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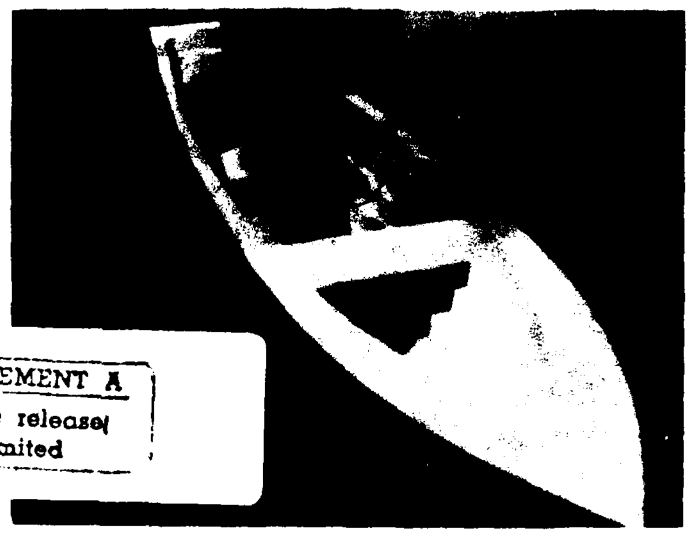
Ship model testing in level ice
An overview





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For conversion of SI metric units to U.S./British customary units of measurement consult ASTM Standard E380, Metric Practice Guide, *published by the American Society for Testing and Materials, 1916 Race St., Philadelphia, Pa. 19103.*

Cover: Views of ship model testing in the CRREL test tank.

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Jean-Claude P. Tatinclaux

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This report presents a general discussion of model testing of ships in level ice. The main points covered are: 1) modeling criteria for ships in ice, which must take into account the presence of a solid boundary at the water surface; 2) types of model ice used in various tanks—saline ice, urea-doped ice, EG/AD/S ice and synthetic ice; 3) techniques for growing model ice sheets, and achieving and monitoring the required ice properties; 4) limitations of both model ice and property measurement techniques; 5) model testing procedures for EHP and SHP tests and their limitations; 6) comparison between model test results and available full-scale trials data; 7) existing empirical and analytical or semi-analytical algorithms for predicting ship performance in level ice; 8) current research at CRREL and other research facilities to improve modeling techniques and data interpretation; and 9) novel bow designs for ice-transiting vessels.

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PREFACE

This report was prepared by Dr. Jean-Claude P. Tatinclaux, Research Hydraulic Engineer, of the Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. It originated from a presentation given at the September 1986 meeting of the New England section of the Society of Naval Architects and Marine Engineers. The CRREL research mentioned in the report was funded under several contracts with the U.S. Coast Guard and under the In-house Laboratory Independent Research (ILIR) program, DA Project 4A161101A91D/00/465.

This report was technically reviewed by Dr. George D. Ashton of CRREL, and by Dr. Stephen Jones of the Institute for Marine Dynamics, National Research Council, St. John's, Newfoundland. Additional comments and suggestions were offered by David Baker of Melville Shipping Ltd., Ottawa, Ontario, and by Dr. Gary Timco, Hydraulics Laboratory, National Research Council, Ottawa, Ontario.

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NOMENCLATURE

A	mean plan area of ice floes
B	ship beam
C_n	Cauchy number
d	propeller diameter
D	ship draft
E	ice modulus
F_d	densimetric Froude number
F_n	Froude number
f_i	ice–hull friction coefficient
g	gravity
h_i	ice thickness
J	advance coefficient (V/nd)
I_n	Atkins "ice" number
k_1, k_2	coefficients
K_Q	torque coefficient
K_T	thrust coefficient
K_{Ic}	ice fracture roughness
l_c	ice characteristic length
L	ship length
L_e	length of ice floe
n	propeller rotational speed
p	porosity
P_w	shaft power
Q	propeller torque
R	total resistance in ice
S_i	ρ_i/ρ
S_Q	torque standard deviation
t	thrust deduction factor
T_h	propeller thrust
V	ship speed
W_i	width of ice floe
β	ship block coefficient
γ	water specific weight (ρg)
Δ	ship displacement
λ	geometric scale
λ_v	velocity scale
η_p	propulsion efficiency
μ	water dynamic viscosity
υ	ice Poisson's ratio
ρ	water density
ρ_i	ice density
σ_c	ice compressive strength
σ_f	ice flexural strength
σ_s	ice shear strength

Ship Model Testing in Level Ice: An Overview

JEAN-CLAUDE P. TATINCLAUX

INTRODUCTION

Model testing in ice of ships and other structures is a relatively recent branch of marine engineering, with the first refrigerated towing tank being built in 1955 at the Arctic and Antarctic Research Institute of the Soviet Union in Leningrad. However, with the rapid development of the arctic and subarctic regions of the globe, spurred by the discovery of large mineral and petroleum deposits, the fields of arctic engineering, in general, and ice engineering, in particular, have rapidly grown in the last decade or so. For economic and geopolitical reasons, the number of ships transiting ice-infested waters has greatly increased. Correspondingly, better and new ship designs specifically adapted to the requirements of a particularly harsh environment led to the development and construction of new facilities devoted to ship model testing in ice. In the two decades from 1955 to 1975, only three ice towing tanks were built, one in Finland, one in West Germany, the other in the United States. In the following decade (1975-1985), ten such tanks were built in Japan, Northern Europe (including the USSR), and North America. Table 1 recapitulates the ice tanks currently operating, with their major characteristics.

All types of ships with varying missions and, thus, requirements are encountered in the Arctic and Antarctic, the Northern Atlantic, the Baltic sea, and as far south as the Great Lakes and St. Lawrence seaway; they range from tankers (oil and liquified natural gas), to cargo and container ships, supply ships, research vessels, and national security or Coast Guard vessels.

As in conventional towing tank tests, the main purposes of ship-model resistance and propulsion tests in ice tanks are: 1) to predict ship performance in ice for a given design, 2) to suggest modifications to a proposed design,

Table 1. Existing ice testing facilities. The basin length given may include the length of the trim tank.

