POAC '99
Espoo, Finland

Proceedings of the 15th
International Conference on
Port and Ocean Engineering
under Arctic Conditions

DETERMINATION OF THE ADMISSIBLE POWER OF ICEBREAKING CARGO SHIPS WITH THE USE OF THE CRITERION OF THE LIMITATION OF ICE LOADS AT THE IMPACT WITH ICE

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ABSTRACT

Until the present time, practice in the design of icebreaking ships did not consider selection of power of main engines in ralation to the requirements to the safety of navigation under ice conditions. However the experience of operation of ships on the Northern Sea Route (NSR) shows that excessive speeds developed in open floating ice at a too high power result in heavy ice damages. This gives rise to the necessity of solving problems of the regulation of admissible speeds of movement through ice and limiting power of the ship's propulsion plant. The work deals with main principles of the selection of power of icebreaking cargo ships bearing in mind safety of movement through open floating ice. Methods of the selection of their power have been put forward. The essence of this methodology is in the combined solution of the equations describing the level of ice loads and of achievable speeds. By these equations a relation has been established between speed, power, thickness and concentration of ice as well as ice loads on the ship's hull. Criterion of the safety of navigation in ice is the level of ice loads regulated by the Russian Marine Register of Shipping (MRS) Rules. Results of the work may be used in the development of requirements to prospective arctic ships and also in their design.

INTRODUCTION

The ice propulsion of ships, apart from the power they develop, is significantly influenced by the concentration of ice: the lower it is, the higher is the speed. At a low concentration of drifting ice a ship or an icebreaker due to its manoeuvrability may proceed practically in open water. In this case the consequences of collision with a large ice floe at a high speed are most dangerous. As the concentration increases the probability of the dangerous impact reduces due to the natural reduction of speed. The above holds both for independent navigation of ships and for that under the icebreaker support. As the methods are designed for the determination of maximum admissible values, they are to be based on the most dangerous scenario of the navigation of ships in ice.

1. SELECTION OF THE MOST DANGEROUS SCENARIO

Main modes of the navigation of ships in ice are as follows:

1. Independently in broken ice (small floe and ice cake) of a high concentration or in fast ice;
2. Under icebreaker support in broken ice of a high concentration or in fast ice;
3. Independently in open floating ice;
4. Under icebreaker support in open floating ice of considerable thickness.

Special features of each of the modes can be judged from the diagram of the ice propulsion constructed in relative values (Figure 1).

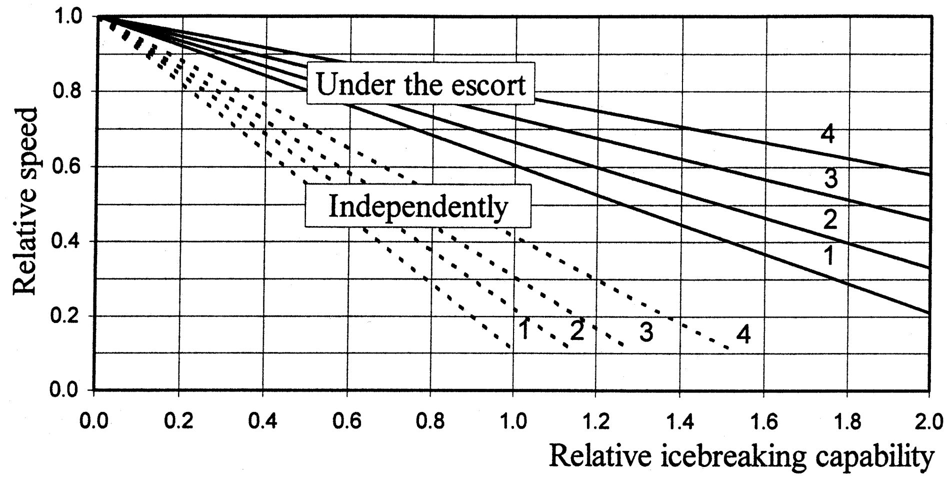

Figure 1. Propulsion of an icebreaking cargo ship while moving independently and under the support of icebreaker in the fast ice (1) as well as in broken ice with a concentration of 9/10-10/10 (2), 7/10-8/10 (3) and 5/10-6/10 (4)

Of the least danger for a ship is the first mode, as at low speeds of movement the level of dynamic loads is not high. In the independent movement in broken ice with a concentration of 9/10-10/10 the achievable speeds of ships do not exceed 40-50 % of maximum speeds in open water. This value is practically constant for ships of all ice categories which sail through ice with a thickness of 70-80 % of their icebreaking capability (Figure 2).

