factors influencing the ability of ships to proceed in ice. Thus specifically the strength requirements is not the subject of this report.

The aim of this work is approached by developing the ice performance requirements of vessels in a form which can be adopted for practical use in planning the navigation system. This may be done by placing minimum values for the propulsion power so that the formulation takes into account the ship particulars, navigation modes and ice conditions in a simple but realistic fashion. The work reported here is theoretical and is based on previous research work done in modelling ship resistance in level ice, ice channels and ice ridges. Especially two M.Sc. theses (Englund 1996, Wilhelmson 1996) should be mentioned as basis for the formulations.

The verification and tuning of the formulations presented in this report is done using the databank of ship navigability in ice. The databank was collected during the winters 1990 to 1994 (Veitch & al. 1991, Kujala & Sundell 1992, Pöntynen 1992, Lehtinen 1993, Lehtinen 1994). The navigation of 32 ships was investigated in the ice conditions present in the northern Baltic. The observations covered the operational modes of the ships, the ice conditions encountered and icebreaker escort in addition to the measurement of the ship's instantaneous position and speed. This report is a synthesis of the observations carried out during the previous years. The other main data used in the report was collected in the early 80's to develop the power requirements for ships in channels (Kannari 1982, Eskola 1984).

The formulations developed are mainly valid for the northern Baltic as the observations concentrated there. The extension to other Baltic sea areas, once it becomes necessary, could be done by extrapolation based on ice conditions on the other sea areas compared to those in the Bothnian Bay.

This report begins with an analysis of the ice navigation requirements and how they are implemented today. A slightly more detailed way to place the requirements follows. This is based on ship ice resistance in specific ice conditions. Thus, a short overview of the Baltic ice conditions is given before the requirements are presented. Thereafter the ice resistance formulations relevant for the present work are briefly described. The final part of the report contains a formulation for the ice navigation requirements in terms of minimum propulsion power levels and their calibration using the ships included in the trafficability studies.

It should be emphasised finally that the analysis and opinions presented in the report reflect only those of the authors and not e.g. those of the Finnish Maritime Administration.

2. FACTORS INFLUENCING THE EFFICIENCY OF WINTER NAVIGATION

2.1 Introduction

The performance of a merchant vessel in ice is determined by its ability to proceed in ice; an ability which usually is measured with transit times through ice-covered areas and the energy consumed in making the transits. Good performance in ice is characterised by low ice resistance, high propulsion efficiency and power resulting in high thrust and also by experience of the crew in manoeuvring the ship through ice. Good ice performance means also that the ship should not get stuck in ice.

The requirement of good ice performance leads to hull shapes that are not optimal in open water. Especially the seakeeping characteristics may suffer. Further the increased machinery power and thus price and weight of the machinery together with higher fuel consumption makes the ice-going ship somewhat less economical in open water.

A normal merchant vessel operating to and from the Baltic year round do not spend many days in ice. An example of the annual days spent in ice by MV KEMIRA during winters 1985 to -91 are given in Fig. 1. The average number of annual ice days is 39. The economy of Finnish vessels must, however, be based on year round operation. Thus the competitiveness of an ice-going merchant vessel is determined by how much the open water characteristics are to be compromised by the ice performance.

The overall performance of individual vessels is relevant from the shipowner's point of view. A broader perspective is presented if the whole winter navigation system is considered. The navigation system may be influenced in three ways: Ice classes, traffic restrictions and icebreaker escort.

The ice class ensures that the vessels have a proper strength level to operate in ice. The strength level required is based on ice conditions and operational factors. In order to ensure as continuous navigation as possible in ice the present ice classes contain some requirements for a basic performance level. A good performance in ice also influences the ice loading in two ways. It reduces the probability of high loads on ship sides by reducing the probability to get stuck in compressive ice. At the same time ships with good ice performance are able to move in more severe ice conditions which cause higher loads. A balance between these factors should be found.

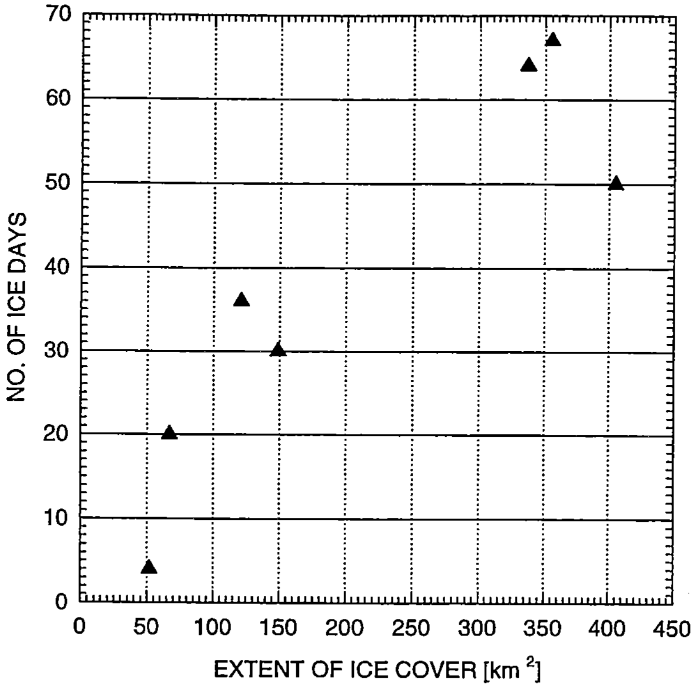


Fig. 1. The numbers of days spent in ice annually by MV KEMIRA plotted versus the maximum extent of ice cover (data from Muhonen 1992).

The present spread of the classes is based on the division of the vessels in basically three categories: two classes of ice-strengthened vessels and basically open water vessels. The first two classes are IA Super and IA. The lower ice classes, IB and IC, are reserved for navigation in early winter or for lake navigation. Each class contains a requirement for minimum propulsion power.

The traffic restrictions state a minimum ice class or deadweight. Ships falling under these limits are not given icebreaker escort when entering Finnish harbours. These restrictions to navigation, based mainly on the recommendations of the icebreaker masters, are updated by the Finnish Maritime Administration as the winter proceeds. An example of the restrictions placed during winter 1993-94 is shown in Fig. 2. These restrictions ensure that there are enough icebreakers to escort vessels which are able to follow the icebreakers in the broken track, because of their momentum or propulsion power.

The icebreakers are used to escort vessels through the most severe ice conditions. The justification for the deployment of icebreakers is to limit the required ice-strengthening of merchant vessels so that they are not uneconomical in open water. Also the number of intermediate shifts in transport mode is minimised when ships are able to proceed to their end destination. An alternative would be to transport the cargo on land from southern ports. The use of icebreakers is a compromise because the merchant vessels are required to have some ice-going capability, otherwise the required number of ice-breakers would be too large.

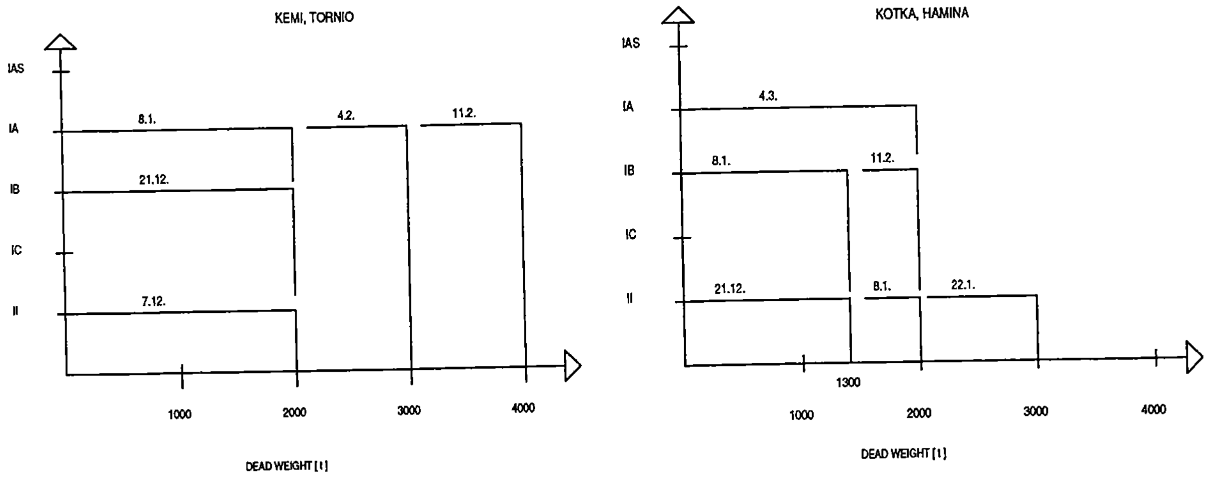


Fig. 2. An example of the progress of the minimum deadweight and ice class included in the traffic restrictions for two harbours in the winter 1993-94. Dates of placing the restrictions are also given.

An appropriate balance between traffic restrictions, power requirements, number of winter ports and number of icebreakers was found in the mid 70's (Edelmann 1984). The mild winters in the beginning of the 90's and a change in the structure of the merchant fleet towards smaller and more numerous vessels have opened the question of redefining the performance requirements in the ice classes. The aim of this investigation is to provide background for the performance requirements which could be included in the definition of ice classes.

2.2 Analysis of ship measures of merit in ice

A ship with good ice performance is characterised by low ice resistance due to icebreaking hull lines, high thrust in icebreaking speeds, an ability to avoid being stuck in ice, and an ability to free herself after being stopped (in an ice ridge for example). The safety aspect belongs to the concept of overall ice performance but structural aspects are not considered here. A rule-of-thumb defining a good ice-going ship is given by the ratio of the engine shaft power, P_s, and deadweight, dwt. The ship is generally deemed to have good ice performance (power in HP and dwt in t) if this ratio is over one.

This very general power over deadweight ratio is an empirical measure applicable to ships which tackle a multitude of ice conditions during the winter season. As Fig. 3 shows, this is too simple when a single ice type and only a short distance is considered. Some authors use the power over displacement ratio as a measure of merit, especially for icebreakers. This ratio is over 2 for icebreakers and about 0.5 for good ice-going merchant vessels (Johansson & al. 1994). The use of displacement rather than the deadweight in these rough estimates is physically more correct despite the fact that deadweight is readily available.

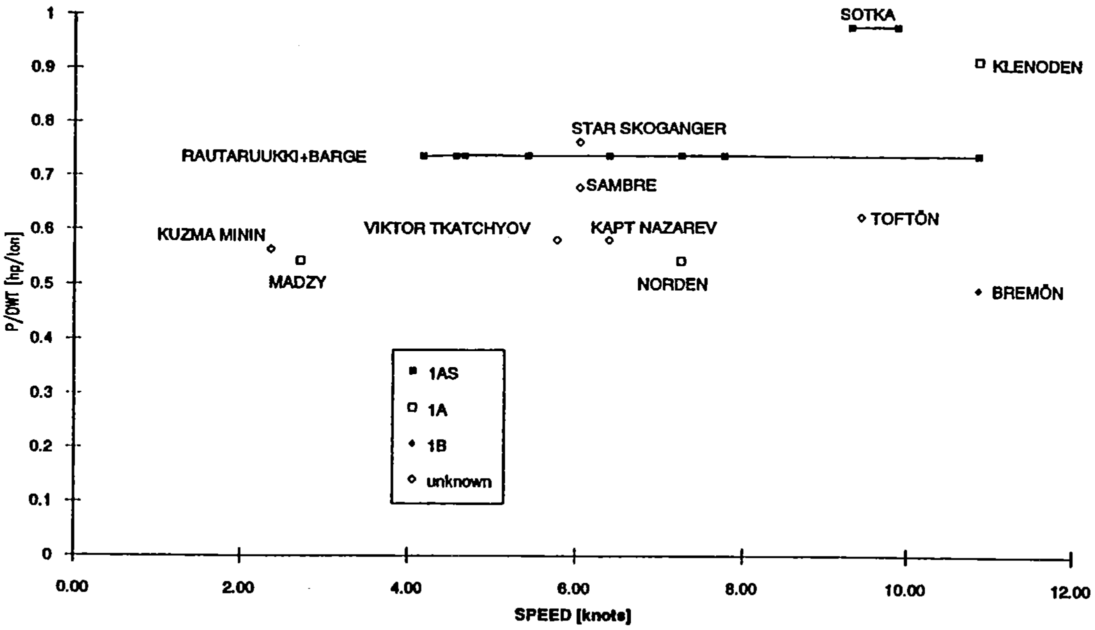


Fig. 3. Power/dwt ratio versus ship speed for vessels in the Raahe channel (Pöntynen 1992).

A somewhat refined rule-of-thumb may be based on the transport efficiency defined as

$$Q = \frac{dwt \cdot v}{P_S} , \tag{1}$$

where v is the average speed in ice. The observations carried out during winters 1993 and 1994 in the Bothnian Bay onboard merchant ships gave the average speeds while navigating in ice (Lehtinen 1993,1994). The transport efficiencies of various ships may be determined using these speeds. The results are shown in Fig. 4.

This figure should be considered with care. A ship with very good transport efficiency despite having a low power to dwt ratio is MV FINNFIGHTER. Her reported voyage included, however, a large portion of open pack ice at the ice edge. On the other hand, the ships with low transport efficiency despite high power to dwt ratio were navigating partially independently in more severe ice conditions as more powerful vessels were less assisted. The conclusion from Fig. 4 is, however, that ship power is not the only quantity describing the performance of the ship in ice. The question is what should be the minimum allowable power while maintaining an adequate transport efficiency (and transport speed).

The low installed power leads to higher transport efficiencies provided that the speed of transport does not decrease to zero. The question may be expressed as an optimisation problem of three variables P_S, v and dwt. The problem is to find the maximum transport efficiency Q assuming that the ships are able to move in the given ice conditions. The assumption of an ability to move may be expressed as a constraint equation relating the required power to ice conditions, speed and deadweight, P_S=f(ice cond.,v,dwt). This problem provides an optimum point (P_S,dwt) for each constant average transportation speed. Fig. 5 illustrates the problem.

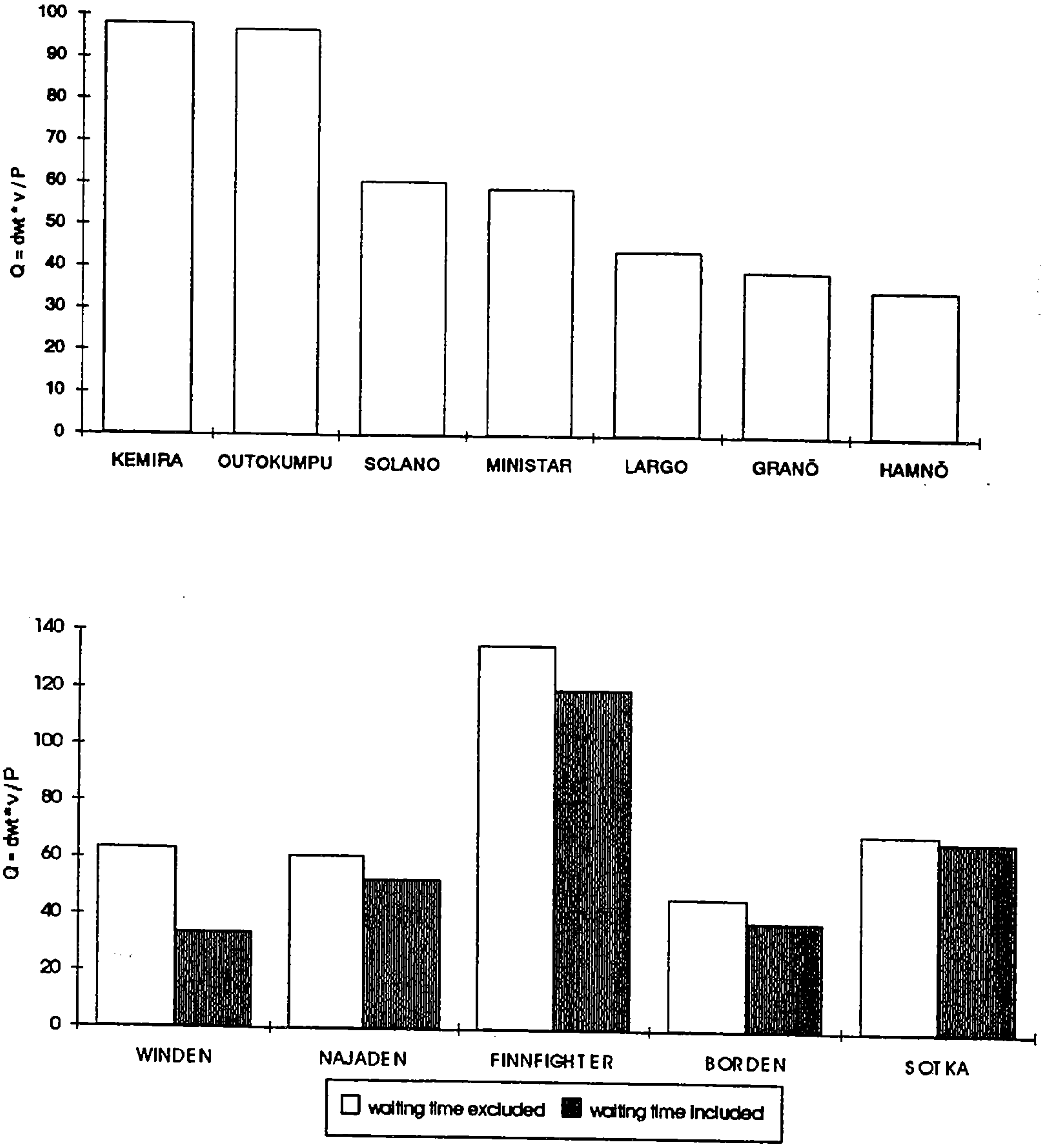


Fig. 4. Observed transport efficiencies of a set of ships observed during winter 1993 (top) and 1994 (bottom) (Lehtinen 1993, 1994).

This optimum power is based on an average speed in average ice conditions, quantities valid only when inspecting the whole transportation system. The minimum speed in ice or the probability to get stuck are more critical requirements for ice performance of individual ships. The problem of these crude measures is that they emphasise the significance of power and do not take into account the particulars of the ship.