	Main dimensions L x B x D *(m)*	*Year of operation*	*Model ice*
	CANADA		
NRC/IMD Institute for Marine Dynamics St. John's, Newfoundland	94.0 x 12.0 x 3.0	1985	EG/AD
NRC/Hydraulics Laboratory Ottawa, Ontario	18.0 x 7.0 x 1.2	1980	EG/AD/S
Arctec Canada Ltd. Calgary, Alberta	30.5 x 7.3 x 1.4	1981	Synthetic
Arctec Canada Ltd. Kanata, Ontario	30.5 x 4.9 x 1.5	1977	Saline

Table 1 (cont'd). Existing ice testing facilities. The basin length given may include the length of the trim tank.

	Main dimensions L x B x D *(m)*	*Year of operation*	*Model ice*
	FINLAND		
Wartsila Arctic Research Center Helsinki	77.3 x 6.5 x 2.3	1983	FG-saline
	GERMANY		
HSVA/Hamburgische Schiffbau Versuch. Hamburg	78.0 x 10.0 x 2.5/5.0 30.0 x 6.0 x 1.2	1984 1971	Urea-doped Saline/Urea
	JAPAN		
SRI/Ship Research Institute Tokyo	35.0 x 6.0 x 2.1	1981	Saline
NKK Tsu Research Laboratory Tsu City, Mie	20.0 x 6.0 x 1.8	1982	Urea-doped
IHI/Ishikawajima-Harima Heavy Industries Yokohama	7.0 x 3.4 x 0.9	1982	Urea-doped
MSB/Mitsui Ship Building Company Ichihara City	5.0 x 1.5 x 0.8	1985	Urea-doped
MHI/Mitsubishi Heavy Industries Nagasaki City	20.0 x 9.0 x 2.3	1986	Urea-doped
	USA		
ARCTEC Offshore Corporation Columbia, Maryland	25.6 x 10.7 x 2.4 30.5 x 3.7 x 1.8	1982 1974	Synthetic Saline
Cold Regions Research and Engineering Laboratory (CRREL) Hanover, New Hampshire	36.5 x 9.1 x 2.4	1978	Urea-doped
Iowa Institute of Hydraulic Research Iowa City, Iowa	20.0 x 5.0 x 1.2	1980	Urea-doped
	USSR		
Krylov Research Institute	30.0 x 6.0 x 1.8	1986	Saline
Arctic & Antarctic Research Institute Leningrad	13.5 x 1.9 x 1.3	1955	Saline

and 3) to investigate new concepts and designs. As a loose analogy with ice-free (clear water) tests either in calm water or in waves, model tests in ice can be divided into two categories, namely tests in level ice and tests in ridges. At this time procedures and techniques for tests in level ice are fairly well established and documented in the literature (e.g., Schwarz 1983; Free, in press), while model tests in ridges are far more recent and their procedures are still being developed. Model tests in level ice have also been the primary concern of the Committee on Performance in Ice-Covered Waters of the International Towing Tank Conference (ITTC), which has only recently begun to tackle the difficulties involved in model testing of ships in ridges. The present paper addresses only model testing in level ice, where there still remains some controversy, as discussed in the main body of the paper.

The views expressed in this paper are those currently held by this writer. It is likely not only that they will change with time as more experience is gained and progress is made, but also that some of them will be challenged by other researchers in this exciting field of ice model testing.

GENERAL CONSIDERATIONS

As in ice-free model tests, the dependent variables to be measured in ice model tests are the total resistance (R) for EHP (effective horsepower) tests, or, in propulsion or SHP (shaft horsepower) tests, the propeller thrust (T_h) and propeller torque (Q), from which other ship propulsion characteristics such as shaft horsepower, propulsion efficiency and thrust deduction coefficient can be calculated.

The difference between model tests in ice-free waters and in level ice is the presence of a solid, flexible, floating boundary at the free surface. This adds considerably to the difficulty of the tests by greatly increasing the number of independent variables or parameters that need to be scaled. These variables, listed in Table 2, include not only the usual ones, namely ship geometric characteristics, ship speed, propeller speed, water properties (density and viscosity) and acceleration of gravity, but also the ice characteristics, namely thickness, density and mechanical properties, and last but not least the ice–hull friction coefficient. All of these parameters must be scaled to satisfy similitude. Therefore, ship modeling in ice involves hydrodynamics as well as mechanics of materials to account for ice deformation and rupture. It is thus strongly dependent on the progress made in the field of ice mechanics. However, the term "ice" encompasses many different materials: freshwater ice, first-year sea ice and multi-year sea ice, to name a few, with varying crystalline structure and corresponding behavior under load. In spite of the difficulties outlined above, the art of modeling ship–ice interaction has made significant advances in the past decade to the point that results from model tests can greatly aid the naval architect in the design of an ice-transiting ship.

Perfect physical modeling of any phenomenon requires exact geometric, kinematic and dynamic similitude. Exact similitude is ensured when all independent, dimensionless parameters involved take the same values at model scale as at full scale. For the particular problem of ship–ice interaction, these dimensionless parameters are listed in Table 2, where the selected nondimensionalizing variables are ice thickness (h_i), water density (ρ) and gravity (g).

Since the gravity, g, cannot usually be altered in the model tests, and the water in the tank has nearly the same properties (density and viscosity) as sea water, it is well known that identity of the Froude number and the Reynolds number between model and prototype cannot be achieved. Since tests in ice are usually made at relatively low velocities, corresponding to a maximum of 6 to 8 knots (3 to 4 m/s) at full scale, the resistance component due to the water itself is usually a small percentage of the total resistance and either can be neglected altogether, or accommodated with a minor correction of the test results. In this respect, it should be noted that the presence of turbulence stimulators at the bow, a common practice in open water tank tests, is not acceptable in ice tests since even a small protrusion in the model hull will unrealistically increase the ice resistance. The main concern of the engineer and scientist in charge of ice tests is, therefore, to model as correctly as possible the ice properties according to the modeling law selected.

