Ships in ice - a review
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Ships In Ice - A Review

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ABSTRACT

A historical review of the literature on the performance of ships in ice is given from 1888 to 2004.

INTRODUCTION

The object of this paper is to provide an up-to-date (2004) review of the scientific literature on ship performance in ice. This forms an updated version of my previous review (Jones 1989), now 15 years old. It considers only unclassified work in the open literature and, unfortunately, probably gives too much emphasis to those papers written in English. It was not the intention to deal with the construction of, or strength of, icebreaking ships, nor is the science of modelling discussed in any detail.

HISTORICAL REVIEW

To 1900

Runeberg (1888/89) published the first scientific paper on icebreakers with particular reference to the Baltic. He discussed both continuous icebreaking and "charging" and derived expressions for the "vertical pressure at the bow", the "thickness of ice broken", and the "total elevation at the fore-end" calculated from ship geometry for the case of continuous icebreaking. He claimed that the results agreed, "tolerably well" with the actual performance of six ships. He recognized the importance of hull-ice friction on resistance, taking, without any apparent justification, a coefficient of friction of 0.05, as well as the role of the stem angle of the bow: "…the vertical component should be as large as possible. This is effected by making the bow very sloping at the waterline." This is still true today. Nothing else was published in the 19th Century.

1900 – 1945

Kari (1921) gave, in a brief note, some empirical equations for determining the required power, displacement, length, and draught of an icebreaking ship but no derivation or justification for them was given. He, also, recognized the importance of low stem angle to provide a downward force. Simonson (1936), in what would appear to be the first contribution from North America, was the first to recognize the importance of the strength of the ice and, referring to some experiments at the University of Illinois (Beach et al. 1895) gave a tensile strength of freshwater ice as 102-256 psi (0.7-1.8 MPa) for temperatures of 19.4° to 23° F (-7° to –5° C). He also showed that the stem angle was important and derived a simple equation for stem angle as a function of thrust, vertical force, and trim angle. He concluded "the maximum thickness of ice that can be broken by a given ship without stalling depends upon the limiting angle that can be built into the bow", and he added "… the frame sections, they should show a marked flare at the waterline to relieve the crushing force of the ice".

The only other pre-World War II paper was a detailed analysis by Shimanskii (1938) who employed a semi-empirical method for investigating continuous mode icebreaking resistance. He developed several parameters for icebreakers, which he termed "conditional ice quality standards", i.e. the form of the equation was developed but certain coefficients in the equation had to be determined from full-scale data. This paper must have influenced the design of the seven large icebreakers built by the Soviet Union at the end of the 1930's.

During the war an unconventional use of ships in ice was explored, namely to build aircraft carriers out of ice. The Habbakuk project (Gold, 1993) has now been well documented and while it led to much Canadian research on ice properties, no such carrier was ever built.

1945 - 1960

After World War II, Johnson (1946) described the U.S. Coast Guard's icebreaking vessels and experience in considerable detail. His comprehensive paper was more concerned with their strength and design rather than their performance. He described the *Wind-class* icebreakers in detail, which had operated around Greenland and the Russian Arctic during the war. Vinogradov (1946) described some of the Russian experience as well as giving an equation for the downward icebreaking force developed.

A significant contribution to the literature was made by Jansson (1956[a] and 1956[b]) with a major review article. He discussed in detail the history of icebreaking from what he considered the earliest true icebreaker, *Eisbrecher 1*, which operated between Hamburg and Cuxhafen and was built in 1871, their bow shapes and propellers, to 1956. He described the history of the bow propellers, which originated with ships operating on the Great Lakes where pack ice was a major problem. There, vessels that got into difficulties were able to force their way through by backing into the ice. The natural consequence was that ships were built with bow propellers. Thus, in 1888, the ferryboat *St. Ignace* was built, with a stern propeller driven by 2000 hp, and fore propeller by 1000 hp. The primary action of the fore propeller is to wash away water and broken ice from the fore end of the ship and thus reduce friction between the ice and the bow sides of the ship. As mentioned previously, towards the end of the 1930's the Soviet ice breaking fleet had been augmented by 7 large icebreakers, designed for work in Arctic waters with three stern propellers, as it would be useless to try and break the hard polar ice with fore propellers. Seven *Wind-class* ships were built in U.S.A. during and after the 2nd world war, as well as the *Mackinaw*, all diesel electric with one fore propeller and two stern. For operations in the Arctic, the fore-propeller could be removed and all the power (10,000 HP) could be split between the two stern propellers. A major advance after the war was the first icebreakers equipped with <u>two</u> bow propellers. This idea originated with the *Abegweit*, a diesel electric ferry built in Canada in 1947 for operations in the Northumberland Straits. The Finnish *Voima*, built in 1953, was the first real icebreaker to be equipped with two bow propellers and two stern. However, the interest in Arctic type icebreakers without bow propellers also increased in the mid-fifties, particularly in Canada.

Jansson (1956[a] and 1956[b]) also discussed the science of icebreaking. He quoted, without reference, values for the physical properties of freshwater ice, apparently at –3^{o}C, as:-

Elastic Modulus = 70,000 kg/cm^2 (6,900 MPa)
Tensile and bending strength = 15 kg/cm^2 (1.5 MPa)
Compressive strength = 30 kg/cm^2 (2.9 MPa)
Shear strength = 7 kg/cm^2 (0.7 MPa)

and said he had failed to find any reliable values for sea ice. He said that the strength increased with lower temperatures and even followed a rule that "… ultimate strength is approximately proportional to the square root of the number of degrees below freezing point." No details were given about these experiments, which is unfortunate. He also quoted values of the coefficient of friction between ice and metal as 0.10 to 0.15 for fresh, or Baltic, ice and 0.20 for salt water and polar ice. He gave a simple formula for the total ice resistance as:-

$$R_{ice} = (C_1 h + C_2 h v^2)\, B \qquad (1)$$

where C_1 and C_2 are experimental constants, h is ice thickness, v is vessel speed and B is breadth of vessel at waterline.

In December 1957 the *Lenin* was launched in Leningrad (St. Petersburg). It was the first atomic or nuclear powered icebreaker and represented a major technological achievement (Alexandrov et al. 1959). It claimed to have a cruising speed of 2 knot in ice 2.4 m (8 ft) thick, and could remain at sea for one year.

At a Society of Naval Architects and Marine Engineers (SNAME) Spring Meeting held to celebrate the opening of the St. Lawrence Seaway, German (1959) and Watson (1959[a][b]) both reviewed the Canadian experience and described the icebreakers then in service and those planned for the Canadian Department of Transport. Thiele (1959) described the technical aspects of icebreaking operation stressing four problems including friction, and Ferris (1959) discussed the proportions and forms of icebreakers.

1960 – 1985

The vast majority of the literature has been published since 1960. The *Manhattan* voyage in 1969, and the dramatic rise in oil prices in 1973 and again in 1979, which led to a promise of extensive Arctic development, contributed to the importance of icebreaker design and to a corresponding interest in structures for use in ice-covered waters. The advent of model tests, ice tanks, analytical and numerical techniques has meant a more scientific approach to the subject. One of the first model tests was described by Corlett and Snaith (1964), who used a wax-like substance for their ice, for the *Perkun,* a small Baltic icebreaker.