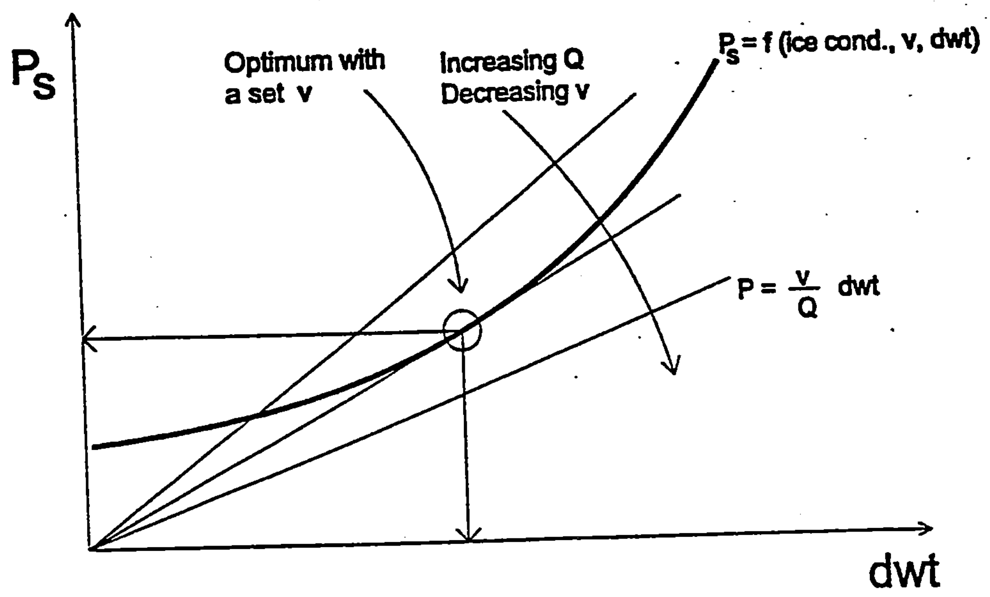


Fig. 5. A sketch of finding the optimum transport efficiency and the corresponding optimum P_S and dwt for a given average transport speed.

Theoretically, the minimum speed could be set based on the ice conditions in the operating area and the ice resistance in those conditions. This is the approach taken by Lloyd's Register of Shipping when they stipulate that the minimum power for a ship with a fixed pitch propeller and icebreaking bow, is to be

$$P_S = 0.66\frac{1.2B}{\sqrt[3]{\Delta}}[240B\,h_i(1+h_i+0.035v^2)+70S_c\sqrt{L}] \text{ [kW]}, \tag{2}$$

where the unit of speed is knot, lengths in m and displacement in t, S_c is the snow thickness taken as 0.3 m and the first factor containing ship breadth, B, and displacement, Δ, is not to be taken less than 1. The speed is to be taken as at least 5 knots and the ice thickness depends on the ice class being 1 m for class IAS and 0.8 m for IA.

$$P_S = C_1\Delta + P_0 \text{ [kW]}, \tag{3}$$

The Russian ice classes relate the minimum power linearly to the displacement where the constant C_1 is 0.35 for ULA, 0.30 for UL and 0.26 for L1 class. The minimum power P_0 is 1500 kW, 1100 kW and 735 kW for these classes, respectively. The present Finnish-Swedish ice class rules (1985) state the minimum power to be

$$P_S = \left(\frac{\phi}{200}+0.675\right)\frac{1.2B}{\sqrt[3]{\Delta}}(f_4\Delta+P_0)\ \text{[kW]}, \qquad (4)$$

for a ship with fixed pitch propeller and not having a bulb, and ϕ is the stem angle with horizontal. The first factor is to be between 0.85 and 1.1 and the second greater than 1. The constants are f_4=0.27 and P_o= 2200 kW for IAS ships and f_4=0.26 and P_o=740 kW for 1A ships with displacement less than 30 000 t.

The above class requirements for minimum shaft power are very similar to each other. The higher the ice class the more power is required and the increase occurs in a stepwise fashion. The two latter ones relate the shaft power linearly with displacement and not much detail about hull shape is included.

2.3 Power requirements based on ice resistance

A physically based way to present the powering requirements is to determine the rule ice resistance based on ship particulars and then determine the corresponding power. The problem is shifted now to determining the rule ice resistance. The Baltic merchant vessels should be open water vessels only slightly modified for navigation in ice (Edelmann 1984). This principle is enhanced by providing icebreaker assistance and enforced by the restrictions to navigation. The different ice classes should be graded so that a clear spread exists; the spread should be based on the navigation area within the Baltic, on the compromise between higher ice class and longer escorting times and on the degree of autonomy required of the vessel.

Ships that have a set schedule, like passenger-car ferries and the Baltic ro-ro vessels, should not be too dependent on icebreaker assistance. These vessels follow set routes and usually do not navigate outside commonly navigated channels. They should have enough propulsive power in order to navigate independently in ice channels. The general cargo vessels and tankers are less dependent on schedules and thus some waiting time for icebreakers may be allowed. The speed of convoys led by icebreakers is determined by the speed of the slowest vessel in the convoy. Thus some minimum performance in newly broken channels should be required. During a severe winter, ships must navigate in the ridged ice fields in the middle of the Baltic sea basins. The average speed in a ridge field depends mostly on the ability of the ship to penetrate ice ridges without getting stuck.

The observations of ship operation during winters 1990-94 indicate that the navigation scenarios described above may be split into two operational modes and two major ice conditions resulting in four navigational modes:

- escorted in an old channel after an icebreaker;
- independently in an old channel;
- escorted in ridge fields and;
- independently in ridge fields.

These cases will form the basis of the development of the power requirements for Baltic merchant vessels in this report.

The first two cases are analysed in the following chapters in detail. The third and fourth alternatives are only preliminarily analysed here as they do not form the design scenario for normal Baltic merchant vessels.

The performance will be described in the following entirely in terms of required propulsion power. The power required can not be determined from the towing power $P_E = R_T \cdot v$ (R_T is the total resistance) because the ship speeds in ice are low close to the design ice conditions. The propulsion efficiencies are naturally also affected by the low speeds. The solution can be found via the bollard pull thrust, which can be calculated based on the K_T and K_Q curves which are characteristic for the propeller. The definitions for K_T and K_Q are written as:

$$K_T = \frac{T}{\rho \cdot n^2 \cdot D_P^4} \tag{5}$$

$$K_Q = \frac{Q}{\rho \cdot n^2 \cdot D_P^5} \tag{6}$$

where T is thrust, ρ density of water, n propeller revolutions per second, D_P propeller diameter and Q the propeller torque. The relation between torque and shaft power, P_S, is

$$Q = \frac{P_S}{2 \cdot \pi \cdot n} . \tag{7}$$

The bollard pull thrust can be calculated using the empirical formula for the quality criterion for bollard pull. Propeller efficiency at zero speed is zero by definition and therefore the quality criterion factor for bollard pull may be used instead (Tornblad 1987)

$$K = \frac{K_T}{K_Q^{\frac{2}{3}}} \tag{8}$$

Higher values for K_e mean better designed vessels in view of bollard pull. After inserting values of K_T, K_Q and Q, re-arranging and dropping of constants (such as ρ) the quality criterion factor can be written as:

$$K = \frac{T}{(P_S \cdot D_P)^{\frac{2}{3}}} . \tag{9}$$

The value of K is affected by the pitch to diameter ratio of the propeller. At optimum pitch to diameter ratio, a typical value for K is 0.81 ... 0.85 for a tug with a CP propeller without a nozzle. By taking into account the thrust deduction factor the bollard pull thrust can be written as:

$$T_{PULL} = K_e \cdot (P_S \cdot D_P)^{\frac{2}{3}} \tag{10}$$

where T_{PULL} is the bollard pull thrust and $K_e = 0.78$ for single, $K_e = 0.98$ for double and $K_e = 1.12$ for triple screw ships with CP propellers (Kujala and Sundell, 1991). Since the propellers of the merchant ships are designed for open water speeds and not for bollard pull a *fixed* pitch propeller will need more torque than the engine can deliver at a bollard pull situation. With a controllable pitch propeller the pitch can be reduced to an optimum at zero ship speeds so that the engine can deliver maximum power but when the pitch is fixed the engine will never reach nominal revolutions and will therefore not deliver maximum power to the propeller. This can roughly be taken into account by multiplying the K_e:s given above with 0.9 if the ship is equipped with a fixed pitch propeller.

At full power, when the speed of the ship is practically zero the total resistance of the ship can be assumed to be equal to the bollard pull thrust:

$$R_T = K_e \cdot (P_S \cdot D_P)^{\frac{2}{3}} \tag{11}$$

At practically zero speed the open water resistance is only a fraction of the total resistance and therefore it can also be assumed that $R_T = R_{ice}$. This applies only in the case where the speed of the ship is restricted by ice resistance or for instance towing and the speed is practically zero.

When the ice resistance decreases the speed of the ship increases. As a result of this the delivered thrust of the propeller decreases, despite that the power delivered to the propeller remains constant. When the ship has reached maximum open water speed the ice resistance is zero and the total resistance encountered by the ship consists of only the open water resistance. At this point the thrust of the propeller and the resistance of the ship are in balance and the *net* thrust is zero. We know that at zero speed the net thrust equals the bollard pull thrust and that at open water speed the net thrust is zero. The net thrust at any speed between these two can be calculated with an empirical formula which has been derived based on a typical K_T-curve. Here the shape of the T_{NET}-curve is assumed to be parabolic. Figure 6 illustrates how this is derived.

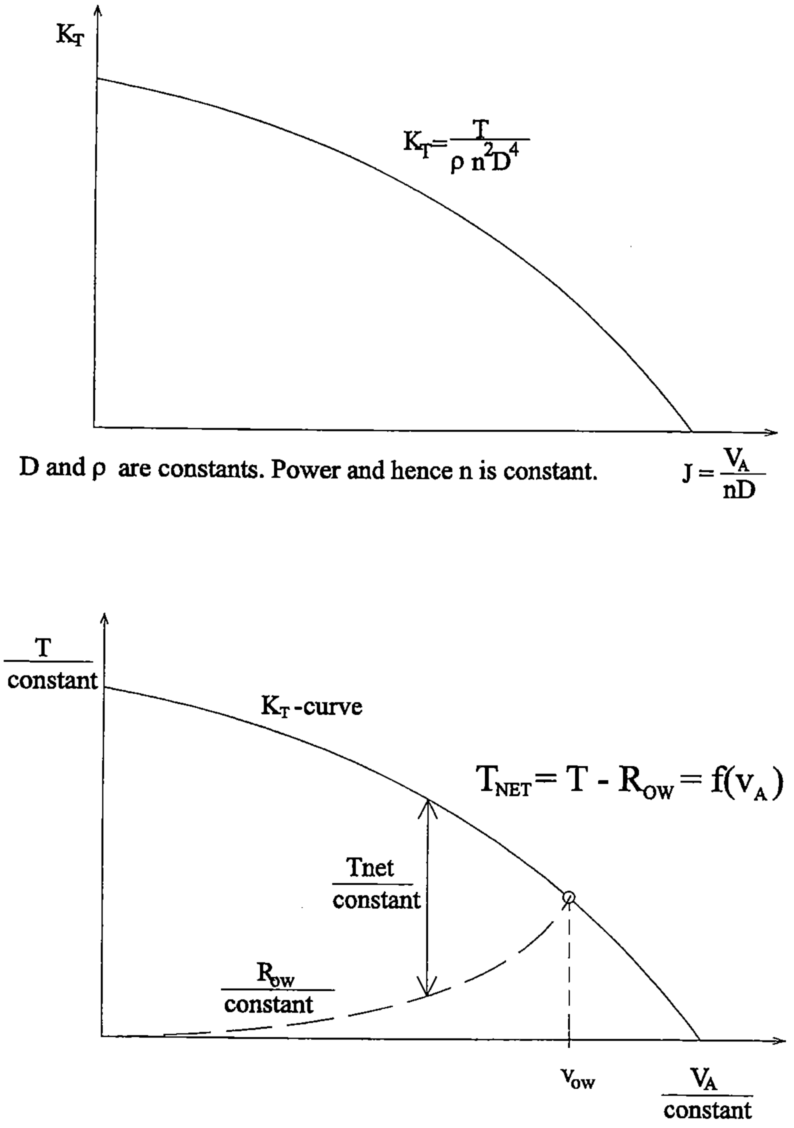


Fig. 6. A scetch of how the net thrust is derived.

The net thrust, T_{NET} is then:

$$T_{NET} = T_{PULL} \cdot (1 - \tfrac{1}{3} \cdot \tfrac{v}{v_{ow}} - \tfrac{2}{3} \cdot (\tfrac{v}{v_{ow}})^2) \qquad (12)$$

where T_{NET} is net thrust (T_{NET} = total thrust - open water resistance), T_{PULL} bollard pull thrust according to formula (10), v ship speed and v_{ow} maximum open water speed of the ship. Now we can write that $R_i = T_{NET}$. On the other hand, the maximum open water speed of a typical merchant vessel is around 15 knots. The minimum speed required for a ship navigating independently in ice can be taken as 5 knots. This gives approximately:

$$T_{NET} = T_{PULL} \cdot 0.8 \tag{13}$$

By using this relationship between bollard pull thrust and the net thrust at 5 knots we obtain the required propulsion power in ice as:

$$P_S = K_e \cdot \frac{R_i^{3/2}}{D_P} \ [\mathrm{kW}] \tag{14}$$

where $K_e = 2.03$ for ships with one, $K_e = 1.44$ for ships with two and $K_e = 1.18$ for ships with three propellers. The units for resistance and diameter are kN and m.

3. THE BALTIC ICE CONDITIONS

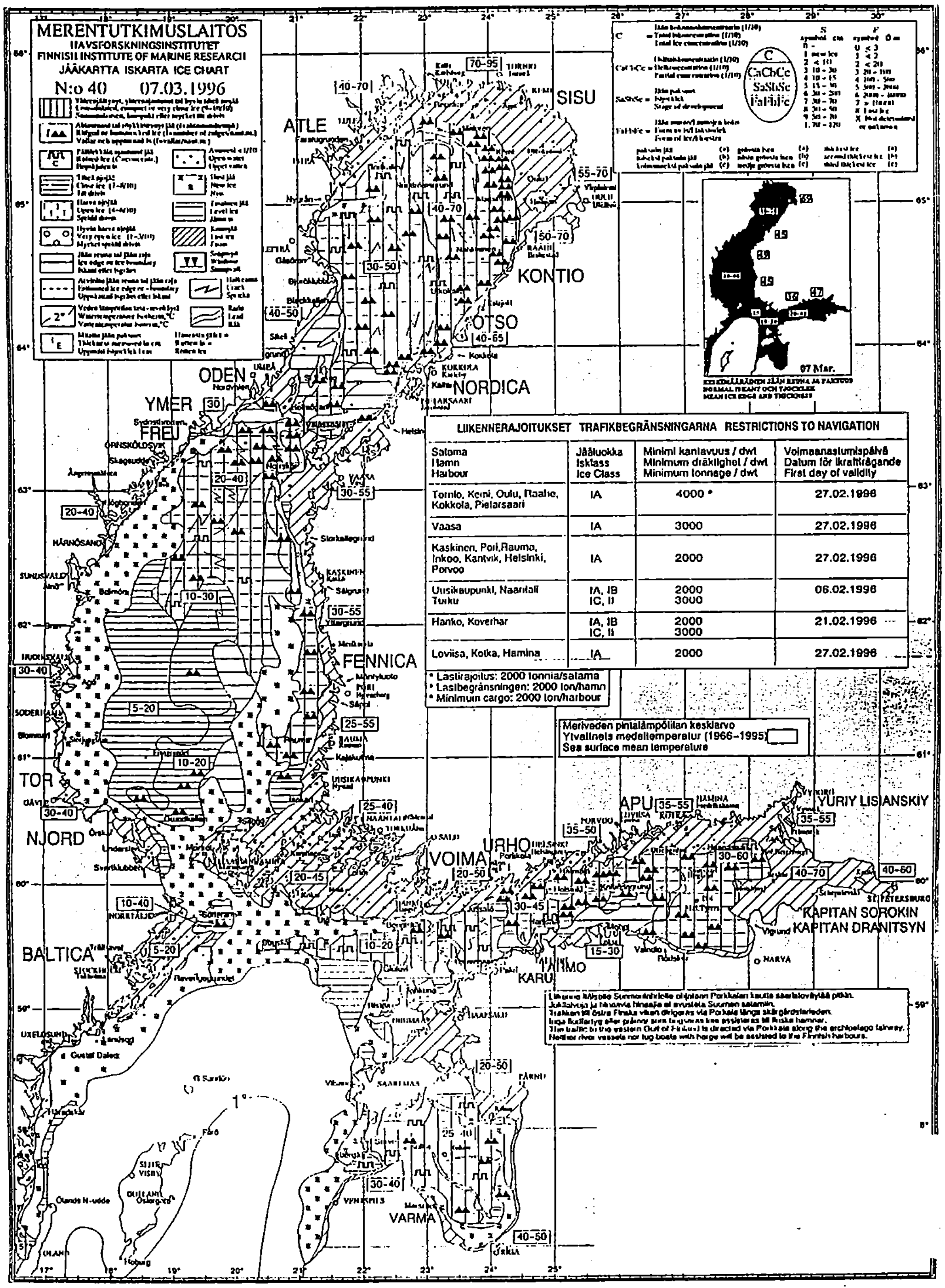
3.1 The ice conditions encountered in the Baltic

The Baltic Sea is a bay with a narrow connection to the ocean. There is not much exchange of ocean water between the Baltic and the North Sea. Thus the Baltic is less saline than the oceans; the salinity of the northern Baltic is about 4 ppt. The salinity increases towards the straits of Öresund and Great Belt connecting the Baltic to the North Sea. The Baltic is also relatively shallow, the deepest point is about 460 m and the average depth is 56 m. The shallowness means that the thermal inertia of the Baltic is small and the development of the ice cover follows closely the air temperature fluctuations.

The development of the ice cover on the Baltic may be divided into phases according to the development of ice cover on different parts of the Baltic (Leppäranta & al. 1988). That the phases may be distinguished at all is due to the different average depth of sea basins and the relatively small water mixing between these. The most notable phases are the freezing of the Bothnian Bay occurring on average in mid-January, the freezing of the Gulf of Finland (on average in the end of January) and the freezing of the Bothnian Sea (on average in mid-February). The ice conditions after the Bothnian Sea has frozen are shown in the ice chart given out on regular basis throughout every winter by the Institute of Marine Research, see Fig. 7.

The phases in the development of the ice cover imply that the Baltic Sea may be divided into four areas which have discernible ice conditions: The Bothnian Bay, the Bothnian Sea, the Gulf of Finland and the Baltic Sea proper. When a ship enters the Baltic, she first crosses the Baltic proper and enters the Gulf of Finland or crosses the Åland or Archipelago Seas to the Bothnian Sea. Ships bound to the northern harbours sail through the Strait Kvarken and enter the Bothnian Bay. In each case the encountered ice conditions consist of (in order of encounter for ships bound to Finnish ports):

1. Thin level ice and open pack ice
2. Ridged ice field
3. Old channel entering the archipelago.



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Satama Hamn Harbour	Jääluokka Isklass Ice Class	Minimi kantavuus / dwt Minimum dräktighet / dwt Minimum tonnage / dwt	Voimaantulemispäivä Datum för ikraftträdande First day of validity
Tornio, Kemi, Oulu, Raahe, Kokkola, Pietarsaari	IA	4000 *	27.02.1996
Vaasa	IA	3000	27.02.1996
Kaskinen, Pori, Rauma, Inkoo, Kantvik, Helsinki, Porvoo	IA	2000	27.02.1996
Uusikaupunki, Naantali Turku	IA, IB IC, II	2000 3000	06.02.1996
Hanko, Koverhar	IA, IB IC, II	2000 3000	21.02.1996
Loviisa, Kotka, Hamina	IA	2000	27.02.1996

* Lastirajoitus: 2000 tonnia/satama
* Lastbegränsningen: 2000 ton/hamn
* Minimum cargo: 2000 ton/harbour

Meriveden pintalämpötilan keskiarvo
Ytvattnets medeltemperatur (1966–1995)
Sea surface mean temperature

The traffic to the eastern Gulf of Finland is directed via Porkkala along the archipelago fairway.
Neither river vessels nor tug boats with barge will be assisted to the Finnish harbours.