Table 2. Variables governing ship–ice interaction.

	Type of variables	*Dimensional variables*	*Dimensionless parameter*
Ship characteristics	Length	L	L/h_i
	Beam	B	B/h_i
	Draft	D	D/h_i
	Propeller diameter	d	d/h_i
	Speed	V	$F_n = V / \sqrt{gh_i}$ or $F_d = V / \sqrt{(\Delta\rho / \rho) gh_i}$
	Propeller speed	n	$J = V / nd$
	Gravity	g	1
Water properties	Density	ρ	1
	Viscosity	μ	$\frac{\rho VL}{\mu}$
Ice properties	Thickness	h_i	1
	Density	ρ_i	ρ_i / ρ
	Poisson's ratio	υ	υ
	Modulus	E	$E/\rho g h_i$ or E/σ_f or $C_n = \rho V^2 / E$
	Characteristic length	l_c	l_c / h_i
	Flexural strength	σ_f	$\sigma_f / \rho g h_i$
	Comp. strength	σ_c	σ_c / σ_f
	Shear strength	σ_s	σ_s / σ_f
	Fracture toughness	K_{Ic}	$In = \rho_i V^2 \sqrt{l_c} / K_{Ic}$ or $K_{Ic} \rho_i g h_i^{1.5}$
Ice–hull friction factor		f_i	f_i

NOTES:

The ice characteristic length, l_c, is defined by:

$$l_c = \left[\frac{E h_i^3}{12 \rho g \, (1 - \upsilon^2)} \right]^{1/4}$$

F_n is the Froude number based on ice thickness.
F_d is the densimetric Froude number.
J is the advance coefficient.
C_n is the Cauchy number.
I_n is the "Ice" number proposed by Atkins (1975).

The current practice in ice modeling is to follow the Froude scaling law. If the geometric scale is selected first, $\lambda = L_p/L_m$ = prototype length/model length, the ratio of prototype velocity to model velocity is given by

$$\lambda_v = V_p/V_m = \lambda^{0.5} .$$

Conversely, it can be envisioned that the available towing capabilities will limit the range of model speeds and therefore dictate the velocity scale λ_v. The geometric scale of the model would then be selected as $\lambda = \lambda_v^2$. Other factors that also affect the choice of the model geometric scale are: model tank size, model cost, minimum model ice strength for which test results are reliable, characteristics of available dynamometers for measuring resistance, thrust and torque, or even size of available model propellers. The model scale finally selected is a compromise between the often conflicting above considerations.

Once the geometric scale has been selected, the scales of all the other test variables and thus their range of values to be achieved in the model tests are specified by the requirements that the dimensionless parameters in Table 2 take the same values in the model as in the prototype. This implies in particular that ice thickness, ice modulus, and ice strength be scaled by the geometric scale λ, while its fracture toughness should be scaled by $\lambda^{1.5}$. The parameters υ (ice Poisson's ratio) and f_i (hull–ice friction coefficient), which have no dimensions, should have the same values in the model as in the prototype. The first requirement is to know the range of prototype values for the ice properties that must be modeled. A brief discussion on ice properties is given in the following section.

ICE PROPERTIES

Much research has been devoted to the field and laboratory measurements of ice mechanical properties. Relevant information can be found in Weeks and Assur (1967), Lavrov (1969), Schwarz and Weeks (1977), Tryde (1979), Mellor (1983), in the chapters on ice physics and ice mechanics of books devoted to ice engineering (Michel 1978, Ashton 1986), and in specialized scientific journals such as *Journal of Glaciology*, *Cold Regions Science and Technology*, and others. The proceedings of specialty conferences such as the Ice Symposia of the International Association for Hydraulic Research (IAHR), Port and Ocean Engineering under Arctic Conditions (POAC) conferences, and Offshore Mechanics and Arctic Engineering (OMAE) conferences are an important source of up to date information.

Even a cursory survey of the literature shows that ice mechanical properties are highly variable. The values measured depend upon the type of ice (i.e., freshwater ice or saline ice) and its structural characteristics (i.e., grain size, crystallography and porosity or brine volume in the case of sea ice), temperature, rate of strain, and even on the measurement techniques. To address this latter problem, the ITTC Committee on Performance in Ice-covered Waters and the IAHR Committee on Ice Problems are attempting to standardize the experimental techniques for measuring ice properties both in the field and in the laboratory (Schwarz 1979). It should be mentioned at the outset that measurement techniques do vary between field and laboratory conditions (Timco 1981b), and that the values attributed to the natural and even more so to the model ice should be treated more as indices than as actual mechanical properties of ice as a material.

Modulus, *E*

The ice modulus, E, used in engineering is actually the initial tangent or effective modulus determined from the load-displacement curve of a plate, a cantilever beam or a simply supported beam. The rate of load application should be high enough for creep deformation of the ice to be negligible or corrections need to be introduced when interpreting the test data. This effective modulus is known to vary with ice salinity and temperature, i.e., with porosity. Vaudrey (1977) gives the following relationship between E and porosity, p, of sea or saline ice:

$$E\,(\mathrm{GPa}) = 5.25 - 13\sqrt{p}\ (p \le 0.1).$$

For freshwater ice (p=0), the effective modulus predicted by the above equation is 5.25 GPa, which is within the measured range of 4 to 6 GPa. The modulus can be as low as 1 GPa for warm sea ice with a porosity of 0.1 or greater (brine volume of 100 ⁰/ooo or more). Other reseachers claim a linear variation of E with p.

The ice Young's or elastic modulus is measured usually by high frequency vibrational methods, i.e., by measuring the rate of propagation of small-amplitude, high-frequency waves or pulses in the ice. The values obtained in this manner are nearly twice those of the effective modulus.

Characteristic length, l_c

When analyzing plate or beam test results for the determination of E, an often implicit calculation is that of the characteristic length, l_c. This length is a measure of the size of the deformation zone of the ice plate or beam when subjected to a vertical static load. The two quantities E and l_c are related by

$$l_c = \left[\frac{E h_i^3}{12 \rho g (1 - \upsilon^2)} \right]^{1/4}$$

for a plate, and

$$l_c = \left[\frac{E h_i^3}{3 \rho g} \right]^{1/4}$$

for a beam.