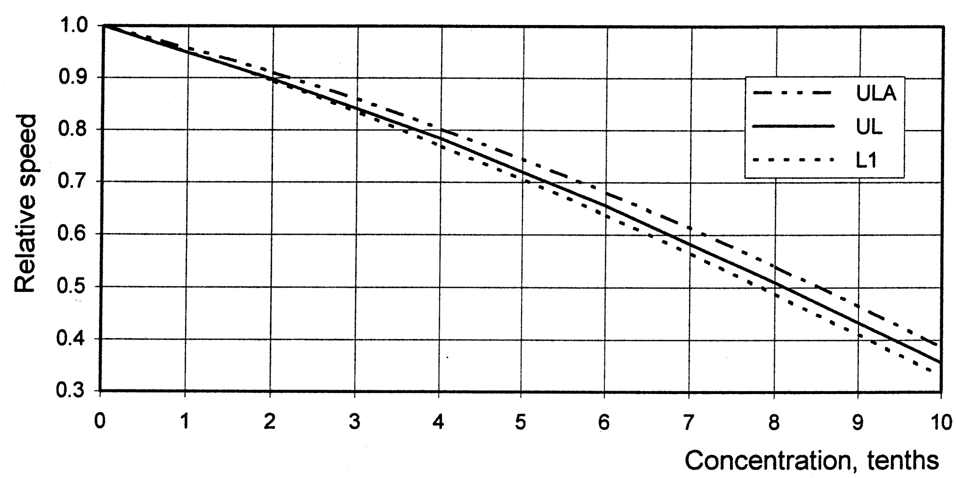

Figure 2. Effect of the ice concentration on speeds of ships of different ice categories

Movement behind an icebreaker through heavy ice of a high concentration (mode 2) is also of no serious danger for a ship: either it is moving at a minimum speed, lower than that of the icebreaker, because of insufficient power or it is restricting power if the icebreaker's movement is hampered. The experience of operation of the Russian fleet under such conditions shows that levels of the real power of ships do not allow them under medium and heavy ice conditions to develop speeds threatening with serious ice damages. This allows to conclude that principal condition for the selection of the ship's power during the movement through ice with a concentration of 9/10-10/10 is the provision of the steady movement of ship behind the icebreaker.

It is not the case when power is to be chosen both in view of the independent navigation (mode 3) and in following the icebreaker (mode 4) through the open floating ice. While moving through ice with a concentration of 5/10-6/10 speeds may reach 70 % of speeds in open water and are considered dangerous. As the experience of operation and the statistics of ice damages of cargo ships show, the greatest number of damages (70-80 %) occur in the forebody in the way of frame lines 2-3 during the movement of ship behind the icebreaker through open floating ice with a concentration of 4/10-7/10. While carrying out full-scale trials of a ship of the *Amguema* type in the small floe 1.5-2.0 m thick with a concentration of 6/10-8/10 the highest ice load values were recorded just in this hull area (Likhomanov and Solostyanskiy, 1973).

Examples of the hazardous movement of ships at a higher speed through the open floating ice may be descriptions of several ice accidents:

1. Two timber carriers (ice category L1, power 4000 kW) during their movement in ballast behind the icebreaker at an average speed of about 8 knots through the open floating ice with a concentration of 4/10-7/10 received damages as a result of collision with debris of old ice fields. Damage areas on the first ship covered forepeak and two fore holds and it sank. The second ship was holed several times above the second bottom in the way of the first hold and remained afloat.
2. A multi-purpose icebreaking cargo ship (ice category ULA, power 15400 kW) sailing independently in ballast at an average speed of 10-12 knots through the old open floating ice was extensively damaged in the forepeak and in the middle part of hull in the way of the second bottom. Dents up to 210 mm deep and cracks with an opening of up to 40 mm resulted in partial flooding of corresponding compartments, but thanks to the presence of second boards holds were not flooded.