Fig. 7. An example of an ice chart of the Baltic Sea. The main sea areas in the Baltic are also given.

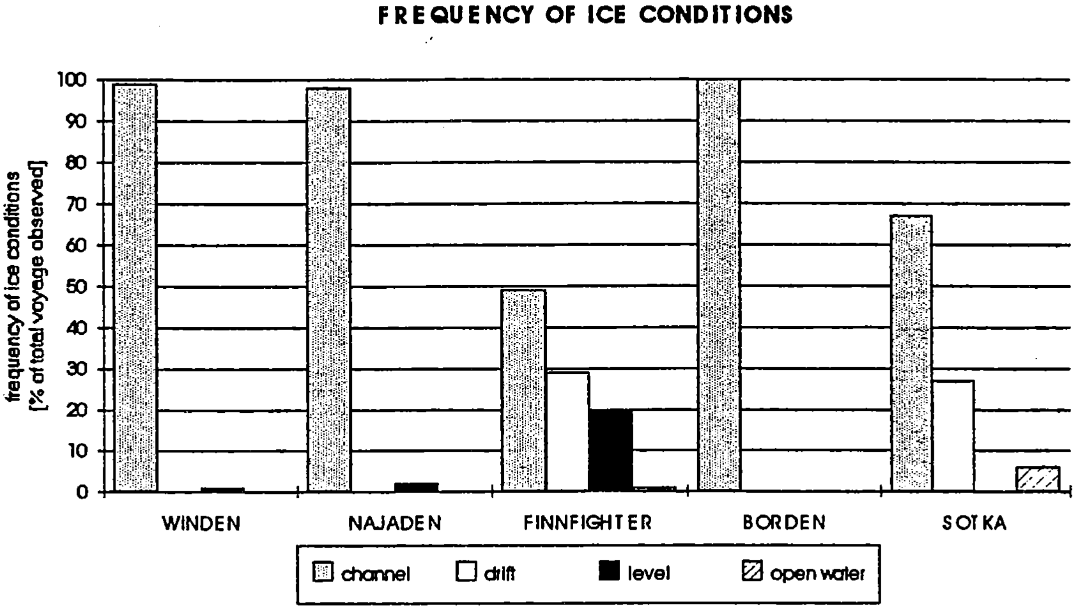
The relative areal frequency of or, rather, the relative distance travelled in each of these conditions varies from winter to winter. A more important factor for ship performance studies is that the ice conditions ships encounter depend on the operational profile of the ships. More powerful ships proceed independently even through the ridged ice fields without waiting for icebreaker assistance. Other ships wait for icebreakers to take them to the harbours from the ice edge.

The operational profiles of two ships are compared in Appendix 1. These show also the ice conditions the ships encountered during their voyages. The voyage analysis of MS FINNFIGHTER shows that when she encountered ridged ice, an icebreaker escort was needed. MT SOTKA, on the other hand, was able to navigate independently in these conditions. The ships, MT SOTKA and MS FINNFIGHTER, are both of Finnish-Swedish ice class IAS. The difference between these ships makes it clear that ridged ice can be the design condition only for the dedicated ice going ships.

A breakdown of encountered ice conditions makes it clear that most ships anticipate icebreaker assistance. The breakdown of the operation mode and encountered ice conditions for the ships included in the data collecting study during winter 1994 is given in Fig. 8. The dominance of channels, both an old channel and channel after an icebreaker, is clear.

Traffic control has an influence on the encountered ice conditions. When the ice conditions become more severe, ships are directed to sheltered archipelago fairways. For example, during a normal or severe winter, most of the ship traffic in the Gulf of Finland is directed to the fairway within the archipelago along the coast of southern Finland. This fairway allows the ships to proceed from the Porkkala lighthouse to the easternmost Finnish harbour, the port of Hamina, in an old channel. Also the fairway through the Archipelago Sea is preferred as opposed to going through the Åland Sea. These re-routings are made in order to avoid the ridged ice and compression in the ice cover in the central Gulf of Finland or the Bothnian Sea.

The pack ice at the ice margin does not usually constitute any limits for ship performance. Only when the level ice gets thicker does it present problems for ships. Even though ships do not encounter the thickest level ice, because it exists only in the shorefast ice zone where ships navigate in old channels, the maximum level ice thickness serves as a good practical measure of the severity of winter. Thus the level ice thickness warrants a study in this context. It makes it possible to compare the four major Baltic sea areas with each other.



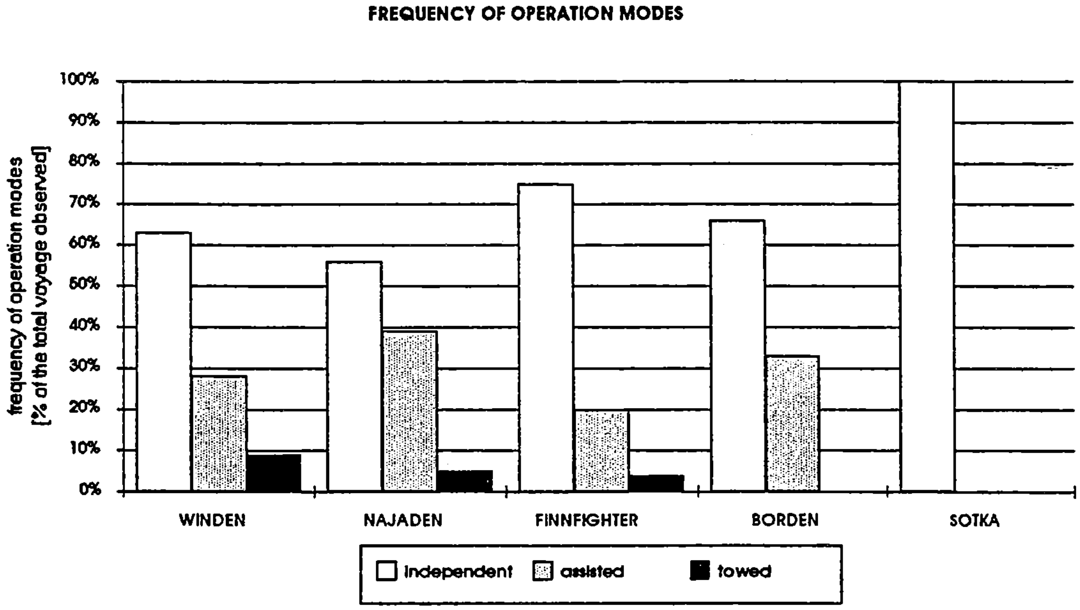


Fig. 8. The encountered ice conditions and operational modes in winter 1994 for five ships (Lehtinen 1994). The drift ice means either pack ice at the ice margin for the case of MS FINNFIGHTER or ridged ice for the case of MT SOTKA.

3.2. Description of ice conditions

3.2.1. Level ice thickness

The simplest measure for the ice conditions in the Baltic Sea is the overall maximum thickness of undeformed level ice. The average value of the annual maximum level ice thickness in the Baltic is given in Fig. 9. The average annual maximum value of level ice thickness in the northern Baltic is about 70 cm and in the Gulf of Finland about 40 cm. These thicknesses are for the ice cover in the middle of the sea basins. The shorefast ice is usually thicker. The absolute maximum thickness of ice observed during the last 100 years is 121 cm in Tornio and 90 cm in Kotka.

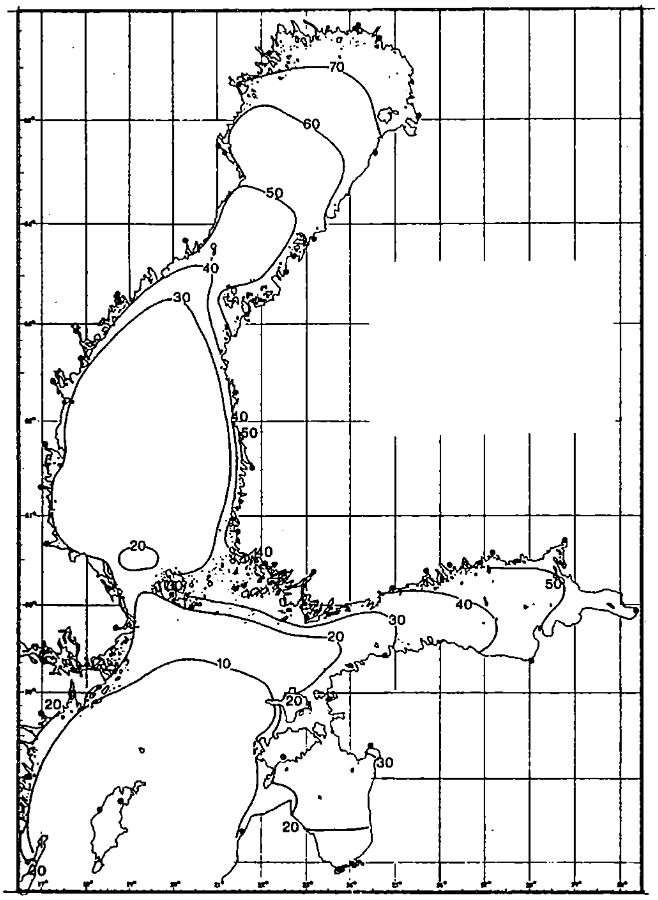


Fig. 9. The average annual maximum level ice thicknesses in cm (Leppäranta et al. 1988).

Ships rarely encounter level ice and practically never level ice of the maximum thickness. A better measure of ice conditions for ice operations is given by the spatial distribution of ice thicknesses found in any sea area. This distribution characterises the refrozen leads, undeformed ice and ridged ice. This distribution is measured by methods which sample the ice thickness spatially in a uniform fashion. An example of the ice thickness distribution is given in Fig. 10.

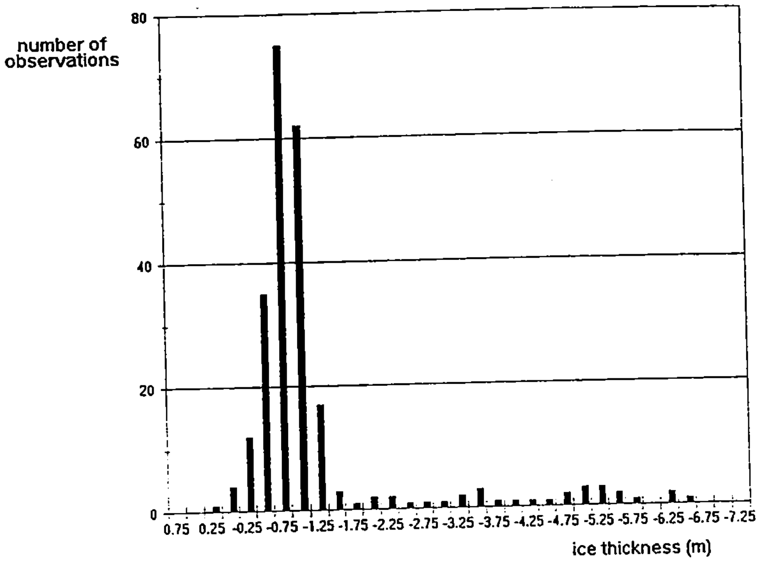


Fig. 10. Distribution of the depth of ice bottom from a 3 km long section measured with the airborne electro-magnetic method in the Bothnian Bay, winter 1993 (Multala et al. 1994).

3.2.2. Ridged ice

A ridged ice field consists of ice ridges surrounded by level or rafted ice and possibly leads of open water. The ridges are narrow and long and a ridged ice field is criss-crossed by the ridges. An idealised ice ridge has a triangular sail above the water level and a similar but bigger keel below the water level. The ridges consist of ice pieces which have been broken when two ice sheets have moved against each other. After an ice ridge has formed, the pieces forming the ridge start to freeze together. Also the voids between the pieces below the waterline freeze. In this way a ridge consolidates. The growth of the consolidated layer is faster than the growth of level ice by a factor inversely proportional to the square root of the porosity (ratio between void volume to total volume) of the ridge (Leppäranta 1992).

An actual Baltic ice ridge measured by drilling is shown in Fig. 11. The ridge was examined at two time instants during the winter and the growth of the consolidated layer is evident. The initial porosity of the ridge was 0.27, which is quite typical as the average value of the porosity of Baltic ridges is about 0.3 (Kankaanpää 1991). The slope angle of the triangular keel is considered in an idealised case to be constant with an average value of 25^0 (Kankaanpää 1991). This description assumes that a ridge may grow in height without limit and thus only one parameter is needed to describe the size of the geometrically similar ice ridges. This may be taken to be the maximum total thickness of the ridge. The keel depth is in most measurements deduced from the sail height as the height is easier to measure and the ratio between the sail height and keel depth may be considered constant (Leppäranta 1981). For the Baltic, measurements have given a depth-to-height ratio of about 7.

The proper way to describe ridge size is a distribution of ridge thicknesses. This distribution has been observed to follow an exponential distribution in most sea areas (Wadhams 1994). Thus only one parameter is needed to determine the size distribution; this is the average ridge sail height $\overline{h}_s$. The ridge density is characterised by the mean distance between ridges along a straight track. This quantity, $1/\mu$, has been found to be also exponentially distributed and to be independent of the size distribution.

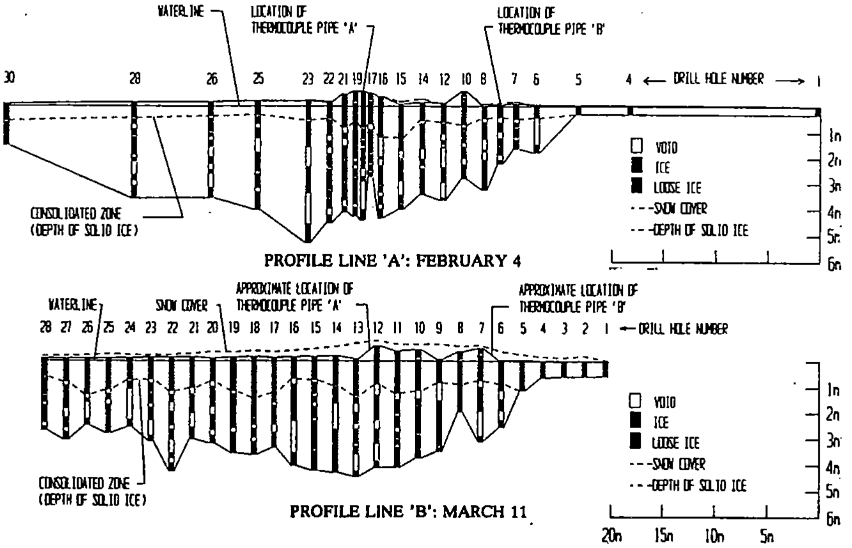


Fig. 11. A ridge in the Bothnian Bay examined twice during the same winter (Veitch et al. 1991).

Summarising, three quantities are required to describe ice ridges in a ridged ice field:

- average ridge sail height $\overline{h}_s$,
- average distance between ridges $1/\mu$ and
- thickness of consolidated layer h_c.

Measurements of the first two parameters have been performed in the Bothnian Bay where typical values were about 0.5 m and 130 m (Leppäranta 1981). The thickness of the consolidated layer must be estimated as it depends on the age of the ridge and on the temperature history. These can be deduced only indirectly. The starting point for the estimation of consolidated layer thickness could be the distribution of level ice thicknesses extracted from the ice thickness distribution. Thus, as a first estimate, the distribution of the consolidated layer thickness is obtained by multiplying the level ice thickness distribution by a factor 1.8 obtained from the average ridge porosity value of 0.3.

The values of the above three quantities have been measured in slightly more general fashion only in the Bay of Bothnia. The only parameter available from the other three Baltic sea areas is the average thickness of deformed ice. The average value of this is given in Fig. 12. As can be noticed, the ridging is on average significant only in the northern Bay of Bothnia and eastern and central Gulf of Finland.

The average thickness of deformed ice, $\overline{h}_r$, may be related to the ridge size and density as follows, Leppäranta (1981):

$$\overline{h}_r = C_1 \mu \frac{\overline{h}_S^{\,2}}{C_2 + \overline{h}_S} \tag{15}$$

where the constants are C_1=53.3 m and C_2=0.28 m.

The average thickness of deformed ice has been shown to correlate quite well with the ice loading on the hulls of ships navigating in the Baltic (Kujala 1994). No studies have been published where the average thickness has been related to ship performance. It is conceivable that in performance studies more resolution than only the average thickness is needed. At present three parameters are available for describing ice ridges: thickness, density and thickness of the consolidated layer.

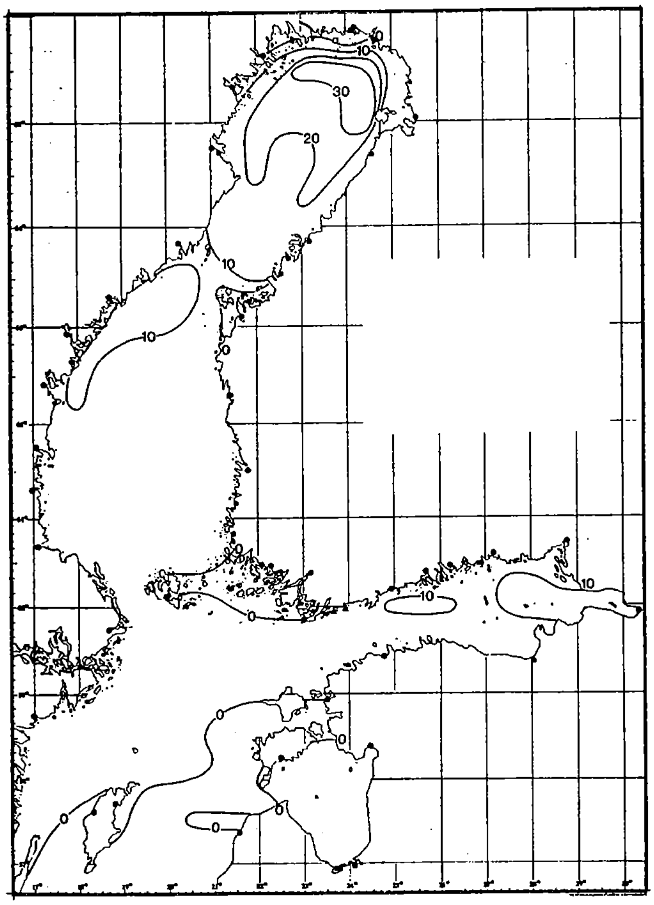


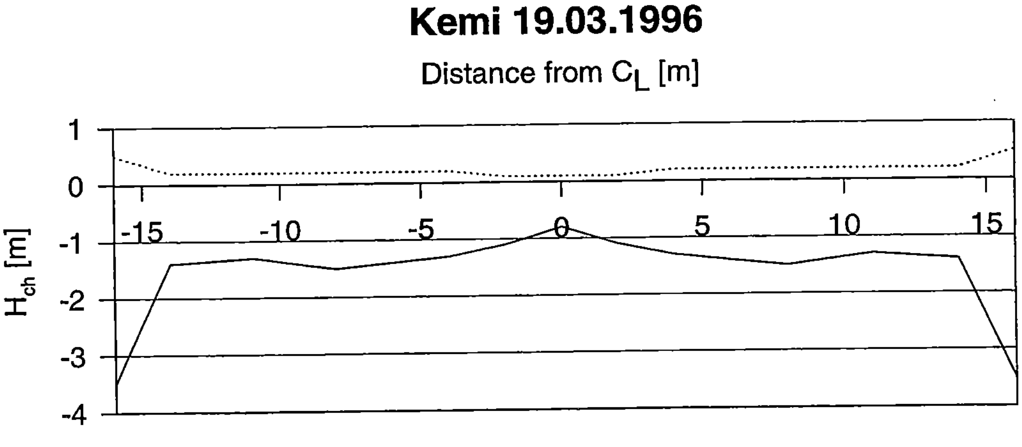
Fig. 12. The average increase in the average ice thickness caused by ridges [cm] (Leppäranta & al. 1988).