To determine E from l_c, one has to take the ice thickness, h_i, into account. Also, it can be seen that an error of 18% in l_c leads to a 100% error in E. Therefore, scaling the characteristic length may be preferable to scaling E. In measuring l_c by the plate method (Sodhi et al. 1982) for both lake ice and first-year sea ice, Sodhi et al. (1985) found that the ratio l_c/h_i for lake ice was on the order 20, while for sea ice it was in the range of 10 to 15.

Flexural strength, σ_f

From results of cantilever beam tests and simply supported beam tests, it was found that σ_f decreased from approximately 1 GPa for freshwater ice to about 300 kPa for sea ice with a porosity of 0.2 or greater. Thus the ratio of effective modulus to flexural strength, E/σ_f, varies approximately between 5000 (for freshwater ice and cold first-year sea ice) to 2000 (for warm, weak sea ice). Vaudrey (1977), in agreement with Weeks and Assur (1967), proposed the following relationship for flexural strength of columnar S2 sea ice in terms of the ice porosity, p:

$$\sigma_f = 960 (1 - 2 \sqrt{p}) \text{ kPa}$$

valid for $p < 0.11$. For $p > 0.11$, σ_f remains approximately constant, equal to 250–350 kPa.

For columnar freshwater ice, it was found that the flexural strength obtained from beam tests (cantilever or simply supported beams) depended on the direction (upward or downward) of load application (Gow et al. 1978). The values of σ_f obtained with the ice top fiber in tension is 1.25 to 2 times that measured with the bottom fiber in tension. This difference is attributed to the anisotropic crystalline structure of columnar ice, where the grain size increases from top to bottom. For sea ice, however, there is no apparent difference in strength between the two loading directions (Tabata et al. 1967, Kayo et al. 1983). Also, the flexural strength of freshwater ice depends on the measurement technique, simply supported beam tests yielding values as much as twice those obtained from cantilever beam tests (Gow et al. 1978, Timco and Frederking 1982, Timco 1985). No such effect of measurement technique on flexural strength was observed for sea ice.

In view of the above, it is worth emphasizing again that σ_f should be considered as a flexural strength index and that, when presenting data on σ_f, one should also indicate the measurement methods and conditions.

Compressive strength, σ_c

Since the maximum ice forces exerted on a structure occur when ice fails in crushing, the compressive strength is the property that has received the most attention from researchers. Through careful testing, it has been determined that this property depends on the following parameters: ice type, grain size, temperature or porosity (or both), strain rate and test conditions (i.e., uniaxial test vs triaxial test, relative orientation of force application to crystalline structure, etc.) (Timco and Frederking 1986). For the purpose of the present paper, i.e., for modeling of ships in ice where the loading rate is high, it may be sufficient to say that σ_c in the horizontal direction is 3 to 5 times σ_f, while in the vertical direction it can be as much as 10 times σ_f.

Shear strength, σ_s

Data on ice shear strength are very few primarily because no fully reliable methodology to measure this ice property has yet been developed. On the basis of limited field experiments, Frederking and Timco (1986) have proposed the following equation relating the vertical shear strength of columnar ice to ice porosity, p:

$$\sigma_s(\text{kPa}) = 1500\,[1 - 1.60\sqrt{p}]$$

which is in agreement with the commonly accepted assumption that σ_S is 1.5 to 2 times the ice flexural strength.

Poisson's ratio, υ

To quote Mellor (1983, p. 53) "the value of υ for non-saline ice of very low porosity is about 0.33 ± 0.03, and variation with porosity in sea ice is likely to be within the limits of uncertainty for the pure ice value." It is common to take a value of $\upsilon = 0.3$ for sea ice and model doped ice (either saline or urea ice).

Fracture toughness, K_{Ic}

Until very recently, fracture toughness had been a property totally ignored in the analysis of ship–ice interaction. It is, however, receiving increasing attention and its importance in ship modeling in ice is being investigated (Jones 1986, Parsons et al. 1986). It characterizes a material's resistance to crack growth. It is likely, therefore, to control the size of the resulting pieces when the material fails in fracture (fragmentation). Defects or flaws in the material will decrease its fracture toughness. Air bubbles in freshwater ice and brine pockets in sea or doped ice are such defects. This material property is possibly the most difficult to measure experimentally. It is therefore not surprising that the data published in the literature for freshwater and sea ice exhibit considerable scatter (see Mellor [1983] for references). The data available in the literature show values for the fracture toughness that vary for freshwater ice from 60 to 300 kN $m^{-3/2}$, and for sea ice from 30 to 140 kN $m^{-3/2}$.

Density, ρ_i

While the density of pure ice has long been established at 917 kg/m^3, that of field and laboratory ice is affected by the presence of impurities such as air bubbles or brine pockets. The density of bubbly freshwater ice can be as low as 890 kg/m^3. For sea ice, the usual range of density is from about 890 kg/m^3 for cold, low salinity ice to 930 kg/m^3 for ice with high brine content.

Ice–hull friction factor, f_i

When a ship penetrates into ice, a significant component of the resistance to motion may come from e friction of the ice on the hull. This frictional force is assumed to be proportional to the force exerted by the ice normal to the ship–hull, and the coefficient of proportionality is the friction coefficient f_i. Numerous studies (e.g., Ryvlin 1973, Calabrese et al. 1980, Oksanen 1983, Saeki et al. 1984, Akkok et al. 1986, Tatinclaux et al. 1986) have been conducted to determine the effect of various parameters on f_i. It was found that ice hardness, relative velocity between ice and hull, wetting properties of the hull, etc., could affect f_i, in addition to hull roughness characteristics such as roughness average and morphology of the roughness elements. Here again, the methodology and apparatus used to measure f_i may affect the values obtained. Most studies were made in the laboratory or under controlled conditions. The few direct measurements of f_i on real ships (Hoffman 1985, Liukkonen 1985, Enkvist and Mustamaki 1986) gave inconclusive and even inconsistent results. Low friction coatings, the best known of which is Inerta-160, have been and are being developed. In practice, it is generally assumed that a new ship hull has a friction coefficient of about 0.1.