The above stated convincingly shows that navigation under the icebreaker support in open floating ice of considerable thickness is of the greatest danger for cargo ships. Methods of the assessment of the power level implies just the above scenario when ice loads upon the ship's hull do not exceed admissible values.

2. MAIN PRINCIPLES OF THE ELABORATION OF THE PROCEDURE

2.1. Calculation of admissible speeds

The ship's ice propulsion is influenced by environmental factors as well as technical characteristics and operational capabilities of ship. The first ones are characterized by thickness h and concentration C of ice, second ones – by the speed in open water V_{max} and icebreaking capability in compact ice $\bar{h}_{max}$ at a maximum power N_{max} of the propulsion plant. In the case when ship is moving at a restricted power level N_j its ice propulsion may be defined by two values – V_j and $\bar{h}_j$. This assertion is true on the assumption of the linear character of the dependence of speed on the ice thickness (Figure 3).

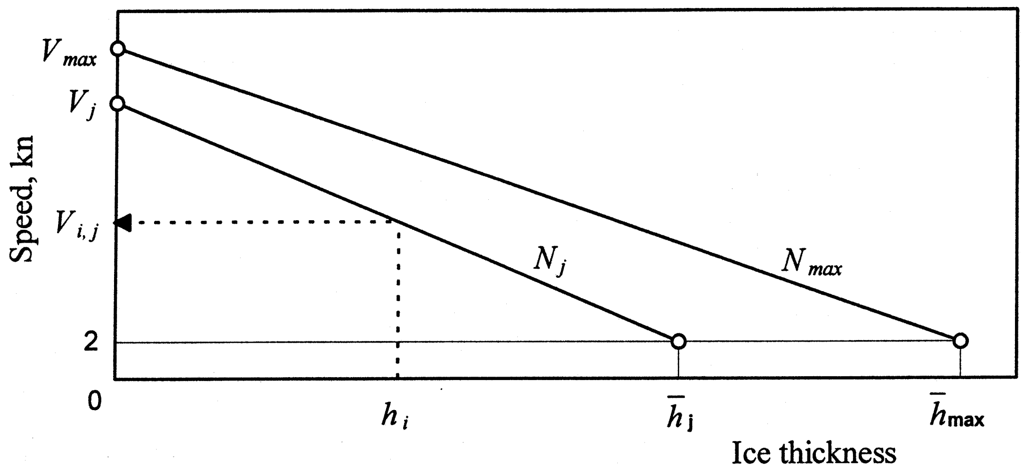

Figure 3. Diagram of the ice propulsion at maximum and restricted power levels

When moving at a restricted power N_j through ice with a thickness h_i, ship's speed $V_{i,j}$ [in knots] as well as parameters V_j [in knots] and $\bar{h}_j$ are determined by formulas (1) - (3), where m and n are exponents:

$$V_{i,j} = V_j - k\,(V_j - 2)\, h_i \,/\, \bar{h}_j \text{, kn} \qquad (1)$$

$$V_j = V_{max}\,(N_j \,/\, N_{max})^n \text{, kn} \qquad (2)$$

$$\bar{h}_j = \bar{h}_{max} - \bar{h}_{max}\,(1 - N_j \,/\, N_{max})^m \text{, m.} \qquad (3)$$

Parameter k of the first equation, apart from ice concentration C, takes into account the effect of the relative breadth b, i.e. the ship's breadth B_s / icebreaker breadth B_I ratio with corresponding factors k_1 and k_2 and exponents p and q.

$$k = (k_1 + k_2\, b^p)\, C^q. \qquad (4)$$

The above dependences establishing relation between the achievable speed and principal parameters allow assessing the effect of each of them. As an example, Figure 4 presents a family of curves characterizing the ice propulsion of ship of ULA category when moving under the support of an icebreaker through open floating ice with a concentration of 5/10-6/10. Ranges of varied values were as follows: ice thickness – 0-5 m, power – 10-100 %.

Analytical relationships have been obtained on the basis of full-scale data gathered in the course of numerous tests of ships of the Russian fleet in the Arctic (Tsoy and Bogdanov, 1983).

2.2. Calculation of ice loads

The determination of design ice loads is based on the solution of the hydrodynamic problem of the collision of ship with a mass *M* moving at a speed *V* against an ice floe (Popov, Faddeev, Kheisin and Yakovlev, 1967; Kurdyumov, Tryaskin and Kheisin, 1979).