3.2.3. Navigation channels

The frequently navigated fairways leading to the main ports along the Finnish coast are covered with brash ice during every winter. The brash ice forms when ships repeatedly break the ice which starts to freeze after each ship passage. The ice pieces become almost spherical partly due to erosion and partly due to the propellers milling the sharp edges. As the Finnish coast is shallow, ships cannot deviate from the fairways and no alternative routes exist. By the end of winter some of these brash ice channels are so thick and consequently difficult to navigate that some ships must be escorted through the most severe parts.

The brash ice covering the frequently transited channels consists of rounded ice pieces of different sizes. In the middle of the channel ice pieces are smaller and a typical diameter is about 30 cm. Much bigger pieces, diameters more than one meter, can be found. As the smallest cross section of the biggest ice pieces is much larger than the level ice thickness, the process of forming brash ice must include repeated breaking and refreezing.

Three typical cross sections of a brash ice channel are shown in Fig. 13. The side ridges or banks grow due to ships pushing ice aside. If ships navigated only along the centreline of the track then the side ridges would be narrow and line-like but icebreakers often try to level these by breaking them. This produces a channel where only the middle part is somewhat thinner and the thicker part is spread out. The first one represents a cross-sectional drilling done in the winter of 1996 (Englund 1996) and the last two of the figures are measured in the early 1980's (Kannari 1982).



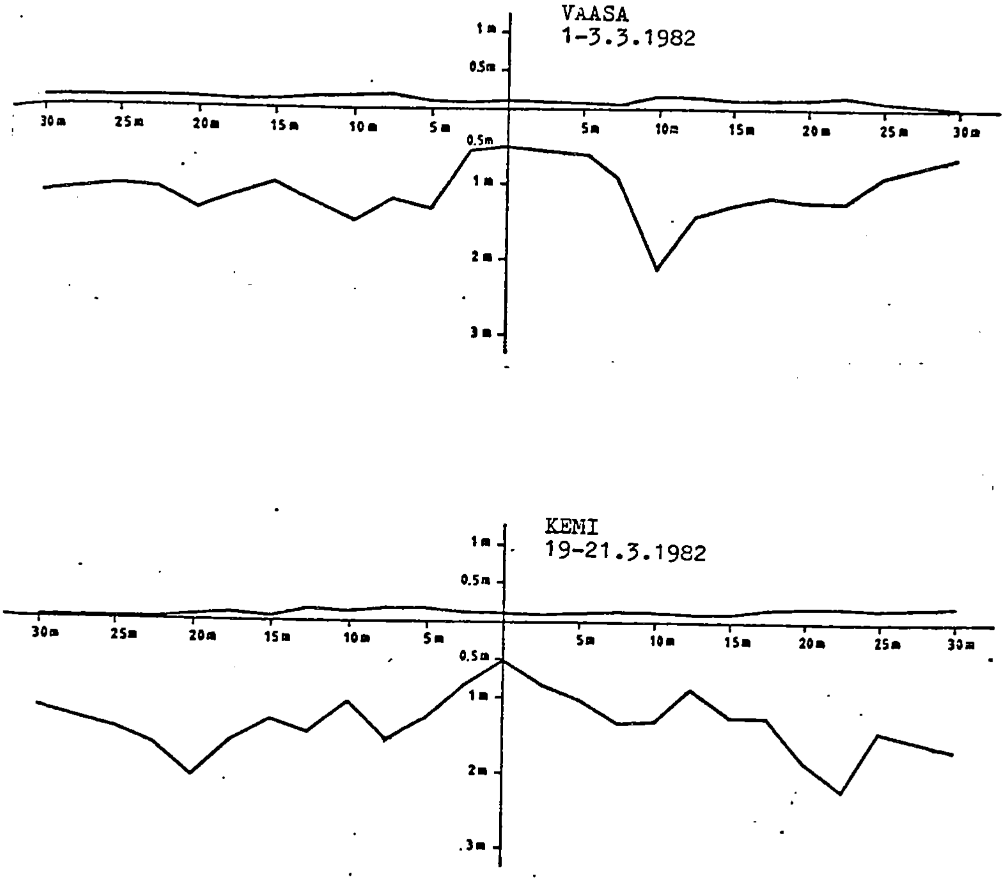


Fig. 13. Three cross sections of channels, measured by drilling.

The growth of brash ice thickness is controlled by the air temperature and the frequency of ship transits. Many models of the growth have been presented, a review of these and the latest thickness growth model is given in Ettema & Huang (1990). A simple version of growth may be obtained considering the growth of ice between two ship transits. In similar fashion as the growth of the consolidated layer of ridges, the brash ice layer consolidates up to the following thickness between two ship passages, if the initial porosity is p (Leppäranta 1992):

$$h_c = \alpha\sqrt{\frac{1}{p}\int_0^{t_i}[T_f - T_a(t)]dt}, \qquad (16)$$

where T_f and T_a are the freezing temperature of water and air temperature, respectively. The integral is called the cumulative degree days of freezing and labelled as DDF. The time between the two ship passages is t_i. The constant α is theoretically

$$\alpha\alpha = \sqrt{2\frac{k_i}{\rho_i L_i}}, \tag{17}$$

where k_i is thermal conductivity of ice ($k_i \approx 2.2$ W/m°C), ρ_i ice density and L_i latent heat of ice fusion ($L_i \approx 330$ J/g). At each ship passage the consolidated layer is broken. Assuming that the porosity value stays constant and that other ice growth e.g. on ice free parts of the channel does not occur, then the thickness increase of brash ice, just after the ship passage is,

$$\Delta h_b = \alpha\frac{\sqrt{p}}{1-p}\sqrt{\int_0^{t_i}[T_f - T_a(t)]dt}. \tag{18}$$

The total thickness after M+1 ship transit is then

$$h_b = h_{b0} + \sum_{i=1}^{M}\alpha\frac{\sqrt{p}}{1-p}\sqrt{\int_0^{t_i}[T_f - T_a(t)]dt}. \tag{19}$$

The initial thickness h_{b0} may be taken as zero.

The porosity value of brash ice is smaller than that of ice ridges. Measurements have given values from 0.1 to 0.2. The theoretical value for α is 34 mm/(°C×day)$^{0.5}$ and thus eq. (19) is the same as that given by Sandkvist (1981) using a porosity of 0.1.

Derivation of eq. (19) assumed that the ice forming in the channel does not move horizontally. This is not the case because a ship passage and especially the propeller stream disperse ice towards the sides of the channel. This effect is difficult to quantify and thus the thickness values obtained with the above method should be considered, as Sandkvist did, as equivalent thicknesses. Before the calculated equivalent thickness can be compared with the measured average thickness of ice channels, the temperatures and the frequency of ship traffic should be obtained. These input values for calculations are given in Table 1. The average temperature is the average value during the period from mid-November until the end of March. Table 1 also gives the calculated brash ice thicknesses. These are large because the horizontal motion of ice pieces is ignored. If the ice is assumed to move towards the channel sides to form triangular slopes, with a similar slope angle, 25°, as ice ridge keels, a thickness reduction of about 10 % is obtained. The conclusion is thus that the horizontal motion of brash ice is much enhanced by ships.

Table 1. Air temperature and ship traffic data for winters 1990-1994. The number of ships applies for the whole winter period (6 months).

Winter	No. of ships		T_{av} [°C]		DDF [°C×day]		h_b [m]	
	Oulu	Kemi	Oulu	Kemi	Oulu	Kemi	Oulu	Kemi
1990	300	394	-5,5	-7,4	750	1000	4,7	6,3
1991	306	398	-6,9	-8,6	930	1170	5,4	6,9
1992	280	354	-2,6	-4,2	350	580	3,0	4,4
1993	434	556	-3,9	-5,4	530	730	4,7	6,3
1994	324	360	-8,8	-10,4	1200	1410	6,3	7,2

The channel measurements conducted during winters 1990-1994 show that the average thickness of the brash ice in the channels decreases slightly as the winter proceeds (the average is taken across the channel to the location where the level ice cover begins). This effect is probably due to icebreakers widening the channels to make them easier to navigate. This observation makes the values of the calculated brash ice thickness quite theoretical. The ratio between the measured average channel thickness and calculated thickness may be calculated as a guideline. It is about 0.4 for the winters and channels covered. If this empirical ratio is taken to be valid for channels in the Baltic, then the thickness given in eq. (19) multiplied by this constant gives the actual brash ice thickness in channels.

4. ICE RESISTANCE FORMULATIONS

4.1 Introduction

The ice resistance of ships has been studied for more than 100 years. Most of the studies have focused on level ice resistance, which has been considered as a measure for the ice-worthiness of the ship. The resistance in other ice conditions - old channels, ice ridges and pack ice - is, however, more important to describe the capability of ships in ice. The formulations of resistance in the other ice conditions are scarce mainly because level ice is easiest to describe; ice thickness being the only parameter. Here the existing formulations for ice resistance in level ice and other ice conditions are summarised.

The published ice resistance measurement results are based on the assumption that the open water and ice resistance components, R_{ow} and R_i, can be separated and superimposed to obtain the total resistance R_T

$$R_T = R_{ow} + R_i . \tag{20}$$

The open water resistance is usually very small relative to the ice resistance in the ice-breaking speeds so that ignoring the cross coupling between ice and hydrodynamic forces does not lead to significant error. The superposition may be questioned but no data exists about its validity. Because the published results assume the superposition to be valid, this practise is followed here. Thus, for exactness, the open water resistance should be added to the following equations of ice resistance to arrive at the total resistance.

The measurement of ice resistance is not direct in full scale. All measurement procedures contain some assumptions on propulsive constants. If the thrust is measured from the propeller shaft then a value for the thrust deduction coefficient must be assumed. If only the torque is measured then the thrust is deduced from the K_T-K_Q diagrams involving more assumptions. The quantity that can be measured directly is the power required to proceed in certain ice conditions with a constant average speed. The required power value is a main design quantity and thus, after describing ways to estimate ice resistance, the ship performance in ice is related to propulsion power.

4.2 Ships used in validation of formulations

The following formulations, be they for ice resistance or for more general performance, must be validated using some actual ships. These ships are partly selected from the ships used during the observation period 1990-1994 supplemented by MS ARCTURUS of which there exists full scale ice resistance data (Eskola 1984). During the first year, 1990, observations of 16 ships were carried out, all of which operated in old channels. Since then the number of ships observed was reduced except during the winter of 1992 when the traffic in the channel to Raahe was observed thoroughly. Based on the observation program, ten ships were selected to be used in validation. They are given in Table 2 where the parameters used are the waterline entrance angle α, length of the bow part of the ship at the waterline L_{bow}, length of the parallel midbody of the ship at the waterline L_{par}, length between perpendiculars L_{pp}, ship draught T, propeller diameter D_{prop} or D_P and ship displacement Δ.

Table 2. The particulars of ships used in the validation program.

Ship/ice class	α [°]	ϕ [°]	L_{bow} [m]	L_{par} [m]	L_{pp} [m]	B [m]	T [m]	P_s [MW]	D_{prop} [m]	Δ [t]
ENVIK/IAS	29.0	39.0	25.6	38.0	96.0	16.2	5.2	2.74	3.05	5583.
KEMIRA/IAS	22.0	35.0	32.3	44.0	105.0	17.0	6.6	4.12	4.15	8565.
LINK STAR/IA	23.0	31.0	32.0	49.0	98.0	17.0	5.8	2.96	3.60	6877.
SOLANO/IA	23.0	31.0	33.4	51.0	116.3	21.0	6.2	5.52	3.80	10458.
TEBOSTAR/IA	19.0	47.0	33.5	37.0	105.3	17.6	6.6	3.68	3.7	7810.
SOTKA/IAS	24.0	29.0	32.4	77.0	150.0	21.5	9.5	11.47	5.45	22033.
AHTELA/IAS	19.0	35.0	43.1	50.0	112.0	19.0	6.1	5.92	3.7	9200.
AILA/IA	23.0	31.0	25.0	33.0	97.4	16.0	5.8	2.96	3.60	6320.
ARCTURUS/IAS	33.0	68.0	49.0	73.0	146.0	25.0	7.3	13.2	5.7	18000.
TERVI/IA	40.0	41.0	32.9	136.0	193.7	30.2	12.0	10.8	7.4	57300.

The selection of ships included in Table 2 is based on ensuring that both IA Super and IA ice classes are included and also that a proper spread in machinery power and displacement exists. MV AILA represents the mini-tonnage which has become an important ship class recently. Her sister ships are MVs WINDEN, NAJADEN, CHRISTINA and LAURA. Further, two ships have bulbs, MV LINK STAR and MV AHTELA. The latter is the sister ship of MV GRANÖ and MV HAMNÖ. MT SOTKA is a tanker intended for independent navigation within the Baltic. Thus she has excellent ice-going capability. The ships MV LINK STAR, MV AHTELA and MV AILA proved also to have good performance in ice during the full scale observation campaign. MT TERVI is the latest addition to the selection of ships. She is significantly larger than the other ships in the selection. She is a tanker equipped with an ice-going bow and vertical sides.

4.3. Level ice resistance

The level ice resistance forms the basic quantity in comparing the ice performance of ships. The level ice resistance arises when a ship breaks ice floes from the intact ice field, turns them parallel to the ship hull and forces them to slide down and eventually up along the hull. A resistance signal from a ship model towing test is shown in Fig. 14. The large variation in resistance occurs due to, at least partly, the intermittent breaking of ice in bending.

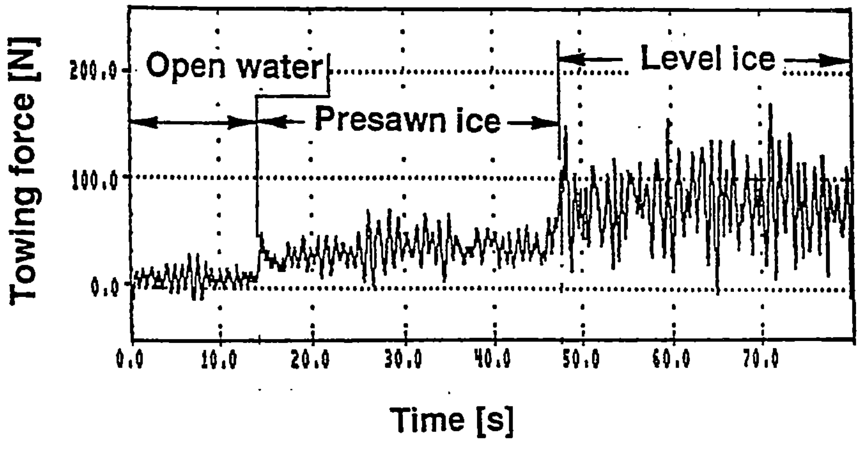


Fig. 14. The measured ice resistance from a ship model test in level ice.

Ice resistance is defined as the average value of the towing force. At very low speeds ships cannot proceed continuously and the average resistance is not directly applicable. When ship tests are done by increasing the thrust until the ship starts to move, then, if the thrust is not reduced, the ship speed eventually reaches several knots. Thus the ice resistance at zero speed must be considered to be higher than that at very low speeds. As the thrust is further increased, the ship speed increases approximately linearly and thus the ice resistance can be considered to be linear with speed. These considerations are sketched in Fig. 15.

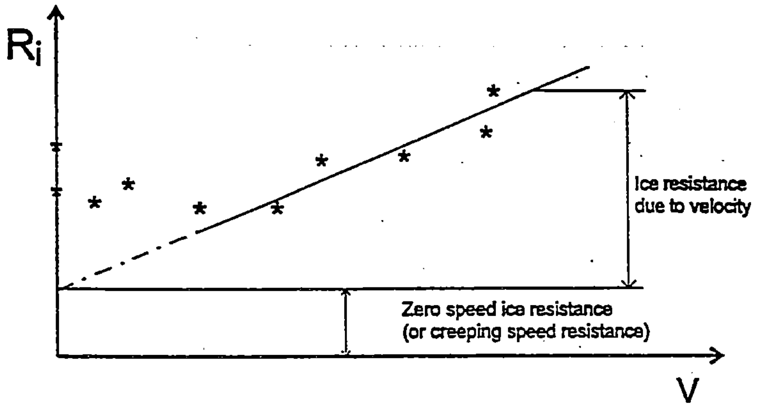


Fig. 15. Ice resistance versus ship speed deduced from full scale tests (Enkvist 1986).

There exists a wide variation in ice resistance predictions obtained by different formulations. This variation has been the subject of several studies, e.g. Bachér (1983) and Kämäräinen (1993). Instead of adopting any of the former level ice resistance formulations, a simplified version based mainly on three formulations is derived here. The three formulations used are those of Ionov (1988), Lindqvist (1989) and Kämäräinen (1993). The aim is to obtain a tool for estimating the power required in ice for use in transit models. First the ice resistance is split into parts and then the parameter dependency of each part is determined.

The main ice variable on which level ice resistance depends is the ice thickness h_i. The ice strength, density and friction between the ship and ice naturally influence the resistance but the values of these may be assumed to be constant for the purposes of the first estimate of ice resistance. The values used in this study for ice constants are presented in Table 3.