Incomplete as it may be, the above discussion should give a fair idea of the difficulty in determining the ice properties. Values for these properties should always be accompanied by a careful description of the test methods and conditions used to obtain them, as well as information on ice structure, salinity, etc. It is worth repeating that, in fact, the values measured do not actually represent the material properties of the particular ice tested, but should be considered as indices to be used for modeling or for comparison between model test results.

MODEL ICE

As discussed previously, once the geometric scale of the model has been selected, the mechanical properties of the model ice ought to be in a specified ratio with those of the field ice to be modeled. There are currently five types of model ice used in the various tanks, as indicated in Table 1, namely synthetic ice, saline columnar ice, columnar carbamide-doped (urea) ice, fine-grained ice and EG/AD/S ice. Except for the first, all types of model ice are grown from water baths containing one or more chemicals or dopants. These dopants are partially trapped between the ice grains, thereby reducing the strength of the ice. Further adjustment in the strength characteristics of the doped ice can be made somewhat by varying the growth temperature and primarily by raising the ice sheet temperature to within a few degrees of the melting temperature for a certain amount of time (warmup period) prior to the tests. An excellent discussion of the morphological properties of ice grown from a doped solution was given by Timco (1979). This section discusses the main properties of these types of model ice with their advantages and disadvantages as can be gathered from the open literature.

Synthetic ice

The more widely known synthetic ice (MOD ice) is a wax-based mixture prepared in a liquid form and poured on the surface of a traditional towing tank where it is allowed to set. The exact composition of the mixture is adjusted to achieve as closely as possible the required density and mechanical properties. Such a synthetic ice was used as early as 1970 (Crago et al. 1970). Its rights were acquired by Arctec Inc. (now Arctec Offshore Corporation) of Columbia, Maryland, where it has been further refined. It is a combination of a "secret ingredient" and flat, round plastic beads or miniature disks, 3 to 4 mm across. Since the exact composition of this synthetic ice is proprietary, no other ice tank besides those of Arctec Offshore Corporation in the U.S.A. and of Arctec Canada, Ltd., has any experience with this model ice and there has been no independent study of its properties. Schultz and Free (1984) presented the results of measuring the properties of 40 model ice sheets. The ice thicknesses ranged from 10 to 60 mm, with most ice sheets (33 out of 40 or 83%) between 15 and 35 mm thick. The flexural strength ranged from as low as 10 kPa to about 80 kPa; however, 34 out of 40 ice sheets (85%) had a flexural strength between 10 and 20 kPa. The range of E/σ_f cited is 700 to 5000 with an average of 1450 and with 90% of the data points lying between 700 and 2000. The ratio of compressive strength to flexural strength, σ_c/σ_f, ranged from 0.6 to 2.3 with an average of 1.14, which is low compared to that of sea or freshwater ice. Finally, the ice–model hull friction factor, f_i, was given as ranging from 0.07 to 0.28, which covers the entire realistic full-scale range that can be expected. Schultz and Free did not give values for the density, the shear strength or the fracture toughness of the synthetic model ice. They did, however, mention that "the size of the broken ice pieces resulting from ship or structure interaction with the synthetic ice ... appears to compare very favorably with the corresponding piece size observed in field trials of icebreaking vessels and structures (p. 239)." They also cite one definite advantage of the synthetic ice over doped model ice: it is handled at room temperature and its properties remain unchanged for days.

Columnar saline ice

The first dopant used to create model ice in a refrigerated ice tank was sodium chloride. By varying the salt concentration in the water bath and consequently the brine content within the ice, almost any required reduction in flexural strength can be achieved at growth temperature, which is normally well below 0°C. This is still the technique used in the ice tanks of the Arctic and Antarctic Research Institute in Leningrad, U.S.S.R. However, high salinity model ice has an extremely low strain modulus E, and the ratio E/σ_f is usually no greater than 500. This ice is therefore excessively plastic, and breaks into floes that are much larger relative to those observed in the field. Schwarz (1975, 1977) suggested use of a low salinity ice grown from a water bath with a salt concentration of 1.6 ‰ or less. The method suggested involves three steps:

1. When the water bath has nearly reached its freezing temperature, a fine mist is sprayed into the cold air above the tank. The

mist freezes in fine crystals that settle on the water surface to initiate the ice sheet. This wet-seeding technique results in a columnar ice sheet with small crystals, one that closely resembles the crystalline structure of sea ice.

2. The ice is grown at as low a temperature as possible (on the order of -20°C), primarily to reduce the growth time to a minimum, but also to minimize the thickness of the nearly freshwater top layer.

3. Once the desired ice thickness is nearly reached, the temperature in the ice tank is raised to about 0°C. During this warmup period, the brine pockets in the ice melt, thereby increasing the liquid volume within the ice and decreasing the flexural strength. With this procedure, Schwarz showed that values of the ratio E/σ_f close to 2000 were possible as long as the ice strength was above 40 to 50 kPa. These were confirmed in an independent study by Timco (1981a). However, when further reduction in strength was required, i.e., for a geometric scale greater than 15 to 10, the ratio E/σ_f could become as low as 500. Another disadvantage of salt as a dopant is that it is highly corrosive. Its use leads to high maintenance costs for the steel components of the ice tank, towing carriage, and other equipment.