Kashteljan et al. (1968) are usually credited with the first detailed attempt to analyze level ice resistance by breaking it down into components.

They gave an equation for the total ice resistance, R_{TOT},

$$R_{TOT} = R_1 + R_2 + R_3 + R_4 \quad (2)$$

where:-
R_1 = resistance due to breaking the ice
R_2 = resistance due to forces connected with weight (i.e. submersion of broken ice, turning of broken ice, change of position of icebreaker, and dry friction resistance)
R_3 = resistance due to passage through broken ice
R_4 = water friction and wavemaking resistance

Their equation is (without R_4)

$$R_{TOT} = k_1\mu_o B\sigma h + k_2\mu_o B\rho_i h^2 + k_3 \frac{1}{\eta_2} B^{k_4} v^{k_5} \quad (3)$$

where σ is ice strength, B is ship beam, h is ice thickness, v is ship speed, and ρ_i is the density of ice. μ_o and η_2 are related to Shimansky's ice cutting parameters and k_1, k_2, k_3, k_4, k_5, are coefficients experimentally determined (0.004, 3.6, 0.25, 1.65, and 1.0 respectively). This equation was developed from model and full-scale tests of the *Ermak*.

Lewis and Edwards (1970) gave a good review of previous work and derived the equation

$$R_{im} = C_o\sigma h^2 + C_1\rho_i gBh^2 + C_2\rho_i Bhv^2 \quad (4)$$

where R_{im} = mean resistance excluding water
g = acceleration due to gravity
C_o, C_1, C_2 are non-dimensional coefficients to be determined experimentally.

The first term represents ice breaking and friction, the second accounts for all resistance forces attributable to ice buoyancy, and the third accounts for all resistance forces attributable to momentum interchange between the ship and the broken ice. They then non-dimensionalized the equation by dividing by σh^2 to get

$$R' = C_o + C_1 B' N_\Delta + C_2 B' N_I \quad (5)$$

where $R' = R_{im}/\sigma h^2$, non-dimensional mean ice resistance
$B' = B/h$, non-dimensional beam
$N_\Delta = \rho_i gh/\sigma$, volumetric number
$N_I = \rho_i \sigma/v^2$, inertial number

and then obtained a best fit with full-scale and model-scale tests of *Wind-class*, *Raritan*, *M-9* and *M-15* with C_0=0.146, C_1=8.840, and C_2=5.905. They went on to analyse the *Wind-class* data more thoroughly in a similar non-dimensional way, and showed best-fit curves between the full-scale *Wind-class* data and their semi-empirical equation utilising (a) all data and (b) just model data. Their model data, however, predicted a v^2 term, which was not found in the full-scale data. They included a snow cover term in their regression analysis of the full-scale data, which gave an added resistance of about 2 long tons/inch (8kN/cm) for the *Wind-class* icebreaker.

White (1970) gave a purely analytical method for calculating bow performance. His major contribution was to identify those qualities of a bow that would be desirable for (a) improved continuous icebreaking, (b) improved ramming and (c) improved extraction ability. He concluded that there were only three qualities that would improve all three capabilities simultaneously namely;

(a) decrease of spread angle complement (i.e. a blunter bow)
(b) decrease of the coefficient of friction
(c) increase of thrust.

He proposed a bow form, shown in Fig. 1, which incorporated these features. This form was used on the *Manhattan* for its voyage in the Arctic.

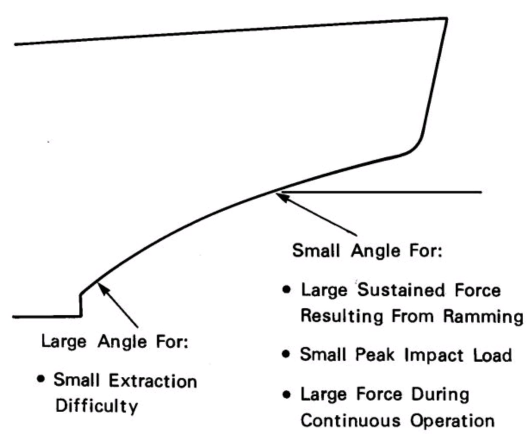


Fig. 1 White's (1969) recommended bow form for a polar icebreaker, as used in the design of the *Manhattan.*

Crago et al. (1971) described a set of model tests in "wax-type" ice on 11 icebreakers. By considering a simple bow geometry and the vertical force acting on the ice sheet, they derived a theoretical equation for the ice thickness, h, broken:-

$$\frac{h\sqrt{\tau}}{\sqrt{T}} = \frac{1.53}{\sqrt{\tan(i+\beta)}} \qquad (6)$$

where τ = ice tensile strength, T= thrust, i = stem angle and $\beta = \tan^{-1}f$, where f is the coefficient of friction.

They then plotted $(h\sqrt{\tau}/\sqrt{T})$ against $(1/\sqrt{\tan(i+\beta)})$, as shown in Fig. 2, and obtained good correlation between equation (5) and their model tests. They also had one full-scale data point from the *CCGS Wolfe*. While the model data did fit their equation quite well, but not with a slope of 1.53, it seriously over-predicted the ice thickness broken for a given thrust, compared to the one full-scale point.

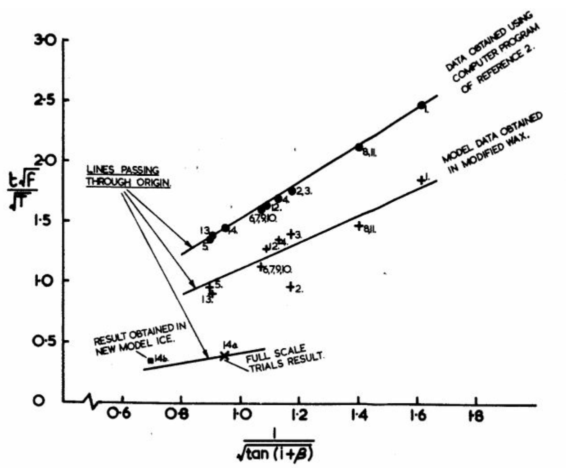


Fig. 2. Showing the relationship by Crago et al. (1971) between their model data, one full-scale point, and one "new model ice" result and their equation for thrust.