Table 3. Ice parameters used in this study

Difference between water and ice density	$\rho_\Delta = 125\ \mathrm{kg/m^3}$
Ice bending strength	$\sigma_f = 500\ \mathrm{kPa}$
Hull/ice friction	$\mu = 0.15$

The parameters ice resistance depends on may be divided into three groups. The first group consists of the external variables: ice thickness h_i and ship speed v. The two other groups contain the shape of the ship (ϕ, B/T, L/B, L_{bow}/L, L_{par}/L) and the size of the ship (L, B, T). The ship length refers to the length between perpendiculars but the subscript is omitted for simplicity. This way the ice resistance is

$$R_i = f(h_i, v; \phi, \frac{B}{T}, \frac{L}{B}, \frac{L_{bow}}{L}, \frac{L_{par}}{L}; B, T, L) = C_1 + C_2 v. \tag{21}$$

The constants C_1 and C_2 dependent of ship particulars must now be determined. This is done by modifying the formulations of Ionov (1988) and Lindqvist (1989). The speed dependency is assumed to be linear as no justification from full scale tests to other forms exists within the natural scatter in the data. The waterplane entrance angle at the bow, α_o, or along the waterline, α, are not included in the formulation because their influence on resistance is contradictory in the three references mentioned earlier. This angle is also difficult to define for all but wedge-like waterlines. The flare angle ψ (=$\tan\phi/\sin\alpha$) has been suggested to influence the resistance significantly (Enkvist & Mustamäki 1986) but as the angle α is neglected then only the influence from the stem angle ϕ remains.

The equations for the functions C_1 and C_2 are

$$\begin{aligned} C_1 &= f_1 \frac{1}{2\frac{T}{B}+1} B L_{par} h_i + (1+0.021\phi)(f_2 B h_i^2 + f_3 L_{bow} h_i^2 + f_4 B L_{bow} h_i) \\ C_2 &= (1+0.063\phi)(g_1 h_i^{1,5} + g_2 B h_i) + g_3 h_i (1+1,2\frac{T}{B}) \frac{B^2}{\sqrt{L}} \end{aligned} \tag{22}$$

where the values for the constants are shown in Table 4. These values are developed based on the performance of the ships given in Table 2. The length unit is m and angles are given in degrees.

Table 4. The constants in the equation for level ice resistance (22)

$f_1 = 0.23$ kN/m^3

$f_2 = 4.58$ kN/m^3

$f_3 = 1.47$ kN/m^3

$f_4 = 0.29$ kN/m^3

$g_1 = 18.9$ kN/(m/s×m^{1,5})

$g_2 = 0.67$ kN/(m/s×m^2)

$g_3 = 1.55$ kN/(m/s×m^{2,5})

The influence of the stem angle ϕ on the ice resistance is usually proportional to the tangent of this angle. The dependence of ice resistance on the stem angle is made somewhat less dominating in the above equation because many merchant vessels have quite vertical bows without the icebreaking performance suffering that much. The stem angle is to be measured without accounting for the bulb. Its influence is discussed later when the performance of vessels is treated.

Resistance predictions for two ships, MT SOTKA and MV ARCTURUS are presented in Fig. 16 together with measured full scale values. The calculated resistance is slightly higher than the measured values. This is partly due to use of somewhat high ice strength and friction values given in Table 3. The performance curves i.e. the speed the ships may attain in different level ice thicknesses are presented in Fig. 17, where the speed is scaled by the maximum open water speed of the vessels.

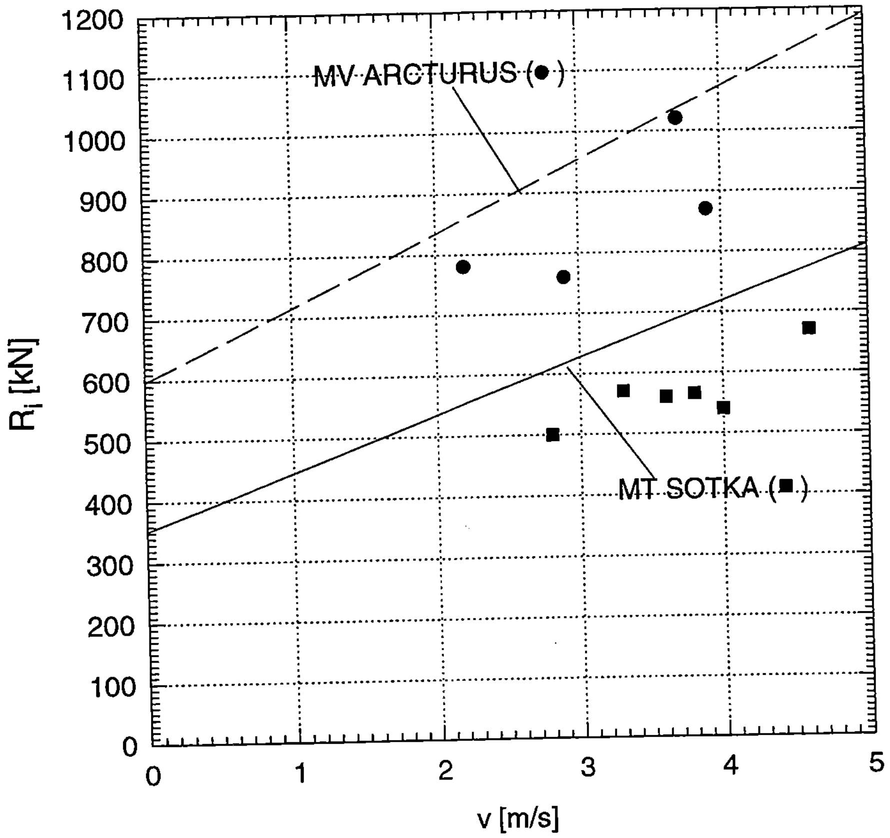


Fig. 16. Calculated ice resistance versus ship speed for two ships; MT SOTKA (h_i=0.54 m) and MV ARCTURUS (h_i=0.45 m) compared with some full scale values.

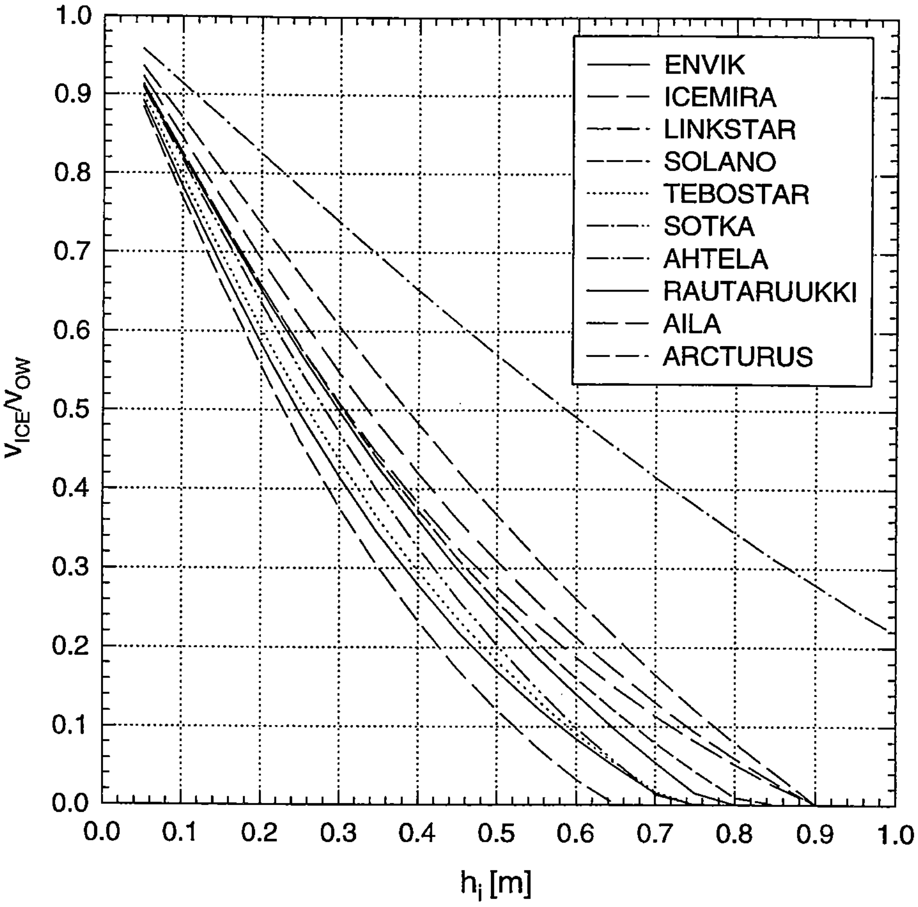


Fig. 17. The performance in level ice of 10 example ships.

4.4 Channel resistance

The channel resistance arises from displacing the brash ice present in the channel both down and sideways. The sideways motion of ice is limited because of the side ridges. Thus the *average* thickness of the channel is not a good measure of how difficult the channel is to navigate. When the channel is left to freeze, the uppermost ice blocks start to freeze together. This forms a consolidated layer on top of the brash ice layer. Thus the channel resistance is composed of two parts: one due to the brash ice and one due to the consolidated layer. The latter is treated here as level ice of the same thickness and the resistance calculated with eqs. (21) and (22). Physically this assumption has two main weaknesses: the consolidated layer does not necessarily have the same properties as level ice and the consolidated layer does not lie on water but on brash ice. No data about these factors are available, however, and thus the assumption has to be contended with.

The resistance caused by brash ice is usually studied using soil mechanics to describe the brash ice in channels, see e.g. Mellor (1980). Brash ice is modelled as a Mohr-Coulomb type of material and the behaviour of it can be described with two parameters: internal friction angle and cohesion. Because of the large piece size of brash ice and also the water surrounding the ice pieces, makes cohesion a material parameter, which can be neglected, since cohesion is a very small force, binding small-grained, humid material together. The formulation for channel resistance used here is based on two M.Sc. theses (Englund 1996, Wilhelmson 1996) which in turn are modifications of an earlier channel resistance formulation (Malmberg 1983) which was also based on soil mechanics. The full scale observations show also that ship draught influences significantly the channel resistance (Kannari 1982, Veitch et al. 1991). Both full scale observations (Vance et al. 1981) and model tests (Wilhelmson 1996) also show a non-linear speed dependency in the resistance. The equations presented by Englund (1996) and Wilhelmson (1996) are modified and put together to form a formula with speed dependency for brash ice resistance:

$$R_{CH} = \frac{1}{2} \cdot \mu_B \cdot \rho_\Delta \cdot g \cdot H_F^2 \cdot K_P \cdot \left[\frac{1}{2} + \frac{H_M}{2H_F}\right]^2 \cdot \left[B + 2 \cdot H_F \cdot \left(\cos\delta - \frac{1}{\tan\psi}\right)\right] \cdot (\mu_h \cdot \cos\phi + \sin\psi \cdot \sin\alpha)$$

$$+ \mu_B \cdot \rho_\Delta \cdot g \cdot K_0 \cdot \mu_h \cdot L_{PAR} \cdot H_F^2 \; + \rho_\Delta \cdot g \cdot \left[\frac{L \cdot T}{B^2}\right]^3 \cdot H_M \cdot A_{WF} \cdot Fn^2 \qquad (23)$$

Where μ_B is 1-p ($\mu_B = 0.8 \ldots 0.9$), ρ_Δ the difference between the densities of water and ice, g the gravity constant, K_P the coefficient of passive stress (soil mechanics) H_M the thickness of the brash ice in the middle of the channel, δ the slope angle of the side wall of the brash ice (22.6 ° is used in this context), μ_H the coefficient of friction between the ice and the hull, ϕ the angle between the waterline and the vertical at B/2, K_O the coefficient of lateral stress at rest, L_{PAR} the length of the parallel middlebody at the waterline, A_{WF} the waterline area of the foreship and Fn the Froude number. H_F describes the thickness of the brash ice layer which is displaced by the bow and which moves to the side against the parallel midbody. This is a function of ship breadth, channel thickness and two slope angles which are dependent of the inner properties of brash ice. H_F is calculated using the formula:

$$H_F = H_M + \frac{B}{2} \cdot \tan\gamma + (\tan\gamma + \tan\delta) \cdot \sqrt{\frac{B \cdot \left[H_M + \frac{B}{4} \cdot \tan\gamma\right]}{\tan\gamma + \tan\delta}} \qquad (24)$$

Fig. 18 illustrates the parameters used in the formula above. The angles γ and δ are taken as 2° and 22.6° respectively.

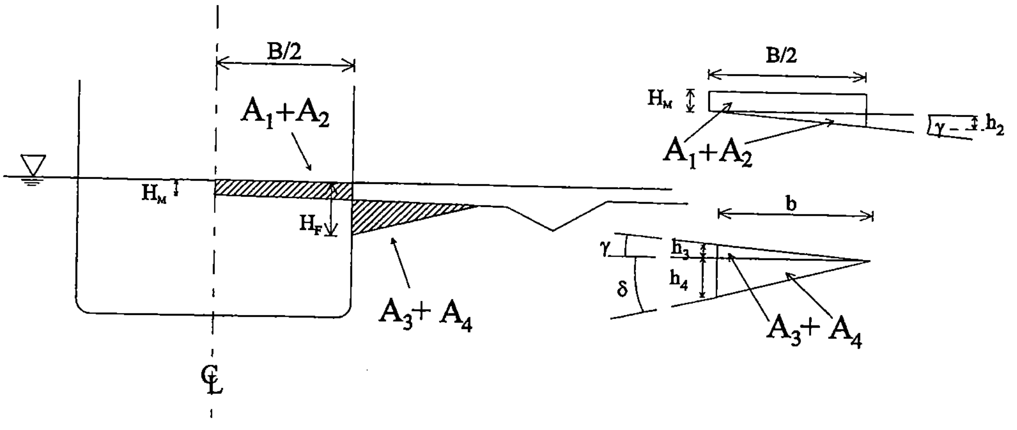


Fig. 18. The different parameters affecting H_F.

The formula for H_F has been simplified by an approximation which is valid when $B > 10$ m and $H_M > 0.4$ m:

$$H_F = 0.26 \text{ metres} + (B \cdot H_M)^{0.5} \tag{25}$$

The flare angle ψ may be eliminated from the above equations using the following trigonometric identities

$$\begin{aligned} \sin\psi &= \frac{\tan\phi}{\sqrt{\sin^2\alpha + \tan^2\phi}} \\ \psi &= \arctan\left[\frac{\tan\phi}{\sin\alpha}\right] \end{aligned}$$

The application of soil mechanics to study brash ice is justified by the observation of slip planes appearing when brash ice is loaded (Keinonen 1979). The brash ice may also be treated as a continuum because ice pieces constituting brash ice are far smaller than the other dimensions in the problem. A typical average piece size is about 30 cm and even the smallest length scale, the channel thickness, H_M, is more than this. Another and more difficult question is the application of the open water and channel resistance superposition. The open water resistance is in any case very small at low speeds. Thus for the purposes of determining the operability limits, the above formulation is applicable.

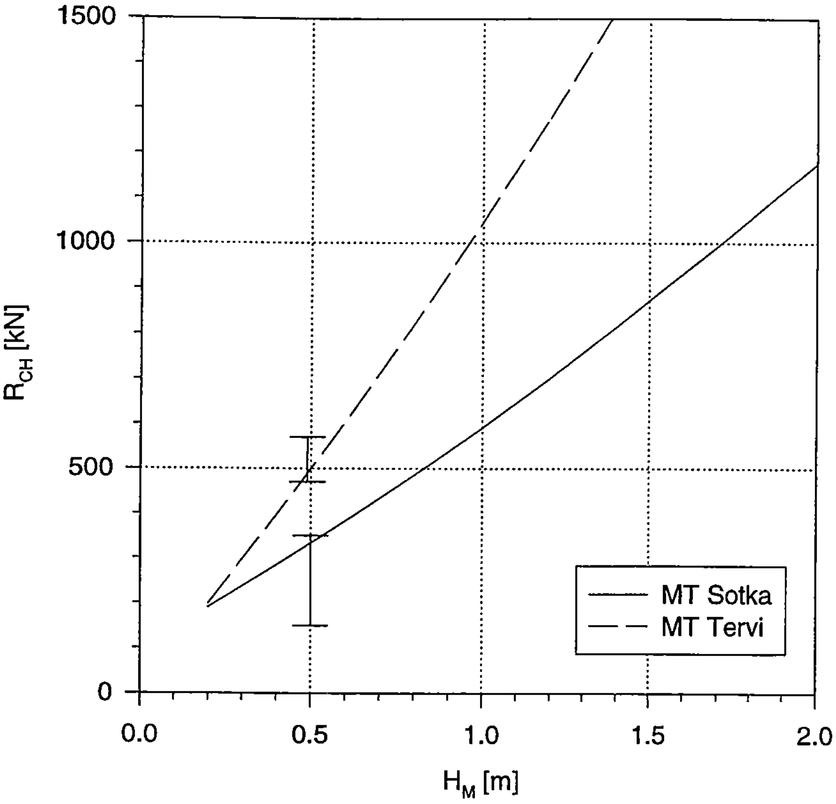


Fig. 19. Channel resistance versus the channel thickness for MT SOTKA and MT TERVI compared with full scale values. There was much scatter in the full scale values so the range of the values is only shown.

4.5 Resistance due to ice ridges

Ice ridges form the main obstacle for shipping in the Baltic during winter. Even the most powerful merchant vessels cannot proceed continuously in a ridged ice field, see e.g. Lehtinen (1994), Fig. 19. Whether or not ridged ice should be a design criteria should therefore also be discussed in this context. The occurrence and size of ridges varies very much in the Baltic. As the resistance caused by ridged ice is affected by probabilities of size and occurrence it would be very difficult to determine the correct relationship between the compromises that have to be made in ship design concerning engine power and ice-going / open water hull shape. Therefore ridged ice is not taken as a design criteria. However, the theory behind resistance in ridged ice will be discussed.

Only two studies concerning the ridge resistance are available at present (Keinonen 1979, Malmberg 1983). The formula developed in Malmberg (1983) is based on applying soil mechanics to study a ship displacing the ridge material. The formula is applicable only to zero speeds and it is

$$\begin{aligned} R_R &= C_1 T H_r\left(\frac{B}{2} + H_r \operatorname{tg}\psi / \cos\alpha\right)(0.15\cos\alpha + \sin\psi\sin\alpha) + \\ &+ C_2 T L_{par}\left[0{,}27\, H_r + \left(\frac{H_r}{T} - \frac{1}{2}\right)B\right] \end{aligned} \tag{26}$$

where H_r is the maximum thickness of the ridge and the constants have the values C_1=7.5 kN/m^3 and C_2=172 N/m^3. The factor $H_r/T-1/2$ in the second term is non-negative i.e. must be taken as zero when $H_r<T/2$.

The ridge thickness H_r may be interpreted as an instantaneous and local quantity, H, when analysing the ship passage through ridges. Thus the ridge resistance varies according to where the ship is located relative to the ridge. The first term in eq. (26) arises when the ship bow is displacing ridge material and the second term arises from the friction along the hull, mainly along the parallel midbody. When calculating the resistance during the ship passage through a ridge, the first resistance component may be taken as a point force applied at the ship shoulder. The second component depends on how far the ship has penetrated into the ridge. It can be determined by integration when the ridge profile H(x), x a co-ordinate along the ship track, is known. If it is assumed that the parallel midbody of the ship has penetrated the ridge a distance d then the ridge resistance due to the parallel midbody is

$$R_{par} = C_2 T \int_0^d \left[0{,}27H(x) + \left(\frac{H(x)}{T} - \frac{1}{2}\right)B\right]dx. \tag{27}$$

Eq. (27) reduces to the second component of eq. (26) if H(x) is taken as a constant H_r and d equals L_{par}.