Columnar carbamide ice

After an extensive study of possible dopants, Timco (1979, 1980, 1981a) suggested carbamide (or urea) as an alternative to sodium chloride for high modeling scale (>20). From test results made on 4- to 5-cm thick ice sheets grown from a 1.3% by weight urea solution in water, Timco concluded that carbamide was superior to low-salinity saline ice and that scale factors up to 40 were possible with this new doped ice. Over the range of flexural strength from 15 to 70 kPa, the ratio E/σ_f remained larger than 2000, the compressive strength in the vertical direction varied between 110 and 250 kPa and that in the horizontal direction varied between 110 and 160 kPa. The shear strength under vertical loading increased from 30 kPa at $\sigma_f = 15$ kPa to 70 kPa at $\sigma_f = 70$ kPa, while that under horizontal loading increased from 35 to 65 kPa. The density of carbamide ice was found to be on the order of 0.95 g/cm^3. Measurements made at CRREL yielded values of 0.93 g/cm^3. A significant advantage of carbamide over salt is that it is not corrosive. It is also a very common, fairly inexpensive chemical used, in particular, as a fertilizer.

Many ice tanks — Arctec Offshore Corporation, Arctec Canada, CRREL, HSVA, NKK — have adopted carbamide ice as model ice. Hirayama (1983), in an extensive study of carbamide ice sheets grown from a 0.95% urea solution in water, confirmed most of Timco's findings. However, in the experience of this writer, while values of E/σ_f of 2000 are possible for relatively thick and strong ice, values of 1000 to 1500 are more common. For thin, weak ice, i.e., for ice sheets less than 3 cm in thickness and with a flexural strength less than 30 kPa, the ratio E/σ_f may even drop below 1000. Correspondingly, while the ratio l_c/h_i is on the order of 12 for ice sheets 4 cm thick or more and with a flexural strength of 40 kPa or above, it may become less than 10 for thin, weak ice (i.e., 2 cm thick and with $\sigma_f = 20$ kPa). For these reasons, this writer discourages users of the CRREL ice tank from conducting tests at thicknesses of less than 2 cm or ice flexural strengths less than 20 kPa. In this writer's experience, the results of such tests would be unreliable.

Another disadvantage of urea-doped ice is its two-layer structure: the top, incubation layer can be 3 to 10 mm in thickness and is significantly stronger than the bottom, dendritic layer. For that reason, the flexural strength measured with the load applied upward (bottom surface in tension) is only about 40% of that measured with the load applied downward (top surface in tension). The thickness of the top layer can be minimized by growing the ice at the lowest room temperature possible and ensuring that the water temperature at seeding is nearly equal to its freeezing point.

Finally, Timco (1985) measured values of the critical stress intensity factor K_{Ic} from an average of about 6 kPa m$^{1/2}$ at $\sigma_f = 40$ kPa, to an average of 17 kPa m$^{1/2}$ at $\sigma_f = 130$ kPa. When extrapolated to full scale according to flexural strength ratio, these values of K_{Ic} are significantly greater than the range of 30 to 100 kPa m$^{1/2}$ for sea ice with a porosity of 0.13 and that of 90 to 150 kPa m$^{1/2}$ for ice with a porosity of about 0.02 (Urabe and Yoshitake 1984, Timco and Frederking 1983). It can be conjectured that the hard top layer of carbamide ice may be at least partially responsible for its high critical stress intensity factor. Another reason might be that model ice has fewer flaws than real ice. This high fracture toughness of carbamide ice, even with a high ratio of E/σ_f, may be one reason that the size of the ice floes produced with this model ice remain relatively larger than those observed during full-scale trials.

While in the opinion of this writer carbamide ice was a definite improvement over saline ice, it is not yet the ideal material for modeling ice–structure interactions.

Fine-grained ice

Almost concurrently with the development of carbamide ice at the National Research Council in Ottawa, Enkvist and co-workers from Wartsila Arctic Research Center (WARC) in Finland were developing another model ice (Enkvist and Makinen 1984). It is a saline, fine-grained ice similar in structure to snow ice (ice type T-1) grown from a 2% NaCl solution. Its structure is nearly homogeneous, as opposed to the columnar structure of sea ice and carbamide ice. It is grown by continuously spraying a mist of tank water above the water surface. Since the air temperature is well below 0°C, the mist freezes in small crystals that deposit on the water surface. This procedure requires that the spray nozzles be mounted on a carriage that continuously travels back and forth along the ice tank. Careful control of the carriage speed, nozzle arrangement and discharge is necessary to create an ice sheet of uniform thickness. Newly formed ice sheets have usually too low a strength, and additional freezing without spraying may be necessary. According to Enkvist and Makinen, the ratio E/σ_f (E measured by the plate deflection method) is on the order of 1200 ± 200 for ice thicknesses of 20 to 40 mm and flexural strengths from 13 to 28 kPa. According to its developers, the uniaxial compressive strength of this model ice is somewhat low.

According to Enkvist and Makinen, the main advantage of this ice, dubbed FG-ice, is that it is more brittle than either saline or carbamide ice, and therefore breaks into smaller floes than either. The resulting icebreaking pattern and flow of ice pieces along a ship's hull are similar to full-scale observations. Also, the rate of growth of this ice is 5 to 7 mm/hour compared to 2 to 3 mm/hour for the other types of model ice, which permits a much faster turn-around time in testing.

Finally, the density and friction factor of the FG-ice are said to be comparable to that of columnar sea ice or model ice. No measurements of its shear strength or critical stress intensity factor were reported.

No independent testing of this fine-grained model ice confirming the above results is known to this writer. A similar fine-grained ice is now in use at the Nippon Kokan K.K. ice tank, where carbamide rather than salt is the dopant. The growth procedure of FG-ice at NKK is also somewhat different from that developed by Wartsila's researchers, but results in a comparable model ice.

EG/AD/S model ice

Timco (1986) introduced a new type of model ice for use in refrigerated ice tanks. The ice is grown from an aqueous solution of three dopants, ethylene glycol (EG), aliphatic (very low sudsing) detergent (AD) and sugar (S). According to Timco, the ethylene glycol serves as a low molecular weight dopant that is trapped in the ice as impurity pockets to reduce the strength of the ice. The aliphatic detergent reduces the surface tension of the solution and allows more of the ethylene glycol to be trapped by the ice. The resulting ice should be nearly single-layered, as opposed to saline or carbamide ice. Finally, the sugar inhibits the lateral growth of the ice platelets to produce a fine-grained ice.