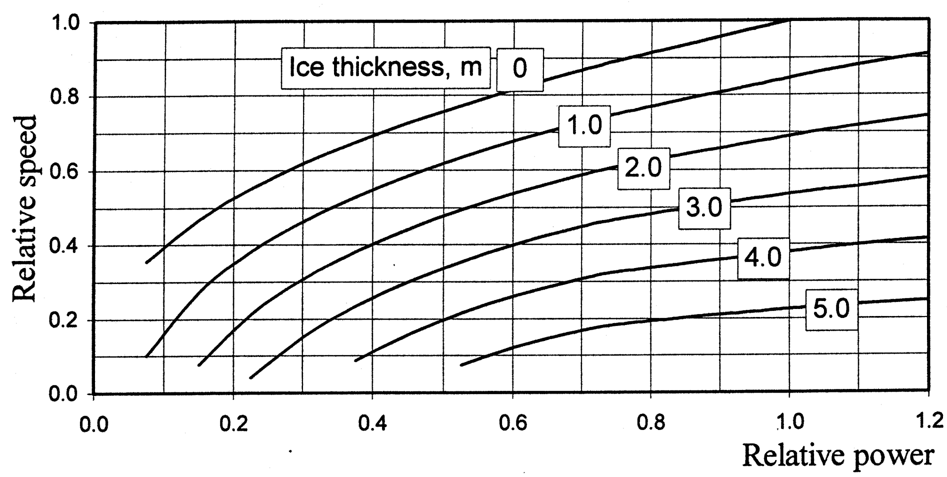

Figure 4. Changes of propulsion at different power levels of an icebreaking cargo ship in ice of different thickness with a concentration of 5/10-6/10

As a result, these authors have developed a calculation procedure, where for the determination of the ice load intensity *p* the following formula was suggested:

$$p = 0.61 V^{13/24} M^{1/6} (2R)^{-1/12} a_p F_p \text{, kPa} \qquad (5)$$

where R - conventional floe radius, m; a_p - ice crushing strength factor, $kg^{5/6}(m\ s)^{-35/24}$; F_p - hull form influence function. Besides, values of main parameters upon which the intensity of ice loads depends are functions of the area of navigation, season of operation and ship's ice category.

As an example, Figure 5 presents relationships obtained by formula (5) for a ship of the ULA category following the icebreaker. Calculated figures have been reduced to a relative form all values of speeds V being brought into correlation with speed in open water V_{max} and loads upon plating p – with load p_{MRS} regulated by Rules of the MRS in dependence on the ship's category. The latter value is determined by formula (6) into which the ship's displacement D [t], angles α [degree] between tangents to waterline and β [degree] – to frame at the point of impact enter in an explicit form.

$$p_{MRS} = 10\, a_1 f(D) f(\alpha^2/\beta)^{1/4} \text{, kPa} \qquad (6)$$

Coefficient a_l is function of the ship's ice category and takes values: 0.38 for L1, 0.54 for UL and 1.0 for ULA.

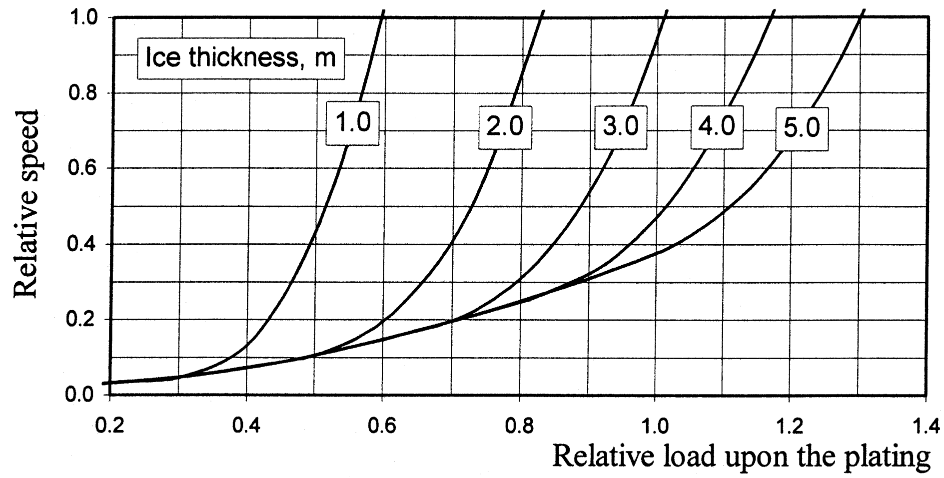

Figure 5. Interrelation between speed and ice loads upon the ship's plating in ice of different thickness