The equations (26) and (27) have not been directly verified. Malmberg (1983) presented some validation which, however, corresponds to ridges whose profiles were only partially measured. Further, the ship speed in penetrating ridges varies significantly making the determination of resistance difficult even if the assumed superposition principle is valid. A further complication arises from the resistance due to the consolidated part of the ridge because it is practically always present in ridges in nature.

5. SHIP PERFORMANCE REQUIREMENTS IN ICE

The different Baltic ice conditions were dealt with in chapter 3 and the ice conditions met by merchant vessels in chapter 2. The conclusion was that channel ice conditions are the most important and dominating conditions for ships navigating in ice in the Baltic and should therefore be the prevailing ice condition in developing the performance requirement formulations. Navigation in ridged ice does not consequently form the design point for ice-strengthened merchant vessels.

The ice classes are presently divided into four categories. The first two, IAS and IA are intended for year-round navigation and the lower ice classes, IB and IC are reserved for navigation in the early winter or for lake navigation. The ships of the highest ice class, IAS should be able to navigate unescorted in the channels leading into the harbours. These channels are most likely consolidated. If the fairway is quite often trafficated and thus broken once or twice a day then a consolidated layer could grow to approximately 10 cm. Thus 10 cm of level ice added to the channel thickness should be the design criteria for the ships of ice class IAS. The ships of ice class IA should be able to trafficate the same channels as the ships of ice class IAS, except that these ships are either escorted or are navigating in a channel which has been broken recently by another ship. Therefore these ships do not need to break the consolidated layer. This gives the same design channel thickness as for IAS but without the consolidated layer. These two cases; a channel with or without the consolidated layer, are investigated next.

5.1 Ship powering based on escorted navigation in channels

The ice resistance of ships in navigation channels consists of two parts, one due to brash ice and one due to breaking the consolidated layer which has developed on the brash ice. The resistance component due to the consolidated layer is absent, however, when the ship is escorted. Right behind the icebreaker there is open water in the channel but already after some ship lengths the channel has closed again. The powering requirement is therefore formulated based on the first component, resistance due to brash ice. The powering requirement should ensure that the ships are able to maintain a continuous but possibly slow movement after an icebreaker. The power requirement is derived by setting the channel resistance equal to the net thrust as in eq. (11). The powering requirement based on the net thrust corresponds to a situation where the ship is moving slowly.

The channel resistance given in eq. (23) contains the waterline angle α which is easy to define only for wedge shaped waterlines. Some investigators use only the waterline entrance angle α_0 and sometimes the average value of this angle up to the shoulder is used. Since using the average angle instead of the waterline entrance angle gives a better description of the whole bow but is too complicated in this context, the waterline angle at B/4 is used instead.

The stem angle value ϕ along the whole bow waterline influences the channel resistance. Thus the definition of the stem angle must be modified to account for the whole bow waterline. Any definition based on the average value of ϕ along the cross section between waterlines and the buttock lines is too complicated. In the following the stem angle in brash ice is taken at the waterline at breadth B/4 and denoted ϕ_2. The level ice resistance uses the stem angle at the very stem, ϕ_1.

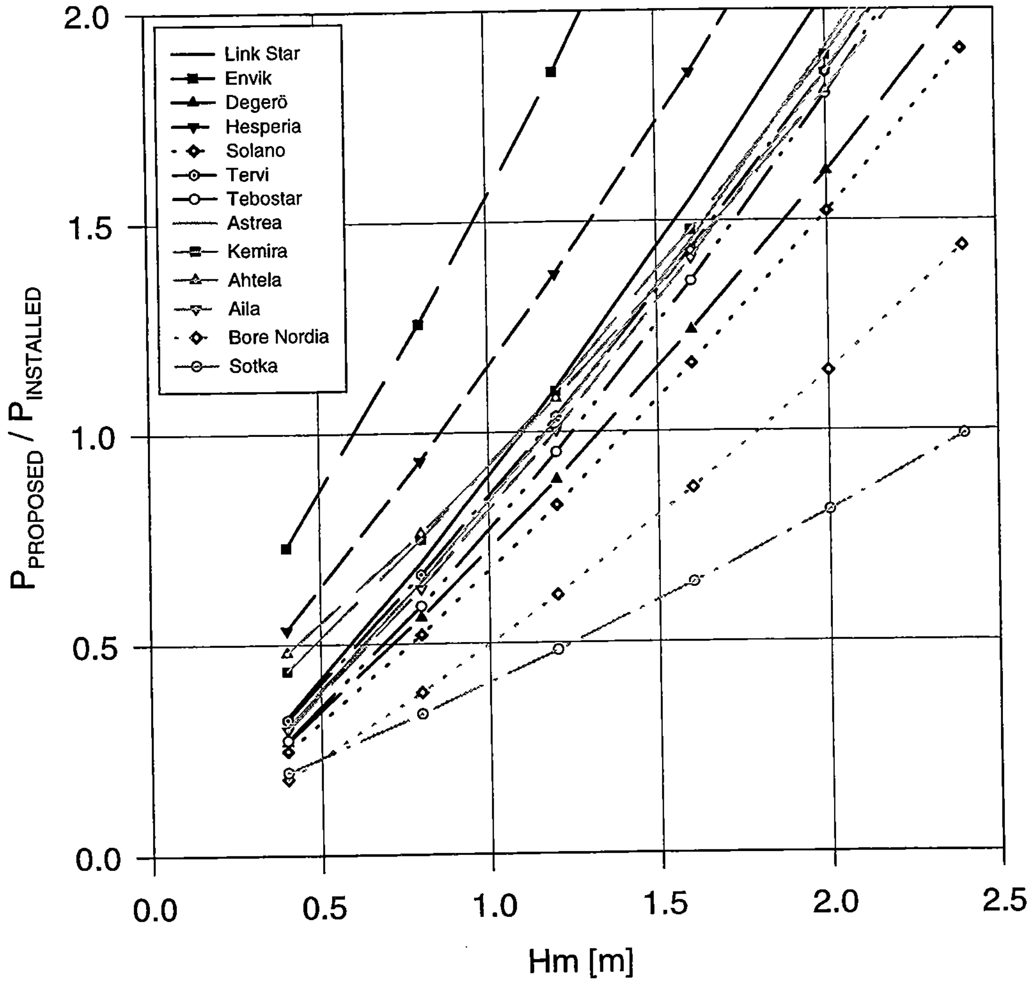


Fig. 20. The required propulsion power for the ships given in Table 2 plotted versus the channel thickness when $h_i = 0$.

Table 5. The calculated power requirement when $H_M = 1m$ and $h_i = 0$ compared with requirements in the Finnish Swedish ice class rules, in kW.

Ship name	P_{calc}	F-S	P_{inst}
	IA	IA	[kW]
ENVIK	3190	1180	2740
KEMIRA	2840	2520	4120
LINK STAR	2640	2690	2960
SOLANO	3700	3390	5520
TEBOSTAR	2810	2510	3680
SOTKA	3530	5500	11470
AHTELA	3510	3370	5920
TERVI	9140	10080	10800
HESPERIA	5460	4300	6050
DEGERÖ	3980	3240	5520
AILA	2400	2690	2960
ASTREA	4050	4100	4860
BORE NORDIA	2930	3400	5920

5.2 Ship powering based on independent navigation in channels

More stringent requirement for ship performance arises if the ship is assumed to be able to navigate in old channels independently. In this case the inbound ships are escorted to and from the edge of the shorefast ice where the fairway starts. The power requirement in this case consists of two parts which stem from resistance in channel brash ice and resistance due to the consolidated layer of the ice in the channel. The first of these resistance components is described by eq. (23). The consolidated part is assumed to be similar to level ice of the same thickness and thus the second component is described by eqs. (21) and (22) assuming a speed of five knots.

The final ice resistance equation contains two environmental parameters, consolidated layer thickness h_c and brash ice thickness H_M. The value of the channel thickness for the power requirement should be the same as in escorted navigation. Here two different stem angles, ϕ_1 and ϕ_2, are used. The resulting power requirement divided by the installed power versus the consolidated ice thickness for the ships in Table 2. is shown in Fig. 21.

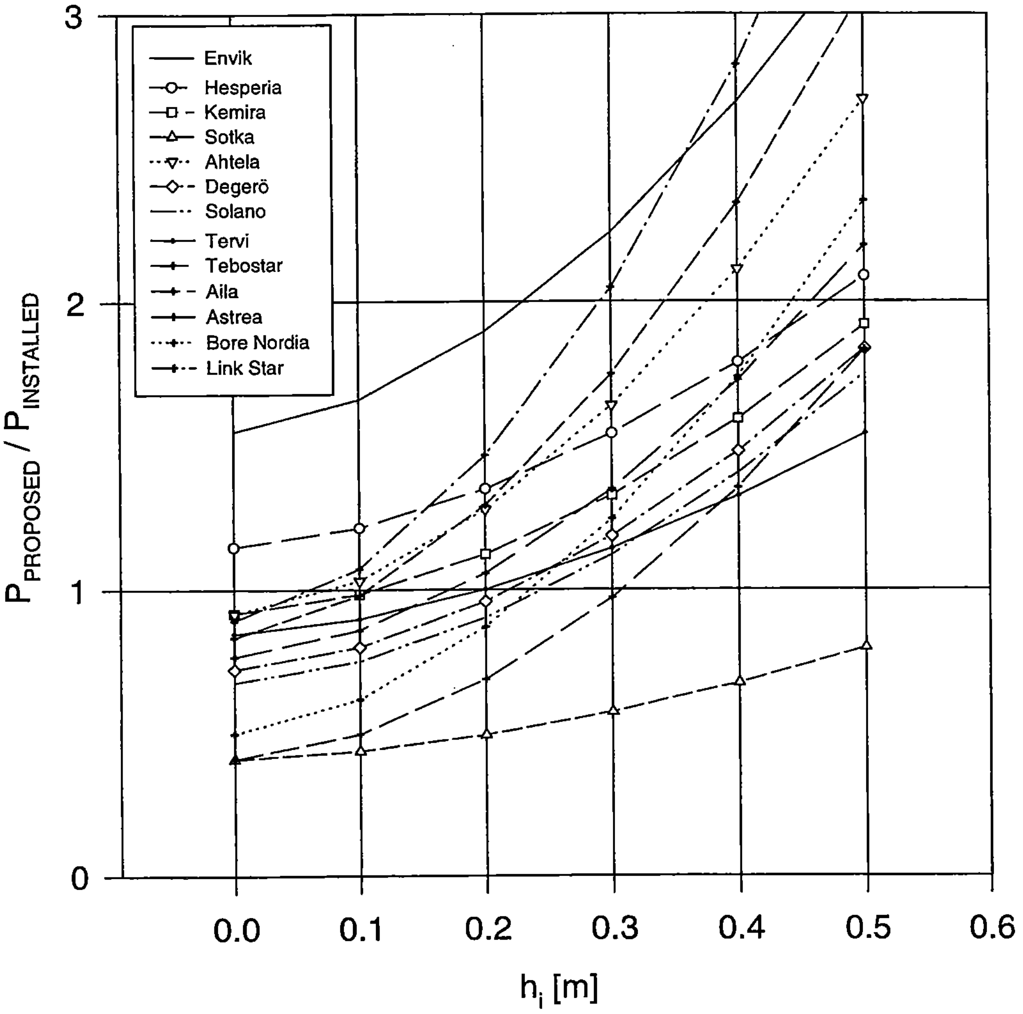


Fig. 21. The required propulsion power for the ships given in Table 2 plotted versus the thickness of the consolidated layer when $H_M = 1$ m.

Table 6. The calculated power requirement when $H_M = 1$ m and $h_i = 0.1$ m compared with requirements in the Finnish Swedish ice class rules, in kW.

Ship name	P_{calc} IAS	F-S IAS	P_{inst} [kW]
ENVIK	4240	3180	2740
KEMIRA	3780	3840	4120
LINK STAR	4120	4310	2960
SOLANO	5120	4920	5520
TEBOSTAR	3950	3900	3680
SOTKA	4660	6930	11470
AHTELA	5420	5050	5920
TERVI	11360	12600	10800
HESPERIA	6950	5710	6050
DEGERÖ	5560	4570	5520
AILA	3810	4690	2960
ASTREA	6110	5840	4860
BORE NORDIA	4800	5070	5920

5.3 Design thicknesses and the final power formulations

Finally the design values for the thicknesses of the channel must be selected. The channel thickness in the resistance formulations is defined and measured at the centreline of the channel. This is the thinnest part of the channel and the maximum thicknesses can be about one metre in the very north of the Bothnian bay. The lower ice classes, IB and IC are reserved for less severe conditions which can be encountered in the early winter and in the southernmost harbours. Their design channel thicknesses are smaller and these ships should always be escorted into the harbours. The resistance component due to the consolidated layer is therefore absent.

Table 7. The design values for the channel thicknesses for the different ice classes.

ICE CLASS	H_M [m]	h_i [m]
IAS	1.0	0.1
IA	1.0	0
IB	0.8	0
IC	0.6	0

The values in table 7 are inserted into the equations (21), (22) and (23) and the equations can be simplified further so that the constants in the resistance equation can be given in a separate table. The lengths are in metres, angles in degrees and channel resistance in Newtons. The parameters used in the resistance formulation are defined in Figure 22.

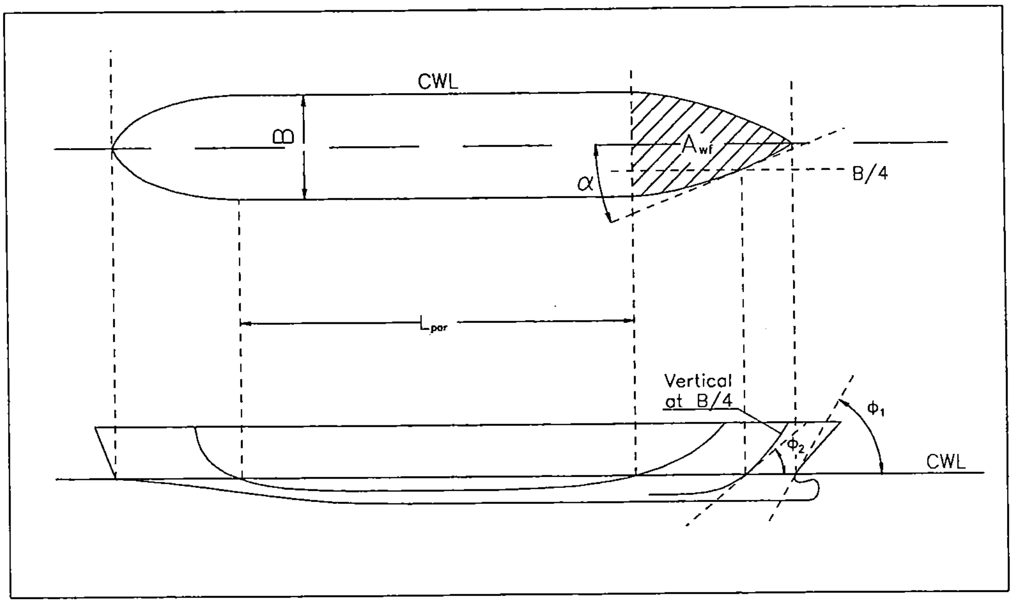


Fig. 22. The definition of the parameters used in the resistance formulation.

The resistance equation is as follows:

$$R_{CH} = C_1 + C_2 + C_3[H_F + H_M]^2\left[B + 1.85H_F - \frac{2H_F}{\tan\psi}\right][0.15\cos\phi_2 + \sin\psi\sin\alpha] + C_4 L_{PAR} H_F^2 + C_5\left[\frac{LT}{B^2}\right]^3 \frac{A_{wf}}{L} \qquad (28)$$

where

$$H_F = 0.26 + (H_M \cdot B)^{0.5} \qquad (29)$$

$$\psi = \arctan\left[\frac{tan\,\phi_2}{\sin\alpha}\right] \qquad (30)$$

$$C_1 = f_1 \frac{BL_{PAR}}{\frac{2T}{B}+1} + [1 + 0.021\phi_1](f_2 B + f_3 L_{BOW} + f_4 BL_{BOW}) \qquad (31)$$

$$C_2 = [1 + 0.063\phi_1][g_1 + g_2 B] + g_3[1 + 1.2\tfrac{T}{B}]\frac{B^2}{\sqrt{L}} \qquad (32)$$

For ships of ice class IAS with a bulb, the stem angle ϕ_1 is to be taken as 90°.

$C_3 = 845.576$ kg / (m^2 s^2)

$C_4 = 41.74$ kg / (m^2 s^2)

$f_1 = 23$ N/m^2	$g_1 = 1537.3$ N
$f_2 = 45.8$ N/m	$g_2 = 172.3$ N/m
$f_3 = 14.7$ N/m	$g_3 = 398.7$ N/m$^{1.5}$
$f_4 = 29$ N/m^2	

The term $\left[\frac{LT}{B^2}\right]^3$ in eq. 28 is to be taken as:

20 if $\left[\frac{LT}{B^2}\right]^3 > 20$ or 5 if $\left[\frac{LT}{B^2}\right]^3 < 5$.

For older ships where the determination of certain parameters is difficult due to eg. lack of linesdrawings the following equation can be used for calculating the channel resistance (R_{CH}). Here it is assumed that L_{par}, L_{bow}, A_{wf}, α and ϕ are related to the main dimensions L, B, T according to average relationships.

$$R_{CH}=C_1+C_2+C_3\left[H_F+H_M\right]^2\left[B+0.658H_F\right]+C_4LH_F^2+C_5\left[\frac{LT}{B^2}\right]^3\frac{B}{4} \qquad (33)$$

where

$$C_1=f_1\frac{BL}{\frac{2T}{B}+1}+1.84\cdot(f_2B+f_3L+f_4BL) \qquad (34)$$

$$C_2=3.52\cdot\left[g_1+g_2B\right]+g_3\left[1+1.2\tfrac{T}{B}\right]\frac{B^2}{\sqrt{L}} \qquad (35)$$

for ships in ice class IAS without a bulb or

$$C_1=f_1\frac{BL}{\frac{2T}{B}+1}+2.89\cdot(f_2B+f_3L+f_4BL) \qquad (36)$$

$$C_2=6.67\cdot\left[g_1+g_2B\right]+g_3\left[1+1.2\tfrac{T}{B}\right]\frac{B^2}{\sqrt{L}} \qquad (37)$$

for ships in ice class IAS with a bulb, and

$C_3 = 459.993$ kg / (m^2 s^2)
$C_4 = 18.783$ kg / (m^2 s^2)

$f_1 = 10.35$ N/m^2 $\quad$ $g_1 = 1537.3$ N
$f_2 = 45.8$ N/m $\quad$ $g_2 = 172.3$ N/m
$f_3 = 2.94$ N/m $\quad$ $g_3 = 398.7$ N/m$^{1.5}$
$f_4 = 5.8$ N/m^2

The term $\left[\frac{LT}{B^2}\right]^3$ in eq. 33 is to be taken as:

20 if $\left[\frac{LT}{B^2}\right]^3 > 20$ or 5 if $\left[\frac{LT}{B^2}\right]^3 < 5$.