However, they pointed out that the one model test in "new model ice" was in good agreement with the full-scale point, as shown in Fig. 2. It is, perhaps, not surprising that the agreement with the full-scale data was poor, since they considered only a simple breaking term in their equation and neglected all others, such as submersion of ice pieces, as had been considered by Kashteljan et al. (1968). Crago et al. (1971) also measured the friction of a dry, unpainted, steel plate toboggan against a dry crusty snow cover. They obtained mean values of static, f_s, and kinetic frictions, f_k, of:-

$$f_s = 0.30 - 0.35 \qquad (7)$$
$$f_k = 0.07 - 0.23$$

Enkvist (1972) made a major addition to the literature of ship performance in level ice. He conducted model tests for three ships; *Moskva-class*, *Finncarrier*, and *Jelppari*, and was able to compare his results with limited full-scale data from all three. From a combination of analytical work, dimensional analysis, and a few assumptions, he derived a semi-empirical equation for ice resistance based on three terms:-

$$R_{TOT} = C_1 Bh\sigma + C_2 BhT\rho_\Delta g + C_3 Bh\rho_i v^2 \qquad (8)$$

where T = draft of ship
ρ_w = density of water and $\rho_\Delta = \rho_w - \rho_i$.

By doing model tests at low speed (v=0) as well as normal speeds he was able to isolate the velocity dependent term, and by doing tests in pre-sawn ice ($\sigma = 0$) he was able to isolate the submergence term. He was able, therefore, to determine the relative importance of the three terms in his equation. Enkvist (1972) also conducted detailed tests on the strength of his model ice, described strength tests on natural ice, and carried out a considerable number of friction tests on his model ice and on natural ice surfaces using a towed sled – the first person to describe such tests in any detail. In a later study, Enkvist (1983) applied his model-scale technique of doing tests in pre-sawn ice and creeping speeds, to 16 full-scale tests. From these tests he obtained the result that the breaking term at full-scale was greater than he had previously estimated, between 40 and 80% of the total zero speed resistance, with the larger figure applying to smaller ships. This is probably still the most reliable published estimate of the importance of the breaking term at full-scale. At model scale, Poznak and Ionov (1981) showed that for a "medium size icebreaker" the breaking term was about 40% of the total ice resistance, and the friction term about 30%.

Johansson and Mäkinen (1973) applied Enkvist's method of analysis to model tests of a parametric series of nine bulk carrier models. Their results showed that

1. A reduction of bow angle from 82° to 20° reduced the ice resistance by about 60%.
2. an increase in length of 38% increased the ice resistance by about 30%. A decrease in length of 38% decreased the ice resistance by 10%.
3. An increase in beam of 33% increased the ice resistance by about 40%. A decrease in beam of 27% reduced the ice resistance by about 36%.

They later (Virtanen et al., 1975) investigated the effect of draft and found no effect on resistance, within the errors of their experiment.

Edwards et al. (1972) conducted an extensive set of full-scale and model-scale tests on a Great Lakes icebreaker, the *USCGC Mackinaw*. Their full-scale "resistance" was, however, determined indirectly as the sum of the estimated thrust in each of the three propeller shafts (two aft, one forward) determined "almost exclusively" from electrical readings of current, voltage, and r.p.m.

Milano (1973) made a significant advance in the purely theoretical prediction of ship performance in ice. He considered the energy needed for a ship to move through level ice, which varied somewhat with ice thickness. For example, for very thick ice the ship moves through the ice-filled channel (E_1), impacts the various bow and cusp wedges causing local crushing (E_2), climbs onto the ice (E_3) until sufficient force is generated to cause fracture, at which time the ship falls (E_4), and moves forward, forcing the ice downward (E_5). The total energy loss due to ship motion is then written as

$$E_T = E_1 + E_2 + E_3 + E_4 + E_5 \qquad (9)$$

Then he derived explicit analytical expressions for each of these terms and compared his predictions with the data obtained on the *Mackinaw*, discussed above, (Edwards et al., 1972) the Wind-class vessel *Staten Island*, and the *Raritan.* He obtained good correlation, as shown in Fig. 3, although this correlation was dependent on the value of ice flexural strength and friction coefficient used. He, also, used a non-dimensional approach, following Lewis and Edwards, and developed a "design chart" for

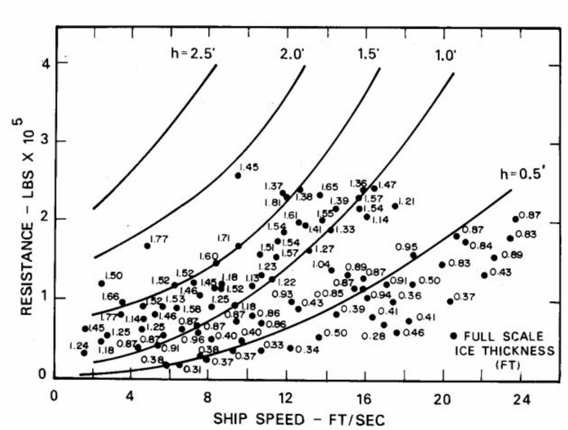


Fig 3. Plot of ship resistance versus speed for USCGC Mackinaw as a function of ice thickness, showing correlation with full-scale tests (Milano, 1973)

predicting total resistance "for all icebreakers in general and large polar-type icebreakers in particular", a somewhat ambitious exercise! In later papers Milano (1975, 1980, 1982) investigated in detail the effect on his analytical model of varying various ship or ice parameters. His proposed speed dependence, at least in thick ice, is interesting because of its complexity (Fig. 4) and shows what has become known as a "Milano hump". His explanation for this hump is related to the different mechanisms involved in the energy equation. Some experimental evidence for such a hump has been found by Tatinclaux (1984), Schwarz (1977) and Narita and Yamaguchi (1981). Milano (1975) then varied numerous ship and ice parameters and showed how this affected his calculated resistance. His plots showed the trend in resistance to be expected by varying ship parameters such as beam, block coefficient, waterplane coefficient, length, etc., and also what would happen if ice properties such as friction, tensile strength and compressive strength were altered.

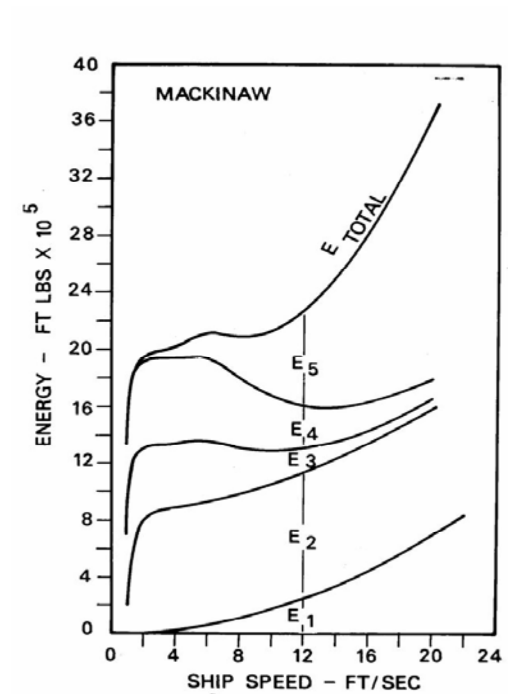


Fig. 4. Milano's (1975) plot of total energy lost versus ship speed showing component energy terms for Mackinaw in ice two feet thick, and showing the development of a "hump".