The methodology to grow and temper this new ice to achieve prescribed thickness and mechanical properties is basically the same as for carbamide ice. Tests were carried out by Timco (1986) on 4-cm-thick ice sheets grown from a solution with concentrations of the three chemicals of 0.46/0.032/0.049% respectively. He reported that a flexural strength from 20 to 100 kPa could be obtained, and that the strength measured by upward loading was about 70% of that measured by downward loading of the cantilever beam. The ratio of unaxial compressive strength with horizontal loading to flexural strength (σ_c/σ_f) was about 3, while with vertical loading this ratio was on the order of 5. The ratio of strain modulus E (plate deflection method) to σ_f was found to fall within the range 1500–

2500, similar to carbamide ice of same thickness. Finally, the K_{Ic} of the EG/AD/S ice appears to be much lower than that of carbamide ice and better simulates the critical stress intensity factor of sea ice over the usual range of scaling factors.

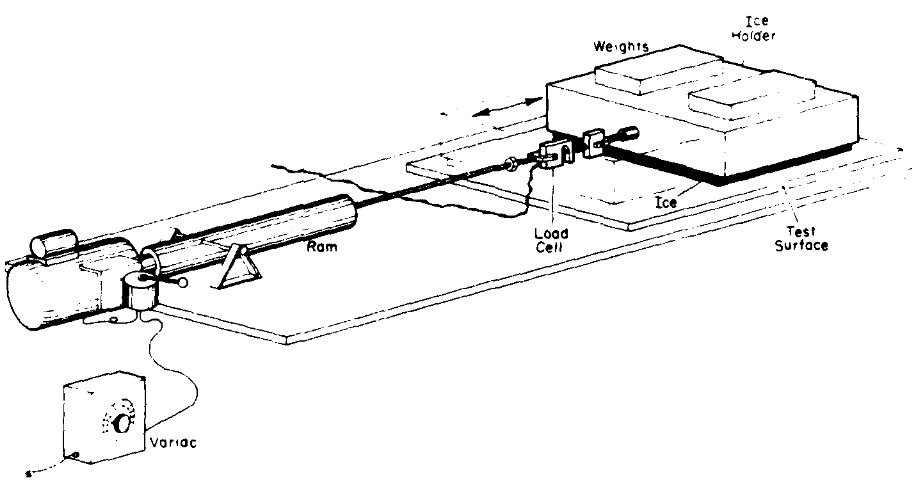
From the above results, it appears that EG/AD/S ice is a significant improvement over urea ice as a modeling material. So far it has been adopted only by the Institute for Marine Dynamics in St. John's, Newfoundland. Because of its cost (about twice that of urea ice) and the time involved in fine-tuning the growth and testing procedures for each particular ice tank, other organizations, which had recently adopted carbamide ice, are awaiting or conducting independent studies of this new model ice before deciding whether to adopt it or not. It can be mentioned that the St. John's tank initially experienced severe growth of bacteria. This bacteria problem was resolved by deleting the sugar from the dopants and installing a sand-type filtering system for the tank water.

MODEL TEST PROCEDURES

Ice growth and monitoring

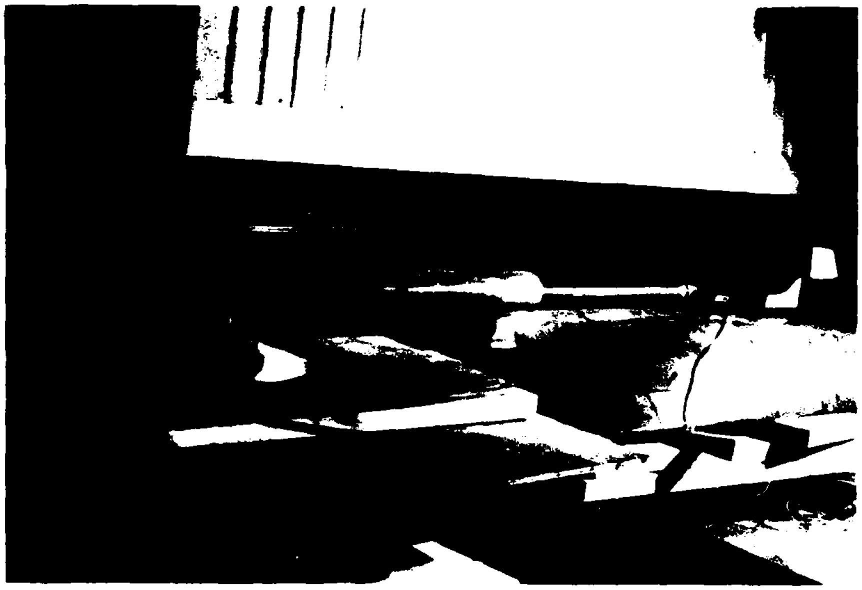
Over the usual full range of geometric scale, $\lambda = 10$ to 40, no existing model ice can scale all the properties of sea or freshwater ice. It is then customary to conduct ship model tests in ice sheets whose thickness and flexural strength are scaled by the geometric scale λ. The other properties are then only measured and recorded. In all cases it is important not only to report the measured values of these properties but also their measurement techniques if meaningful comparisons among test data are to be attempted.

Flexural strength is usually measured from in situ tests of small cantilever beams and the effective or strain modulus, E, by the plate method. The kinetic friction coefficient is measured by pulling a loaded ice sample over a flat area of the ship hull or a test board whose surface was prepared in the same manner as the ship hull (see Fig. 1). The pulling force is measured and divided by the total normal load to yield the friction coefficient. Tests may be conducted at different pulling speeds and normal pressures to determine possible effects of these two parameters on f_i (ITTC 1984). Test methods for other properties may vary greatly from one test facility to another when those properties are measured at all. For refrigerated facilities, the size of the tank and its refrigeration characteristics will dictate the time for ice to grow to a specified thickness and the tempering time required to achieve a particular flexural strength. When the target flexural strength is nearly reached, there is usually only a narrow time window during which the ice properties must be measured and the tests per-



a. Diagram of friction test apparatus.