H_M, h_i , C_1 , C_2 and C_5 . as in table 8:

Table 8. H_M, h_i , C_1, C_2 and C_5.

ICE CLASS:	IAS	IA	IB	IC
H_M [m]	1.0	1.0	0.8	0.6
h_i [m]	0.1	0	0	0
C_1 [N]	as eqs. (31, 34 or 36)	0	0	0
C_2 [N]	as eqs. (32, 35 or 37)	0	0	0
C_5 [kg/s^2]	825.6	825.6	660.5	495.4

The power requirement for all ice classes is then (the units are in kW, kN and m. Note that formula (28) gives the resistance in N.):

$$P_{req} = K_e \frac{R_{CH}^{3/2}}{D_P} \qquad (33)$$

where K_e is dependent of number of propellers and their type. K_e is given in table 9.

Table 9. K_e for different numbers and types of propellers.

Propeller type:	CP	FP
1 propeller	2.03	2.26
2 propellers	1.44	1.6
3 propellers	1.18	1.31

The power requirements calculated with the above constants for the ships in table 2 are shown in tables 5 and 6. A summary of the calculated power requirements for almost 60 ships is shown in appendix 2. Their ice class range from IAS to IC. The table has to be taken as an approximate one because all of the data needed for the calculations has not been available and therefore some parameters have been estimated based on average values for all ships. However, two plots to illustrate the effect of the new power requirement are made. In Fig. 23. the new requirement is plotted versus the present requirement in the Finnish-Swedish ice class rules for the vessels in the table in Appendix 2. It is seen that especially for lower powers the new requirement is more stringent.

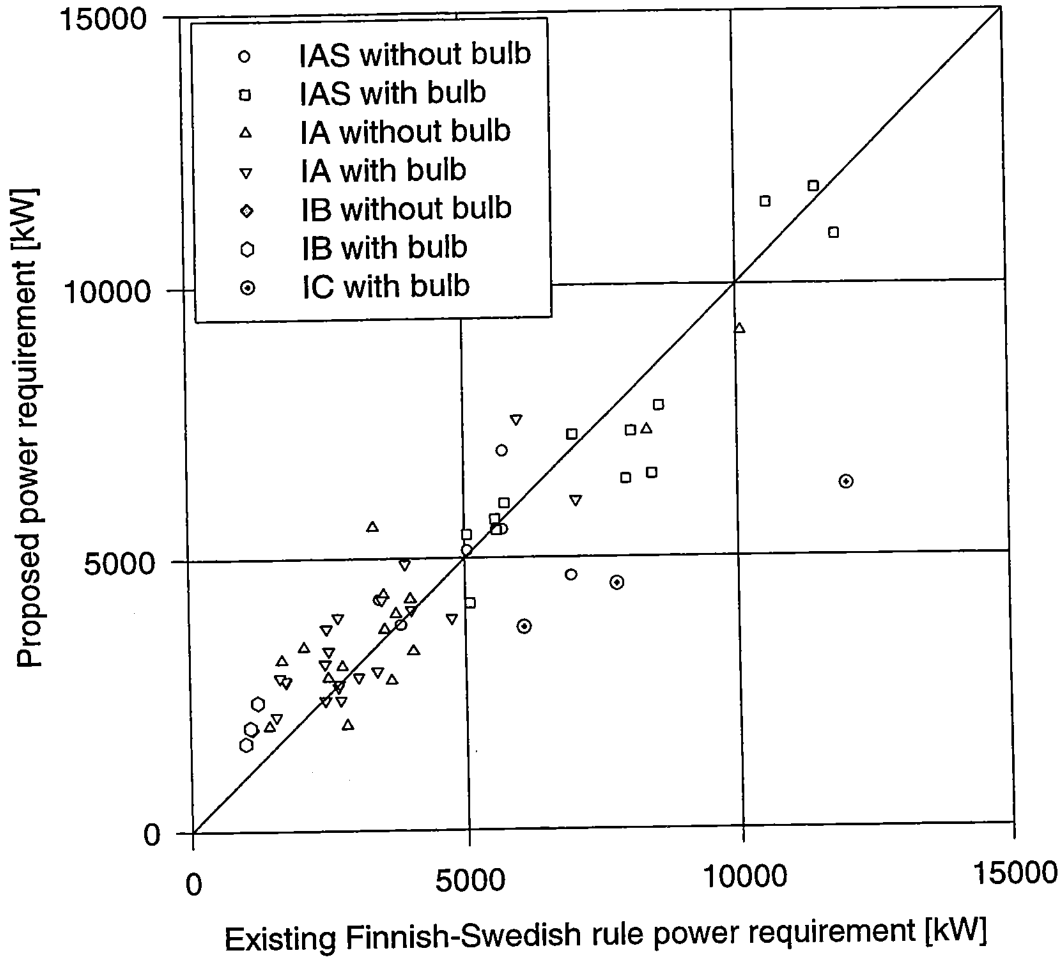


Fig. 23. The proposed power requirement vs. the Finnish-Swedish rule power requirement

The situation changes somewhat when the actual installed power is used as shown in Fig. 24. Now only the vessels of low power are required to have more power. The question is, are these low powered vessels also small or only of lower ice class.

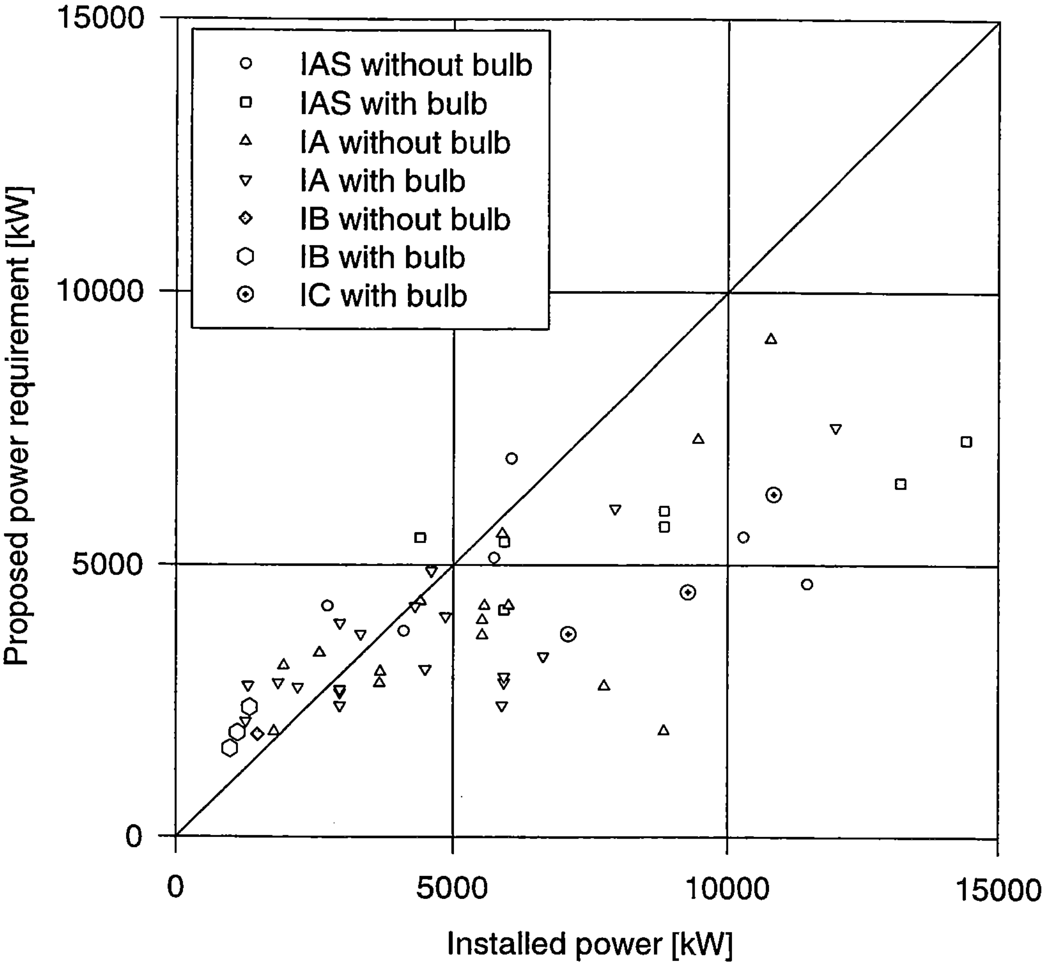


Fig. 24. Proposed power requirement vs. installed power

Figures 25 and 26 clarify this. It can be noticed that even if smaller vessels are required to have more power compared with the old requirements, in actuality this is not the case as most of the smaller vessels are much over-powered compared with the class requirement.

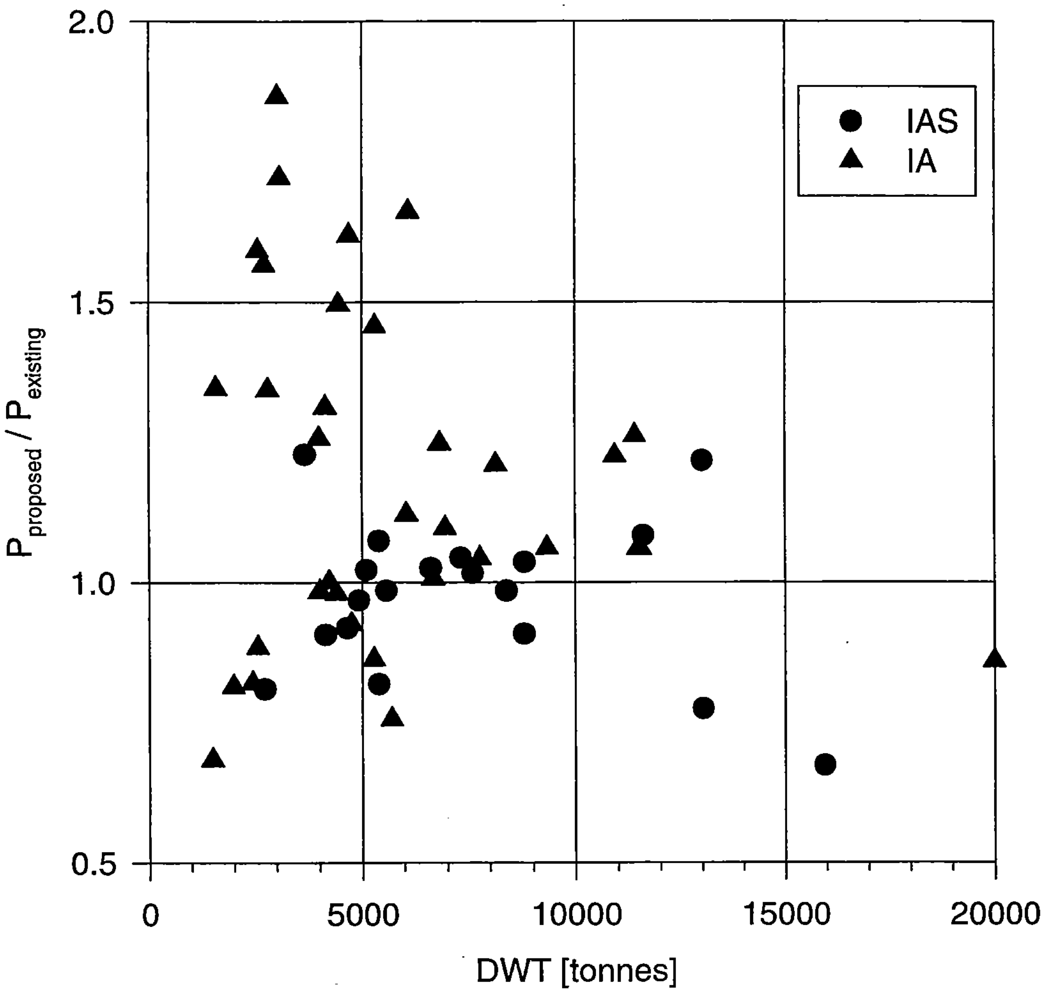


Fig. 25. Proposed / Existing power requirement as a function of dwt.

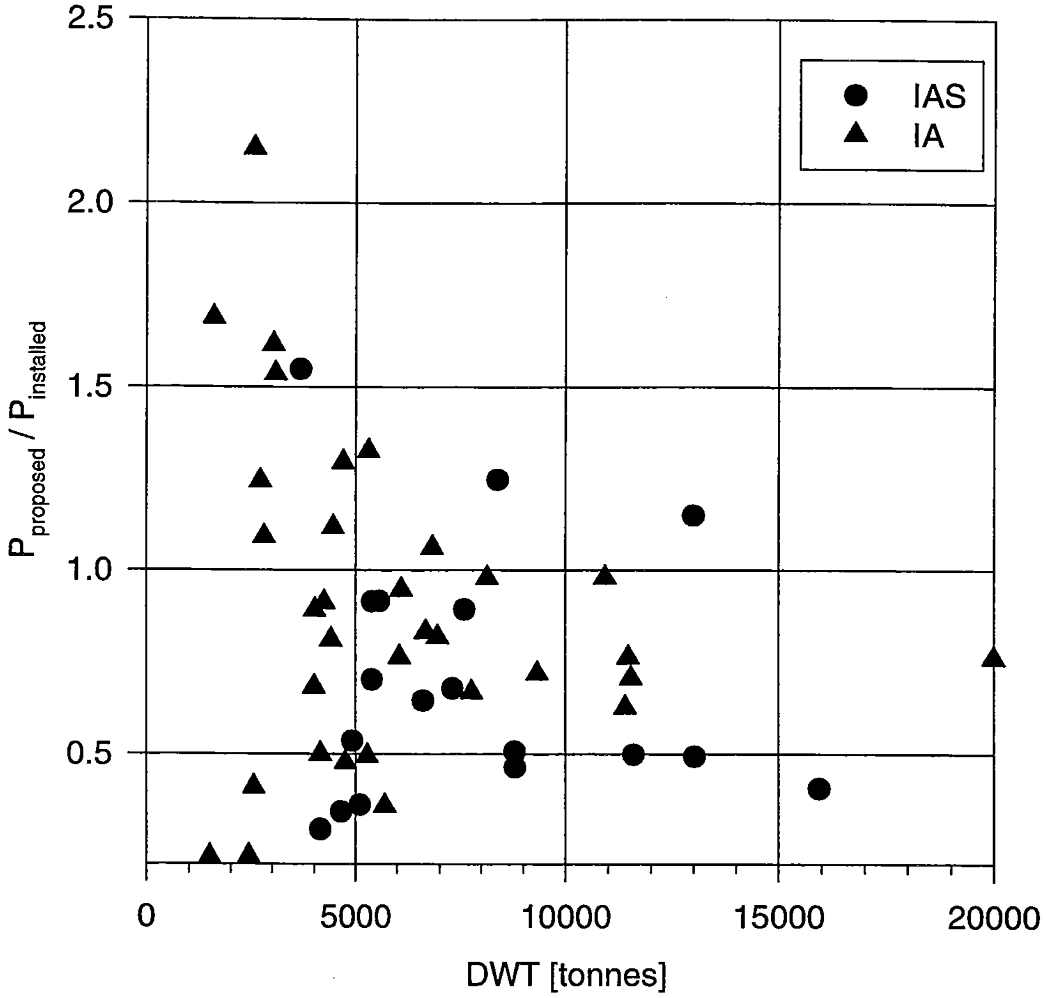


Fig. 26. Proposed requirement / installed power as a function of dwt.

Only vessels smaller than about 4000 dwt have a noticeably increase in the power requirement. These vessels are the ones, however, which are excluded from winter navigation by restrictions to navigation, see Fig. 2.

The question of a bulb on ice going vessels has been discussed often. It is clear that if the bow at the waterline is vertical, as the case is in many bulb designs, the vessels cannot break ice well. The presented requirements include two bow angles just for this case. The IA super class vessels are intended to break a thin layer of level ice on top of the channels. The ice resistance caused by this layer is calculated using the stem angle at the very bow while the channel resistance uses a kind of an average bow angle. This difference leads to somewhat higher power requirements for ships with bulbs in ice class IA super but not in ice class IA as Figures 27. and 28. show.

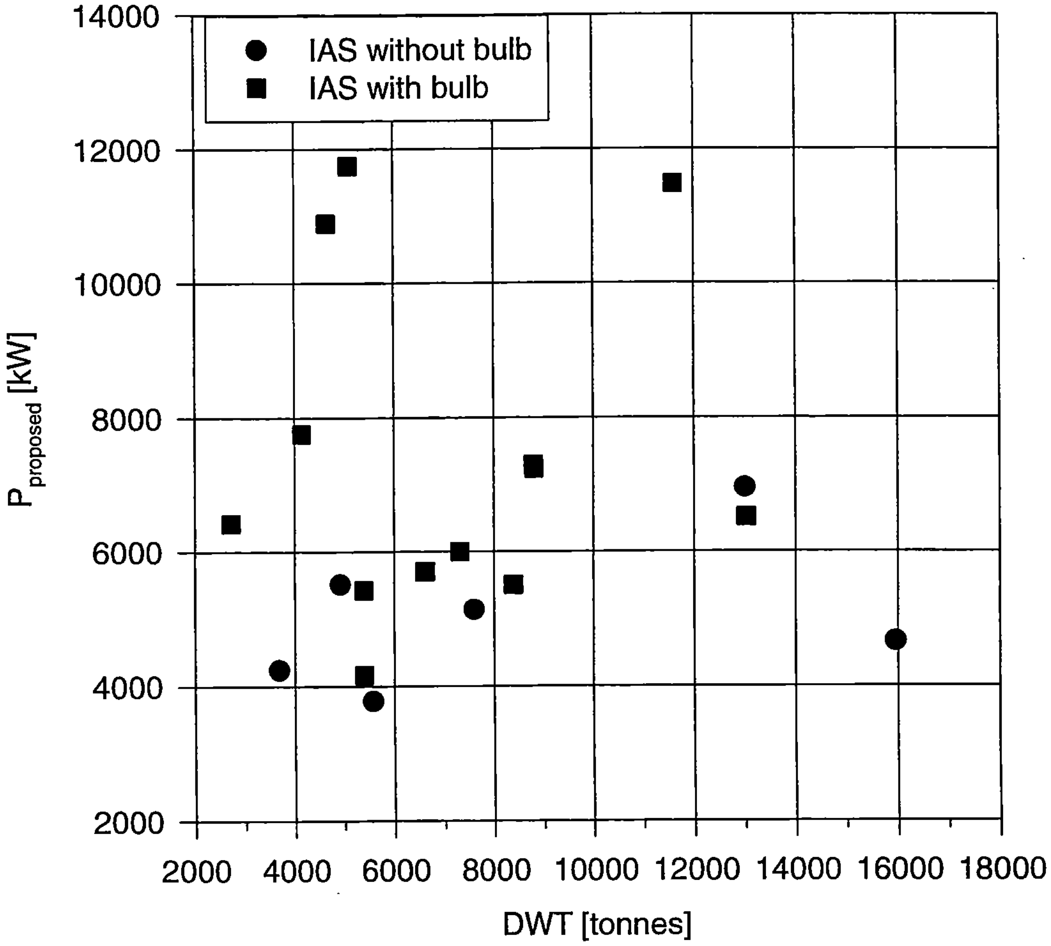


Fig. 27. Proposed power requirement as a function of dwt, ice class IAS.