Carter (1983) has also attempted an analytical approach to ship resistance in ice. He derived a relatively simple equation for the maximum resistance to ship motion. He neglected inertial forces and buoyancy forces entirely on the grounds that the effect of upturning and submerging the ice pieces was small and could be ignored. The net total energy lost was set, in his theory, equal to that absorbed in icebreaking by bending, buckling, or crushing. However, model tests by Enkvist (1972) and others, do not bear out this assumption. Despite this, Carter (1983) obtained reasonable agreement between his theory and data for six icebreakers.

Scarton (1975) investigated the role of friction in icebreaking and specifically studied theoretically the direction of the frictional force. He derived a relationship between bow angles and the coefficient of friction such that a ship would not get stuck in the ice. Mäkinen et al. (1975) showed clearly the importance of friction in the most direct way. By attaching stainless steel plates, which had a friction coefficient of about half the remainder of the hull, to the *Jelppari*, they showed that the resistance dropped significantly, particularly at low speeds. They also compared two full-scale ships with different surface finishes as well as observing model scale effects. All showed a significant drop in resistance with reduced friction coefficient. They described tests with the *Murtaja* using different coatings at different places on the hull and found a solvent free epoxy (INERTA 160) was the best in terms of reducing friction and staying attached to the hull.

Vance (1975) obtained an "optimum regression equation" from five sets of model and full-scale data, of the *Mackinaw* (same data as used by Edwards et al., 1972), *Moskza*, *Finncarrier*, *Staten Island*, and *Ermak*. His equation was :-

$$R_{(ice)} = C_S \rho_\Delta g B h^2 + C_B \sigma B h + C_V \rho_i v^2 L h^{0.65} B^{0.35} \qquad (10)$$

where $R_{(ice)}$ is the resistance due to ice, L is length of vessel, and C_S, C_B, C_V are empirically determined values. The first term is a submergence term, the second a breaking term, and the third term is a velocity dependent resistance.

An example of a fit to his equation is shown in Fig. 5, in which the *Mackinaw* full-scale data (labeled FS) are shown fitted to his equation above (labeled FSR) and a model-scale regression to his equation (MSR) is also shown. Good agreement is found between the model and full-scale results.

Edwards et al. (1976) presented full-scale data for the *Louis S. St. Laurent* collected by analyzing ramming type tests using a non-dimensional equation:-

$$\frac{R}{\rho_w g B h^2} = 4.24 + 0.05\frac{\sigma}{\rho_w g h} + 8.9\frac{v}{\sqrt{gh}} \qquad (11)$$

which is linear in velocity. Their results are shown in Fig. 6 in which the five lines are obtained from their regression above using the values of σ and h appropriate to the "course". They compared these results to two sets of saline ice model data, one collected at a scale of 1:36 and one at a scale of 1:48.

They quote hull-ice friction coefficients varying from 0.08 to 0.48 but did not explain how these were obtained.

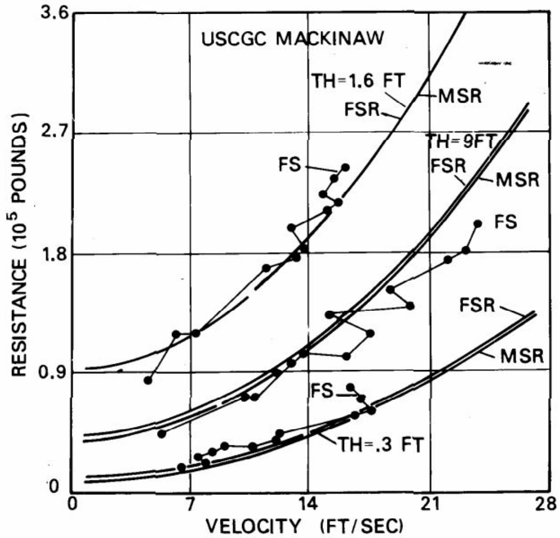


Fig. 5. Vance (1975) analysis of Mackinaw data. MSR is the model-scale regression curve (i.e. obtained from model tests) and FSR is the full-scale regression curve (i.e. obtained form full-scale tests). FS is the actual full-scale data. All for three different ice thicknesses, 0.3, 0.9, and 1.6 ft (9, 27 and 49 cm).

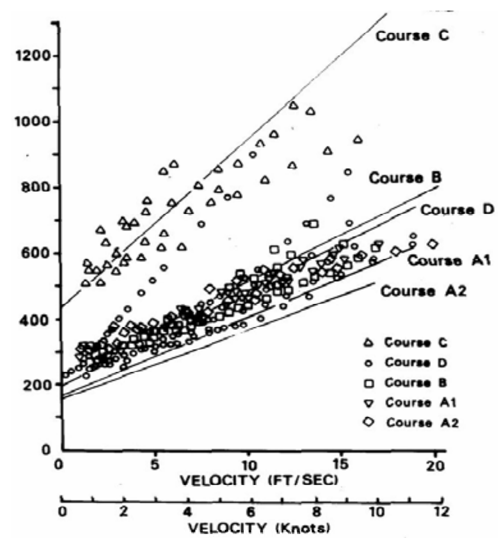


Fig. 6. Edwards et al (1976) regression of full-scale data from the Louis S. St. Laurent using values of σ and h appropriate to the "course".

They also conducted a parametric series of tests on nine different models. They concluded that level ice resistance was

(a) directly proportional to beam
(b) independent of length
(c) proportional to block coefficient, and
(d) proportional to draft.

These results are somewhat surprising, and in some disagreement with the earlier work of Johannson and Mäkinen (1973). Particularly surprising is the independence of length, since Edwards et al. (1976) had earlier shown the importance of a frictional term, which one might expect to be a function of length. They also conducted manoeuvring tests.

In a related series of experiments, Kitagawa et al., (1982, 1983, 1986) investigated the effect of parallel mid-body length, and beam, on an Arctic tanker model

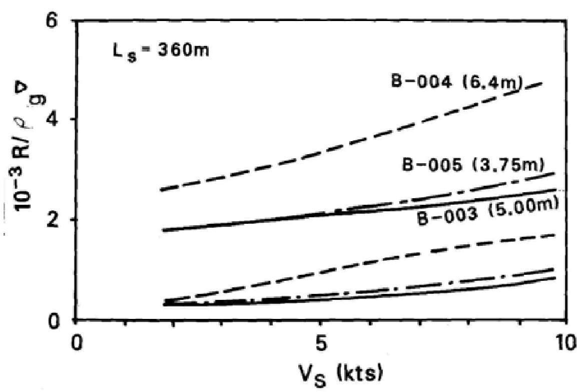


Fig. 7. Resistance per unit displacement for three Arctic tanker models of different lengths as shown, scaled-up to a ship of length 360 m (Kitagawa et al., 1982)