2.3 Calculation of safe speeds and the selection of power

Equations (1)-(5) establish relation between speed, power, thickness and concentration of ice as well as intensity of the ice impact upon the ship's hull. Combined solution of these equations in view of the safe ice navigation criterion p_{MRS} (6) allows determining safe (as to the power developed) modes of the movement of ships in ice. As an example, zones which are dangerous for ships of the ULA category are shown in Figure 6 as hatched regions. Outside these zones the safety of ships is ensured at any level of power. In this case a maximum level of power exists at which the probability of damage is excluded at any ice thickness ($C = const$). Its exact value is defined by a point where tangent to the curve bounding the dangerous zone is parallel to the ordinate.

In accordance with the above scheme, at $C = var$, $h_i = var$ and $N_j = var$, authors have made numerous calculations for Russian ships of L1, UL and ULA categories resulting in the obtaining of dependences of the safe power level on the concentration of ice (Figure 7).

Analysis of the results obtained has shown good compliance between the MRS requirements and the operational experience of ships of UL and ULA categories on the NSR. As a rule, during the operation of ships of these categories in the Barents and Kara Seas there are no serious hull ice damages. For L1 category ships real ice loads turn out to be excessive this being confirmed by high level of the damageability. Principal way permitting to reduce the probability of ice damages is the restriction of power. However, it is not advisable to reduce power below the set value because on ships of this category power is selected based on the speed in open water, and not from the icebreaking capability which is usually about 0.3 m thick ice for these ships. High damageability of ships is indicative of the necessity to review classification requirements of the MRS to ice ships, including the analysis of the possibility of making MRS requirements closer to the unified IACS requirements.