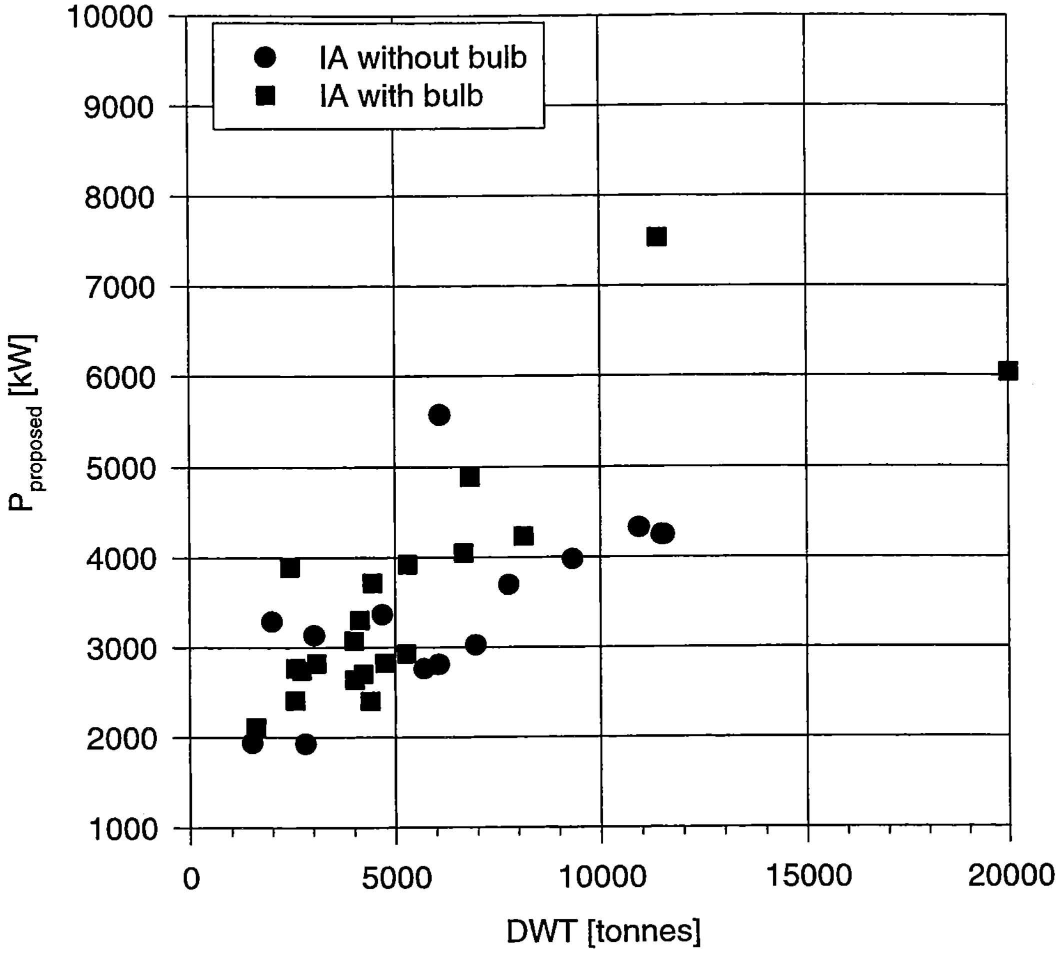


Fig. 28. Proposed power requirement as a function of dwt, ice class IA.

6. CONCLUSION

The purpose of the present report is to analyse the factors influencing the performance of merchant vessels navigating in the Baltic during wintertime. The performance is analysed in order to put design requirements on these vessels. These requirements could be applied in many ways and in the Baltic a two stage approach is used at present. Restrictions to navigation placed by the Board of Navigation state that ships less than a certain dead weight and ice class are not escorted to Finnish harbours. Additionally the Finnish Swedish ice classes state the minimum shaft power that ships in each ice class must have. The analysis of the latter type of power requirements is the specific topic of this report.

The ice conditions in the Baltic may be divided several broad categories: ice in navigation channels, ridged ice fields, level ice etc. The two operation modes considered are ships escorted by icebreakers and ships operating independently in old channels. The escorted ships need not break ice, they merely displace the channel ice aside inducing ice resistance due to friction, buoyant and inertial effects.

Ships that have strict schedules like passenger-car ferries and certain ro-ro vessels should be able to proceed independently in broken channels. If some waiting time for icebreakers is tolerated then the design requirement may be formulated based on escorted navigation in channels. Navigation in ridge fields, escorted or not, presents quite stringent requirements which only the ships intended for independent operation year round can fulfil.

The power requirements developed are based on ice resistance in the two types of old channel conditions. This study relies on previous developments of ice resistance formulations which are modified for the present purposes. The simplifications were made in order to have only the ship main dimensions and stem or buttockline angle included in the formulation.

The developed power requirement for old navigation channels proved that most of the existing vessels can proceed continuously behind an icebreaker in channels where the brash ice thickness is up to 0.7 m. This thickness is not an extreme one and thus the design thickness was selected to be 1 m. This thickness separates clearly the ships that have an unsuitable hull shape from the better ice-going vessels, a division validated by the field observations.

Once the ice in the navigation channel is allowed to consolidate, most of the normal merchant vessels do not have enough power to proceed independently. If the consolidated layer thickness is 10 cm only five out of the 13 example ships were able to proceed continuously. This shows that a refrozen channel can be the design condition only for higher ice classes.

In summary, the requirement of propulsion power of normal merchant vessels is suggested to be based on two different operation modes. One is based on the independent navigation in old channels. Ice resistance arises in this case from brash ice in the channel and from the refrozen consolidated layer. The resulting power requirement is somewhat more stringent than the present power requirement for IA Super ice class in the Finnish Swedish ice class rules. The other design point is the escorted navigation in the old channels. This gives power requirements which are slightly higher than those of the present IA class when the channel brash ice thickness is taken as 1.0 m.

The other operational modes considered in this report include independent and escorted navigation in ridge fields. These were analysed in a preliminary fashion. Especially the escorted navigation in a ridge field could form a further basis for power requirement for higher ice classes. This case was treated only briefly and a more thorough analysis should concentrate on the probability of getting stopped in ridges when following an icebreaker. This work must be based on the statistics of ridge density and ridge size. Also the effect of an icebreaker penetrating the ridges before the merchant vessel should be clarified. When these questions are tackled, a detailed gradation of the power requirements for Baltic merchant vessels may be given.

ACKNOWLEDGEMENTS

The project of defining the operability characteristics of merchant vessels in ice was initiated by Mr. Gunnar Edelmann from the Finnish Board of Navigation. His continual support is gratefully acknowledged. This work was made possible by the financial support from the Winter Navigation Research Board and Maritime Foundation. Many thanks are due to these. The present work is based on earlier work of many colleagues, mainly on the work of Dr. Pentti Kujala and Ms. Päivi Lehtinen. The authors acknowledge the fruitful starting position. Prof. Petri Varsta has been supervising the project which support and many demanding discussions is acknowledged. Ms S. Wang made most of the figures in the report and Ms. M. Seppälä made the final editing. Their precision in an unthankful work is acknowledged.

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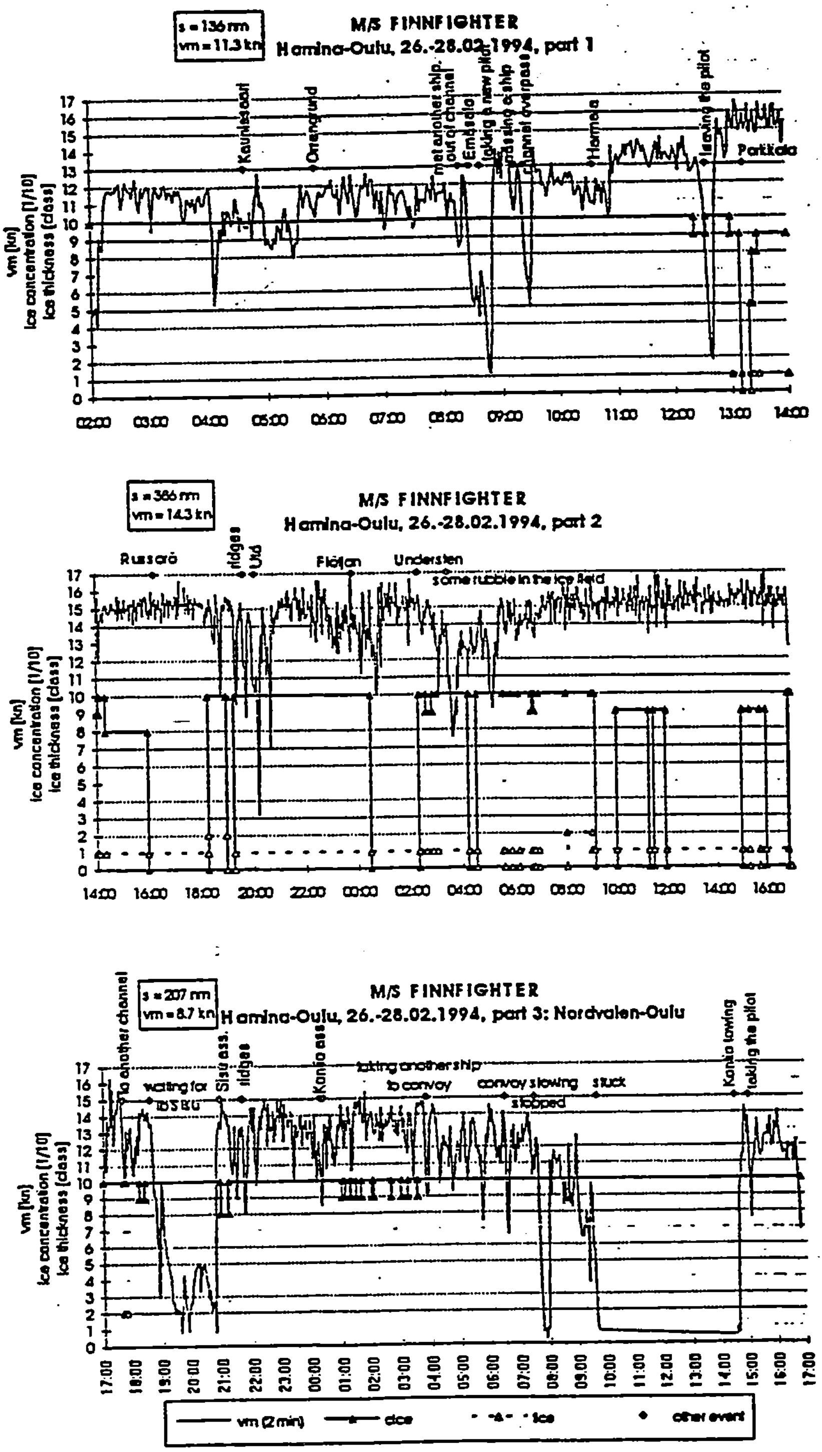
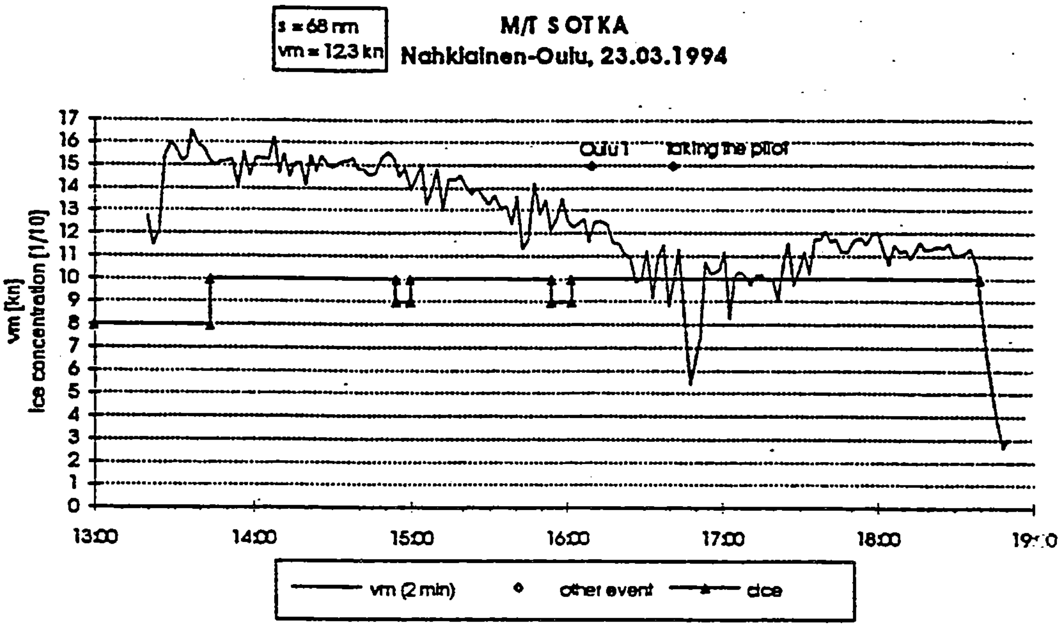
APPENDIX 1

Voyage analysis of two ships, MS FINNFIGHTER 26.-28.2.1994 and MT SOTKA 23.3.1994



Description of MS Finnfighter's voyage Hamina-Oulu, February 26-28 1994 (in three parts).



The speed profile and the ice concentration on the voyage Nahkiainen-Oulu onboard MT Sotka on March 23 1994.

APPENDIX 2

A table of the calculated power requirements of over 60 ships. The ship parameters used are based on the best available knowledge for each ship and thus the parameters of some ships are based on average values. The table shall therefore not be used as reference when determining the power requirements for these ships.

Name	DWT [t]	Lwl [m]	B [m]	T [m]	Isklass	Ps [kW] Installed	Fin-Swe rule	Proposed requirement
I A Super without bulb								
Envik	3683	96	16.2	5.2	1AS	2740	3453	4242
Hesperia	12999	133	21.6	8	1AS	6050	5711	6951
Kemira	5583	105	17	6.6	1AS	4120	3836	3779
Sotka	15954	150	21.5	9.5	1AS	11474	6927	4656
Finnfellow/Finnmaid	4922	131.3	23.9	6.1	1AS	10298	5698	5513
Camilla	7598	126.65	20.6	6.86	1AS	5737	5048	5132
I A Super with bulb								
Ahtela	5399	116.2	19	6.1	1AS	5921	5046	5422
Antares/Finnsailor	8793	150.5	25.3	7.3	1AS	14400	8037	7295
Borden	6615	134.19	19.2	7.02	1AS	8828	5562	5703
Finnhansa/-partner/-trac	11600	175.3	28.7	7.4	1AS	23040	10591	11477
Finnjet	2728	200	25.4	6.5	1AS	55000	7937	6420
Finnmerchant/Oihonna	13025	150.6	25	8.45	1AS	13200	8423	6512
Garden	7316	141.87	19.2	6.99	1AS	8828	5741	5994
Hamnö, Granö, Styrsö	5400	117.5	19	6.16	1AS	5920	5092	4164
Silja Europa	4650	171.6	32	6.8	1AS	31808	11859	10888
Silja Festival	4150	156.49	27.6	6.5	1AS	26400	8562	7758
Silja Serenade	5100	180.7	31.5	6.8	1AS	32580	11493	11748
Vikla	8388	126.43	19	7.2	1AS	4413	5587	5501
United Shipping NB	8800	145.1	22.7	6.95	1AS	15600	6981	7235
I A without bulb								
Degerö	9334	131.51	21	6.7	1A	5520	3747	3977
Fennia	1500	123.2	19.36	5.02	1A	8828	2838	1938
Finnpine (ex Solano)	7769	116.27	21	6.7	1A	5520	3543	3697
Tervi	45000	197.3	30.2	12.5	1A	10800	10081	9138
*Tebostar	6060	105.3	17.6	6.6	1A	3678	2507	2812
Bona Fe	2815	79.34	11.9	5.5	1A	1765	1432	1925
Bore Song	6100	122.39	19.2	6.4	1A	5884	3356	5575
Finnmaster	5710	130.5	22.3	6.6	1A	7722	3657	2763
Kontula	31850	169	25.7	11.05	1A	9450	8335	7301
Melkki	11538	134.26	21.2	7.3	1A	6000	4006	4247
Norden	10935	134.67	18.5	7.53	1A	4413	3531	4328
Outokumpu	4693	91	16	6	1A	2600	2079	3367
Sirri	6954	100	17.5	7.3	1A	3692	2757	3026
Susanna	3035	80.68	14.03	5.12	1A	1940	1680	3135
Tebo-Olympia	11474	134.26	21.2	7.3	1A	5560	4006	4247
Wasa Queen	1995	147	22.31	5.84	1A	17652	4048	3291
I A with bulb								
Ann-Mari	4750	107.7	18	6.1	1A	5921	3057	2828
Astrea	6672	121.4	21	6.42	1A	4860	4020	4048
Birka Princess	2441	129	24.7	5.75	1A	17600	4750	3894
Bore Nordia	5282	115.6	19	6.1	1A	5920	3402	2932
Fjärdvägen	2566	103.1	18.9	4.95	1A	5884	2729	2411
Link Star	4017	98	17	5.8	1A	2960	2685	2641
Aila	4402	97.4	16	5.8	1A	2960	2450	2403
Bore Sea	4234	101.2	17	5.8	1A	2960	2701	2703
Christina	4452	96.9	16	6.07	1A	3330	2487	3720
Crystal Amethyst	8143	112	18.24	7.512	1A	4320	3498	4234
Forte/Largo	4001	90.82	15.85	6.42	1A	4500	2448	3076
Gunilla	4150	113.47	16	5.95	1A	6620	2519	3307
Jenolin/Julia	5314	97.34	16.8	6.25	1A	2960	2693	3924
Kihu	19999	149.95	23.1	10.09	1A	7920	7030	6036
Lagard	2720	76.29	13.5	4.96	1A	2207	1751	2743
Lillgaard	1596	70.73	12.8	4.18	1A	1250	1568	2112
Nestefox	6830	116.54	19.5	7.6	1A	4608	3920	4890
Norking/Norqueen	11400	163.06	23	7.6	1A	12000	5972	7531
Sydgard	2574	75.92	13.4	5.05	1A	1290	1740	2772
Westgard	3085	79.15	12.6	5.05	1A	1839	1640	2825
I B without bulb								
Marika	2900	74.63	13.75	5.4	1B	1464	1127	1875
I B with bulb								
Helen	2213	74.2	12.8	4.5	1B	1104	1085	1904
Majgard	2399	70.6	11.8	4.96	1B	971	996	1611
Östgard	2866	91	13.5	4.3	1B	1320	1227	2368
I C with bulb								
Arkadia	47442	180.97	32.2	11.68	1C	9267	7746	4496
Finnwood	29094	184.5	27.5	10.3	1C	7080	6063	3719
Futura	96058	231.26	40	14.52	1C	10860	12021	6295