They found a clear increase in resistance with increase in length, using three models of lengths 3.75 m, 5.0 m, and 6.4 m. They plotted their results as resistance per unit displacement against speed at both model scale and scaled up to a 360 m long, 280,900 m^3 displacement, vessel. This involved different scaling factors for the three models, and therefore ignored differences in model ice strength, which was probably not insignificant (Kloppenburg, 1975). Their results, both at model and full-scale, indicated an optimum parallel mid-body as shown for example in Fig. 7 in which the data are scaled up to a 360 m long ship. Model B-003 has the least resistance per unit displacement and is the 5.0 m long model i.e. the middle length of the three tested, with a $L_{parallel}/L_{model}$ of 0.4. Correcting for model ice strength would have the effect of increasing the resistance of B-004 even more and reducing B-005 slightly. They concluded, therefore, that for this particular hull form, the <u>maximum length</u> of parallel body should be 0.4 L_{PP}. In a corresponding series of self-propulsion tests, they concluded that a minimum parallel body of 0.25 L_{PP} was needed top avoid excessive propeller-ice interaction. When they varied the beam of the model for a fixed draught, using values of L/B=8 and 6, they found an increase in resistance with increase in beam. However, the wider ship had a significantly lower resistance per unit displacement. They also investigated the effect of an 8^o side flare to the parallel mid-body. While this increased the level ice resistance somewhat, it had certain advantages; the open-water channel width was slightly wider, and no asymmetrical roll was observed, as had been seen with the vertical sided model. They also observed that a 5^o rise of floor in the parallel body had a significant beneficial effect in allowing broken ice pieces to rise to the surface before reaching the propellers.

In 1981, a STAR symposium held in Ottawa published a number of model tests and some full-scale data. Narita and Yamaguchi (1981) published a very detailed account of model tests, which had led to the building of the *Shirase*. First, they tested three model bows and showed that a cylindrical bow with a low stem angle of 22.5^o had less resistance than the other two, because it avoided crushing at the bow. They went on to test a triple-screw ship in resistance and self-propulsion. They also showed, at model-scale, that the resistance almost doubled as the hull-ice friction coefficient doubled from 0.1 to 0.2. Schwarz et al. (1981) published model tests of the *Polarstern*, and Juurmaa and Segercrantz (1981) stressed the importance of propulsion efficiency in ice, rather than just resistance, pointing out that while different models might have the same resistance, they could have very different efficiencies due to ice/propeller interaction. They showed that a propeller with a nozzle could have very low efficiency if it became blocked with ice.

Full-scale data for the Canadian "R-class" icebreakers were also presented at this conference (Edwards et al., 1981; Michailidis and Murdey, 1981), as well as a set of parametric variation model tests, which examined different bow forms based on the R-Class as parent (Noble and Bulat, 1981). Resistance tests only were conducted, and these, again, showed the superiority of rounded bows with low stem angle in breaking ice, but since no self-propulsion tests were conducted it is impossible to judge the overall performance of the different ships.

Vance (1980) and Vance et al. (1981) conducted full-scale tests of the 140 ft (43 m) Great Lakes icebreaker, *Katmai Bay*. He analysed his results somewhat differently from other workers, plotting Propulsive Coefficient (PC) against velocity, where

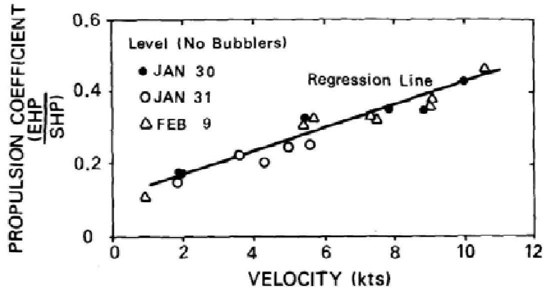


Fig. 8. PC versus velocity for *Katmai Bay* in level ice with no bubblers operating. Clearwater value, not shown, was 0.565 (Vance, 1980).

PC = EHP/SHP (12)

and EHP = Effective horsepower, SHP = Shaft horsepower. EHP was calculated from

EHP = Resistance X Velocity (13)

and resistance, R, was determined from

R = T(1-t) (14)

where T was the thrust measured on the shaft, and t was a thrust deduction factor, taken as 0.2. SHP was calculated from

SHP = Measured torque X R.P.M. (15)

He found that PC in level ice was always lower (0.12-0.45) than in clearwater (0.565) as shown in Fig. 8, and he suggested several reasons for this loss in efficiency, namely:-

1. increase in t
2. decrease in w (ice-free wake fraction)
3. decrease in relative rotative efficiency by disturbances to flow pattern by ice blocks
4. decrease in propeller efficiency for other reasons, as discussed in the paper.

Tatinclaux (1984) performed resistance tests on two models of the Katmai Bay, 1:10 scale and 1:24 scale, in level and brash ice. He found that the dimensionless ice resistance in level ice was essentially the same for both models i.e. no scale effect. Newbury and Williams (1986) did find a scale effect when testing 1:40 and 1:20 scale models of the R-Class icebreakers, but they attributed it to differences in the friction coefficient between the models. Tatinclaux's (1984) tests in level and broken ice allowed ice resistance to be divided into a submergence-inertia component and an ice-breaking component. The ice-breaking component was found to be proportional to the Cauchy Number $(\sigma/\rho_w h)$, as expected, but was influenced by Froude Number $(v/\sqrt{gh})$. In particular a rapid change in the ice-breaking resistance was found to occur at a Froude Number of 0.4-0.5, as shown in Fig. 9.

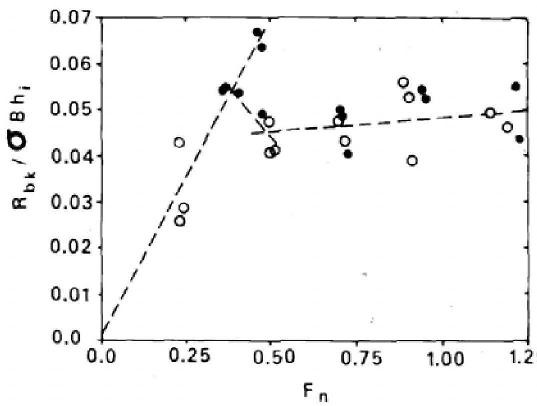
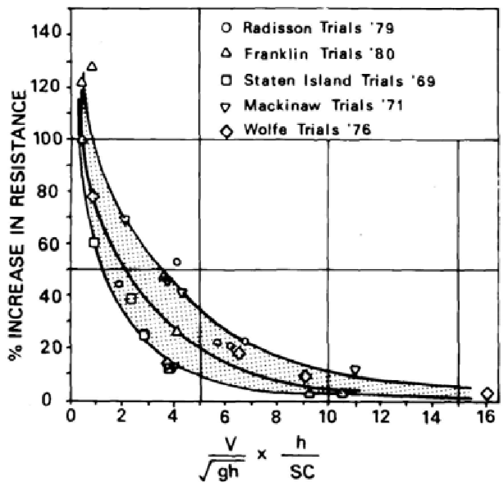


Fig. 9. Plot of $(R_{bk}/\sigma B h_i)$ as a function of Froude number, F_n (dimensionless quantities) for *Katmai Bay* model tests (Tatinclaux, 1984).