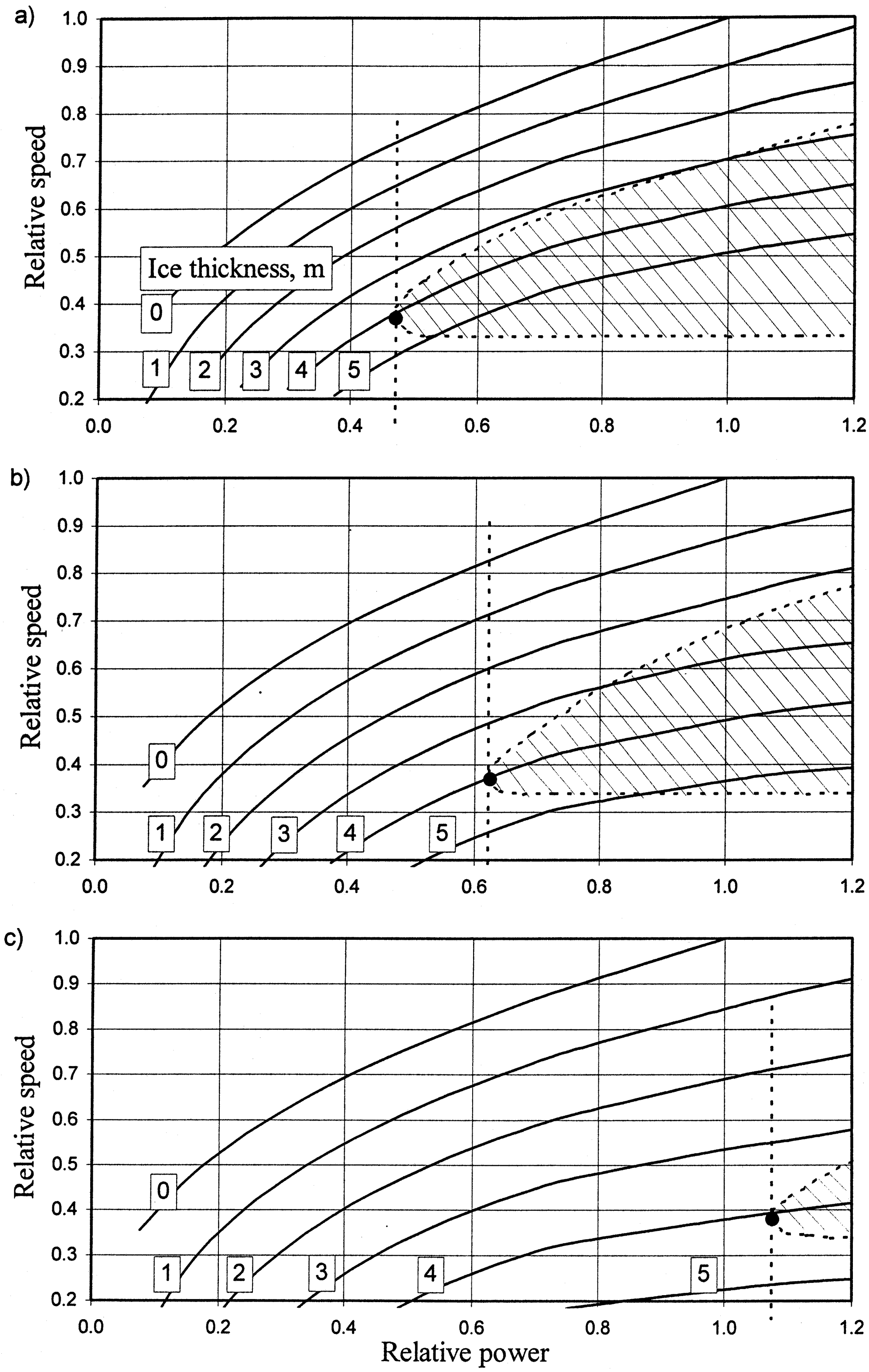

Figure 6. Zones of dangerous speeds during the movement of the ULA category ships through ice with a concentration of 3/10-4/10 (a), 4/10-5/10 (b) and 5/10-6/10 (c)

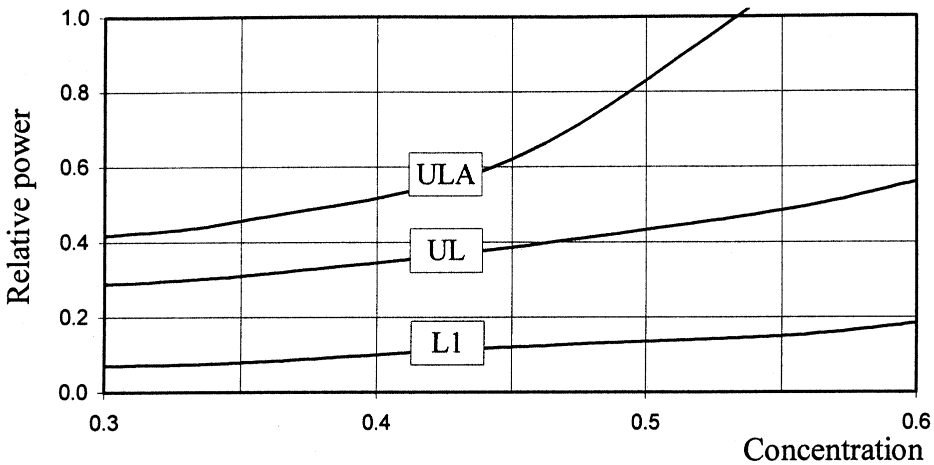

Figure 7. Influence of the concentration of ice on the safe power level of ships of different categories

3. CONCLUSION

While specifying ice hull strengthenings of polar ships there is no necessity of imposing for them a particular requirement as to the power of a propulsion plant. Icebreaking capability, i.e. maximum thickness of ice broken through by a ship in steady motion should be adopted as an important operational criterion in the classification of polar ships. The power is taken into account, in an indirect way, as one of the parameters in the calculation of ice loads, but is selected under the condition of ensuring the needed level of the icebreaking capability. As the regime of movement through the compact ice at low speeds in the context of strength is not a crucial factor, ice loads are calculated for the most dangerous scenario – for the movement at considerable speeds in broken ice and through ice field debris of different concentration. Criterion of the safe movement under these conditions is the inadmissibility for ice loads to exceed the design level specified by the MRS for ship of a certain ice category.

4. REFERENCES

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