This behaviour was attributed to corresponding observed changes in the amplitude of pitching and heaving motions of the models, and may correspond to a "Milano Hump" as discussed earlier. Comparison with full-scale data (Vance, 1980) indicated that the model resistance was significantly larger, when scaled up, than the full-scale data, and several possible reasons were suggested. A further set of self-propelled model tests (Tatinclaux, 1985) showed reasonable agreement with full-scale but several possible sources of error were identified; the Froude Number was not the same for model and full-scale tests, a stock propeller was used in the model tests which might not have been as efficient the real propeller, and the model friction coefficient may have been higher than the full-scale value.

Bulat (1982) investigated the effect of snow cover on level ice resistance. He used published data from five full-scale trials (*Radisson, Franklin, Staten Island, Mackinaw, Wolfe*) and plotted the percentage increase in resistance against non-dimensional snow cover, as shown in Fig. 10.



$\frac{V}{\sqrt{gh}} \times \frac{h}{SC}$

Fig. 10. Plot of actual data points from full-scale trials to show the influence of snow cover on ice resistance (Bulat, 1982).

This was done by comparing full-scale data points with and without snow cover, but in similar ice conditions. He concluded that there was no evidence that the actual hull shape influenced ship performance in snow covered ice (at least within the range of hull forms tested) and that the relative resistance increased with decrease of speed, increase of snow cover, and decrease of ice thickness.

Lewis et al (1982) re-analysed earlier data in a different manner, the major improvement being the inclusion of a thrust deduction factor applied to their full-scale measurements. They assumed that $t_i = t_p$, the thrust deduction factor in open water tests, which they used to convert the thrust measured during ice breaking trials to resistance which could be compared to model-scale resistance measurements. This they did for the *Mackinaw*, *Katmai Bay*, and *Radisson*, plotting model-test resistance against full-scale resistance and found reasonable agreement.

Kotras et al. (1983), in a paper based on Nagle's thesis (Nagle, unpublished) describe yet another semi-empirical approach in which the total ice resistance is given by

$$R_{ice} = R_B + R_{Bf} + R_T + R_{Tf} + R_S + R_{Sf} \quad (16)$$

where R_{ice} = total ship-ice resistance

R_B, R_{Bf} = normal and frictional resistance due to breaking of level ice

R_T, R_{Tf} = normal and frictional resistance due to turning broken ice floes.

R_S, R_{Sf} = normal and frictional resistance due to submerging broken ice floes.

The resulting equation contained four empirical coefficients – these were determined from best fits to some of the data from *Katmai Bay*, *Mackinaw*, *Radisson*, *Staten Island*, and *Manhattan*. The remainder of the data, plus that used to optimize the coefficients was then plotted as "measured ice resistance" against the ice resistance predicted from their equation. The "measured ice resistance" had been obtained from the full-scale measurements by applying a thrust deduction factor as discussed by Lewis et al. (1982). 72% of the data fell between ±25% of the "perfect correlation line", which they claimed was a significant improvement over the equation given by Lewis et al. (1982).

1985-2004

This modern period has seen the development of new icebreaking forms, and a more scientific approach to the modeling of ships in ice with extensive model testing and, most recently, numerical methods. Canadian Arctic oil exploration and development led to new designs such as the *Kigoriak*, and *Terry Fox*, while other activities led to the *Oden*, double acting tankers (DAT) with Azipods, FPSO's in ice, and research ships such as the *Nathaniel B. Palmer*, *USCGC Healy*, and the converted *CCGS Franklin* now called *CCGS Amundsen*.

Baker and Nishizaki (1986) described a new bow form for an Arctic tanker and compared model tests done by several laboratories. The results were somewhat disappointing scientifically because the full-scale predictions by the three laboratories differed widely as shown in Fig. 11. Reasons for this were suggested by the authors as differences in ice modeling and analysis procedures, as well as a lack of understanding of friction and thrust deduction effects. Similar comparison work by the ITTC, Fig. 12, on a model of the R-Class icebreaker, has also shown a certain lack of agreement, but closer than the Baker and Nishizaka (1986) comparison. This disagreement is attributed to the different model ices and analysis procedures used by the tanks. However, Takekuma and Kayo (1988) apparently obtained quite good agreement in two ice tanks with both structure and ship models.

A study of the dynamics of continuous mode icebreaking (Ettema et al., 1987) using 1:48 scale model of the Polar-class icebreaker, showed that a free hull (free in pitch, heave, and roll) experienced larger values of mean resistance than did a fixed hull.

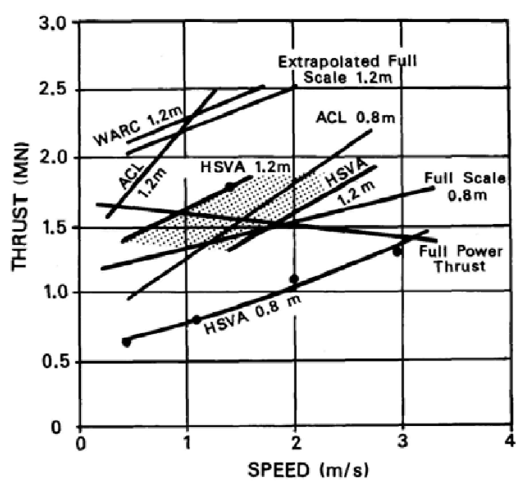


Fig. 11. Comparison of full-scale thrust predictions from three laboratories, ACL, HSVA and WARC, for the old bow of the *MV Arctic*. Ice strength = 500 kPa. Considerable differences in predicted thrust are apparent (Baker and Nishizaki, 1986).

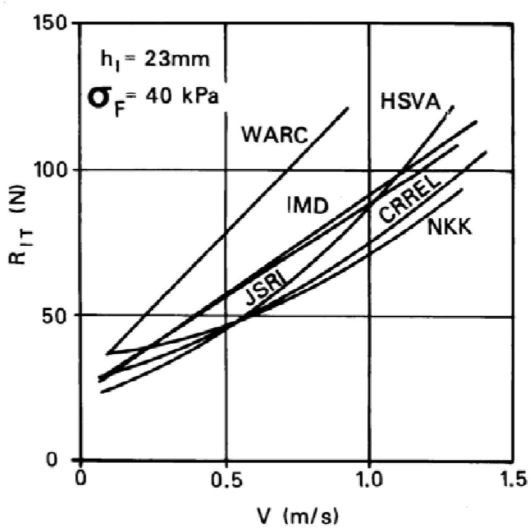


Fig. 12. Comparison of resistance tests conducted by different ice tanks on a model of the "R-Class" icebreaker (18^{th} ITTC Proceedings).

The dominant frequency of ice resistance and hull motions experienced by the free hull occurred either at integer fractions of icebreaking frequency, ω_b, or at the hull's natural frequency of coupled pitch and heave, ω_n. The fixed hull experienced cycles of resistance predominantly at frequency, ω_b. Further experiments such as these to study the dynamics of icebreaking, should help us to understand more clearly what is happening in the icebreaking process.

The 1980's saw the design and construction of icebreakers with unconventional bow forms all of which have low stem angles of approximately 20^o and are different from the classical wedge-shaped bow. These are the "spoon-shaped" bows of the *Canmar Kigoriak*, *Robert LeMeur*, and other similar designs, and the Thyssen-Waas bow form of the modified *Max Waldeck* and the converted *Mudyuq*. Fig 13 shows these types of bow at model scale, in which the bow forms of four ships are compared: an original bow of the Bernier a CCG Navaids vessel, an R-Class bow, a Beaufort Sea bow typical of the *Kigoriak*, and a Thyssen-Waas type bow.

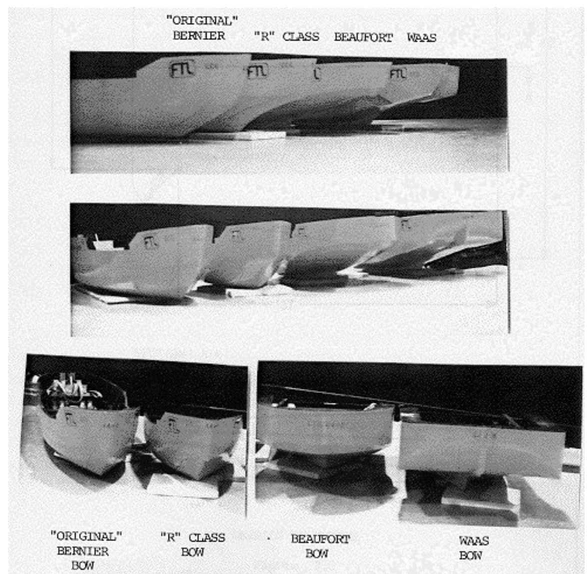


Fig. 13. Models of typical icebreaking bows showing from L-R, the original bow of a CCG Navaids tender Bernier, an R-Class bow, a Beaufort Sea type bow, and a Thyssen-Waaas bow (Glen et al. 1998).

The general design and operation of these ships has been published (Churcher et al., 1984; Ghonheim et al., 1984; Freitas and Nishizaki, 1986; Schwarz, 1986[a]; German, 1983; Tronin et al., 1984; Johansson and Revill, 1986) but little in the way of full-scale trials or even detailed model tests. Hellmann (1982) described model and full-scale tests with the *Max Waldeck* before and after conversion to a Thyssen-Waas bow form. He showed an approximate 25% drop in resistance model tests, and 100% increase in speed, for the same power, in propulsion tests. Full-scale data gave reasonable agreement. Enkvist and Mustamäki (1986) have published results of model and full-scale tests of a bow, which was derived from tests of a circular and square bow form. They showed, first of all, that ice crushing at the stem of two small ships accounted for 20-40% of the total low-speed resistance. By cutting slots in the ice ahead of the stem and removing the ice, the resistance was reduced by this amount. Clearly this is the major advantage of low stem angle, non wedge-shaped bows. Their model tests compared a circular bow, a square bow, and the original *Mudyuq* bow, and showed that the circular bow had the lowest resistance. They then selected an experimental bow for further testing and analysis and after model testing, made a full-scale bow to attach to the *Protector*. Their full-scale results showed a considerable improvement in the *Protector*'s performance in level ice although they admitted that the original *Protector* was not particularly efficient. They measured full-scale friction using two panels installed on the bow of the *Protector* and obtained somewhat scattered results as shown below:-

Low pressure panel, f = 0.16-0.26
High pressure panel, f = 0.05-0.13

Similar panels were installed on the *Polarstern* (Schwarz et al., 1986), and results (Schwarz, 1986[b]; Hoffmann, 1985) also show a decrease in friction coefficient with increasing normal force. Good correlation with model data, of the performance of the new *Protector* bow, was obtained with a model friction coefficient of 0.05 as against the measured full-scale values shown above. A major disadvantage of the bow was higher slamming pressures. A similar disadvantage was noted by Freitas and Nishizaki (1986) who tested an ice class bulk carrier model with a Thyssen/Waas bow, which otherwise showed considerable improvement in icebreaking ability. This bow form was fitted to the *Mudyuq* and results showed that in snow-free ice, hull speed increased 50 to 100% without the aid of the "Jastram hull lubrication plant" (Varges, 1987, 1988). Improvements in turning circle and in clearing of ice from a broken channel were also reported, as well as agreement with model tests. A series of comparison tests by Glen et al. (1998) on four bows, one of which was a Thyssen-Waas form, showed that while it was superior in breaking level ice, this had little real significance on the overall performance of a Navaids vessel in service with the Canadian Coast Guard, which spent a lot of its time in open water. For such a vessel a conventional R-Class type bow was superior overall.

An interesting development in the mid-80's was a full-scale towed resistance trial of the *Mobile Bay* in uniform level ice (Zhan et al., 1987). In principle, this parallels the open water trials of the *Greyhound* (Froude, 1874) and *Lucy Ashton* (Denny, 1951). While such tests are clearly difficult to perform, in theory they provide a direct measurement of full-scale resistance. They also conducted full-scale propulsion tests. They found the best fit to their towed resistance results was with the equation (one of 15 equations that they analyzed):-

$$\frac{R_i}{\rho_w g B h^2} = C_o + C_1 \frac{v^2}{gB} \frac{L}{h}^{3} \qquad (17)$$

where $C_o = 4.25$
$C_1 = 3.96 \text{ X } 10^{-5}$

Which implies a v^2 dependence of resistance on speed, as well as an h^2 dependence. From their propulsion data they determined a thrust deduction fraction as a function of ice thickness, but as I have commented in a discussion to their paper, their range of thickness (and strengths) was so small, and the normal errors associated with thrust and torque measurements so large, that such a relationship is difficult to justify. However, it is a valuable addition to the literature and, hopefully, could be repeated in the future with significantly different ice conditions, for comparison.

Since 1990 the major development has undoubtedly been that of using podded propellers in ice with double acting tankers (DAT), which has taken place principally in Finland (Juurmaa et al., 2001) and appropriate for the Baltic Sea. Starting in 1990 with a 1.3 MW buoy tender, *MV Seili*, podded propellers have been used in conjunction with designs which allow the ship to go astern in heavy ice and forward in open water and light ice. Full power can be applied in either direction by rotating the Azipod. Fig 14 shows the stern of the *Seili* with an Azipod fitted.

Fig. 14. *MV Seili*, the first ship to be fitted with an Azipod

The development has now progressed to a 16 MW tanker with one Azipod unit, two of which were recently (2003) delivered to Fortum Shipping by Sumitomo Heavy Industries, for use in the Baltic.

The idea was to design an efficient icebreaking stern for the vessel, while keeping an efficient open water bow. Fig. 15 shows one of the ships going astern in ice during its ice trials.

Fig. 15. A 106,000-dwt Masa-Yards-developed DAT crude carriers built by Sumitomo Heavy Industries in 2003.

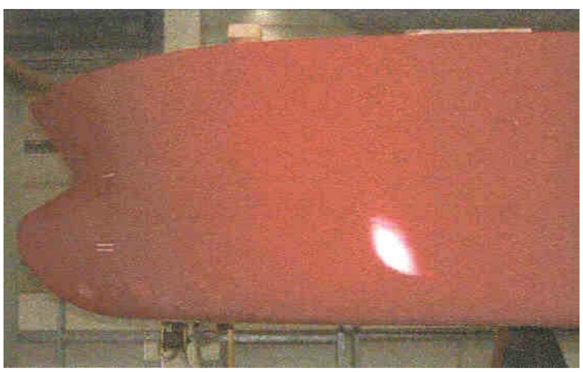


Fig. 16. Bow form of the DAT in Fig. 15.

When entering a ridge field at slow or moderate speed, a DAT vessel lets its pulling propeller chew up the ridge and slowly pull the vessel through, without any need for ramming. Whether this would work on a massive arctic ridge without damage to the propulsion unit seems unlikely, but the vessels are well suited to Baltic ice conditions.

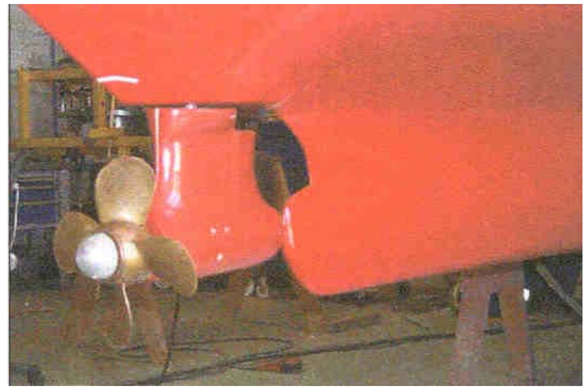


Fig. 17. Stern model of the DAT in Fig. 15.

The most recent new icebreakers in North America are the *Nathaniel B. Palmer* (1991)and the *USCGC Healy* (2000) designed principally to be Antarctic and Arctic research/supply ships. The *Healy* is shown in Fig. 18.

Fig. 18. *USCGC Healy* entering St. John's harbour.

It has a conventional bow form with two conventional propellers. A complete set of trials in ice was conducted with this ship in 2000 with the results published in the literature (POAC 2001). The design icebreaking capability of the Healy was for continuous icebreaking at 3 knots through 4.5 ft (1.37 m) of ice of 100 psi (690 kPa) strength. The full-scale trials were conducted in ice half this strength, but by extrapolation from model-scale tests (Jones and Moores, 2002) the ship was shown to meet this requirement.

An icebreaker for the Great Lakes, GLIB, to be named *USCGC Mackinaw* and scheduled for delivery in October 2005 will have two Azipod units of 3.3 MW each. The ship, shown in Fig. 19, is

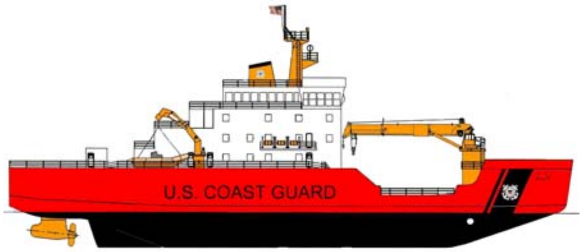


Fig. 19. Profile of the GLIB to be delivered in 2005.

designed to break 32"(0.82 m) of ice at 3 knots ahead and 2 knots astern. In addition it should be very maneuverable with the Azipod units, which can turn 360°. Full-scale trials of that ship will also be conducted.

Fig. 20. The Terra-Nova FPSO off Newfoundland

With the advent of the offshore oil industry in Newfoundland two FPSO's have been built for the ice infested waters, the *Terra-Nova FPSO*, shown in Fig. 20, and the *Sea Rose*. These ships are not icebreakers but are ice strengthened and can withstand pack ice forces. They are designed to disconnect if threatened by a large iceberg. Smaller icebergs are towed away by support ships, as shown in Fig. 21.

Fig. 21. Towing a medium sized iceberg off Newfoundland

The oil is transported to market in ice strengthened tankers. At IOT we have been conducting a major research program into the impact of a ship with a small iceberg, or bergy bit. The results remain confidential for a little longer but Cumming et al. (2001) has described the extensive model and full-scale experiments including full-scale impact tests with the *Terry Fox*, shown in Fig. 22.

Fig. 22. The *Terry Fox* impacting a bergy bit.

The last twenty years has seen advances in ship-ice modeling techniques both experimental and numerical. Jones et al (1989) has described the different model ices in use throughout the world. In short, large ice tanks have allowed model scales of around 1:20 and at that scale the model ice properties of strength, stiffness and brittleness are reproduced remarkably well. Different tanks have used different chemical dopants to give the best ice properties at model scale, and at IOT we have always used a combination of Ethylene Glycol (EG, 0.39%) aliphatic detergent (AD, 0.036%) and sugar (S, 0.04%), thus giving us EGADS model ice. The glycol acts like the salt in real sea ice forming brine, or glycol, pockets on freezing, the detergent reduces the surface tension at the growing interface allowing more dopant to be included in the model ice, and the sugar acts as a long chain molecule to keep the grain size small as the ice grows. The resultant model ice and its properties have been described by Timco (1986) who concluded that it was a "significant improvement in model ice technology".

Another other major advance in the last twenty years has been in numerical methods to predict resistance in ice. Valanto (2001) has developed a 3-D numerical model of the icebreaking process on the ship waterline, which predicts the forces on the waterline. These were compared with load panel measurements on the *MS Uisko* with good agreement. He then calculated the resistance in ice for several ships using his numerical model, combined with a semi-empirical model of Lindqvist (1989) for the underwater components of resistance, and obtained good agreement with measured values, as shown in Fig 22.

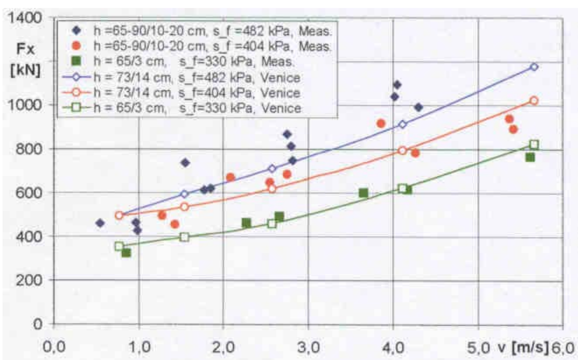


Fig. 22. Measured and computed resistance values in level ice for the Otso-class icebreakers (Valanto, 2001).

In future, further developments in numerical methods will continue to take place

SUMMARY

Enormous technological progress has been made in the last 100 years from *Eisbrecher I* to Double Acting Tankers. Ice will continue to be important factor for oil exploration and production in certain offshore areas as well as for marine transportation. Increased tourist, as well as commercial, traffic in the Arctic and Antarctic will bring demands for safer and more efficient travel in such areas. Modelling will continue to improve with emphasis on numerical simulations as well as physical modeling.

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