Figure 1. Measurement of ice–hull friction coefficient.



b. Friction test apparatus in operation.

Figure 1 (cont'd). Measurement of ice–hull friction coefficient.

formed. This lack of available time often precludes measuring all ice properties other than σ_f and E, which are considered as the most important to measure, unless sufficient personnel are available to conduct the measurements simultaneously or nearly so. To add to this problem, the weaker the ice, the narrower the time window available and the more difficult and time-consuming the measurements.

EHP tests

Resistance or EHP (effective horsepower) tests in level ice are conducted in a manner similar to traditional resistance tests in calm water. The model hull is connected to a towing carriage, free to heave, pitch, roll and possibly yaw. Depending on whether the towing mechanism is stiff or soft, the hull may be totally or only partially restricted in surge and sway. One major difference between open water and ice resistance tests is that in the latter the hull motion is only steady in the mean. As the hull penetrates into and crushes and bends the ice, the resistance increases until the ice fails, at which point it decreases suddenly. This quasi-periodic or cyclic phenomenon, an example of which is shown in Figure 2, requires that digital sampling of the analog signals be done at high enough rates to avoid aliasing effects. Once the towing carriage has reached a steady speed, the model resistance is averaged over a sufficient travel distance (one model length or more) to yield reliable values. Since model tests in ice are far more expensive than those in ice-free water, as many tests as possible are to be conducted in one ice sheet.

In addition to resistance, the most common quantities measured during EHP tests are heave, pitch and roll.

The tests results are sometimes presented as the total resistance, R, versus velocity, V. However, the whole range of tests usually requires more than one ice sheet, and the ice characteristics — thickness, strength, strain modulus, etc. — will vary slightly from one ice sheet to the next. This writer prefers to plot the data in dimensionless form as shown in Figure 3.

In addition to quantitative measurements, qualitative test documentation by means of photograph, films or video recording are extremely useful. In particular, underwater photography or video showing the motion of the ice floes along the model hull can be used to indicate potential interference between ice and appendages. These visual aids may sug-

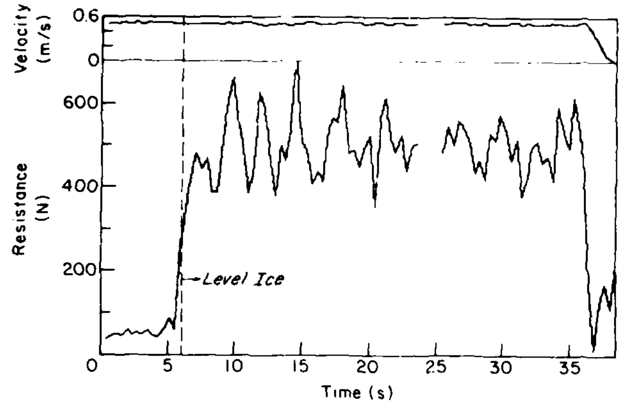


Figure 2. Example of resistance signal in level ice.

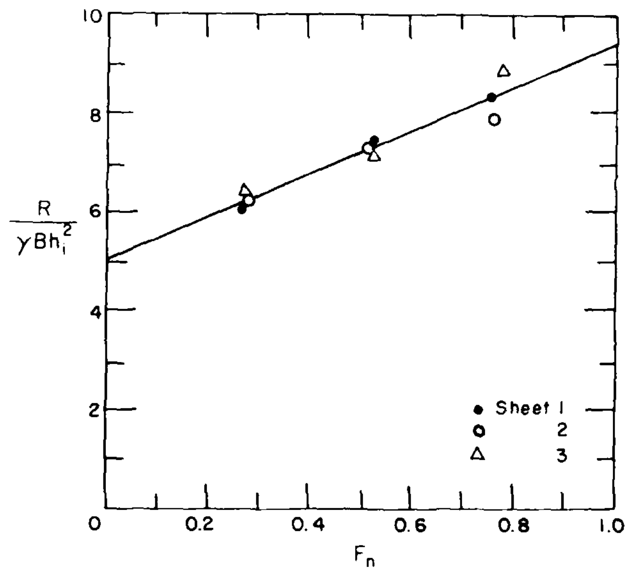


Figure 3. Example of nondimensional resistance test results.

gest modifications to hull design and appendage location to minimize such interaction.

SHP tests

As in open water tests, propulsion or SHP (shaft horsepower) tests in ice can be conducted either with a towed model or with a free model that is tethered to the towing carriage only by the power and analog data signal cables. In the former method, two to three tests at different propeller speeds for each model speed must be conducted. The force (pull) between carriage and model must be measured, and the test data are interpolated to zero pull to determine the self-propulsion point (rpm, thrust, torque) at the particular speed. In the free-model tests, the propeller speed is usually set at a particular value, and the corresponding model velocity is then measured, together with propeller torque and thrust. Since model speed in ice is only quasi-steady, this method requires that the main carriage be able to follow the model within a fairly close distance, and model speed or position relative to the main carriage, or both, must be measured. This test method has the advantage of yielding the self-propulsion points without any interpolation or other adjustments of the test data. On the other hand, the method requires a rather long tank, especially at high speed, to allow the model to reach its quasi-steady state, and is, therefore, more appropriate to the longer ice basins.

Since one of the goals of propulsion tests in ice is to investigate potential ice–propeller interaction, high-speed data acquisition systems are required to sample the thrust and torque signals at high enough rates (about 10 times per revolution).

Examples of propulsion tests results under the captive-model method are shown in Figure 4. As for resistance tests, visual documentation is very useful, especially of any ice–propeller interaction.

TEST DATA ANALYSIS — COMPARISON WITH FULL SCALE

Analysis of test results

Ship model tests are conducted to predict either the power required to achieve design performance or the performance to be expected for a given shaft power. In the first case, predictions are usually plotted as power versus speed in level ice for several ice thicknesses. In the latter case, the expected speed at full power is plotted versus ice thickness.

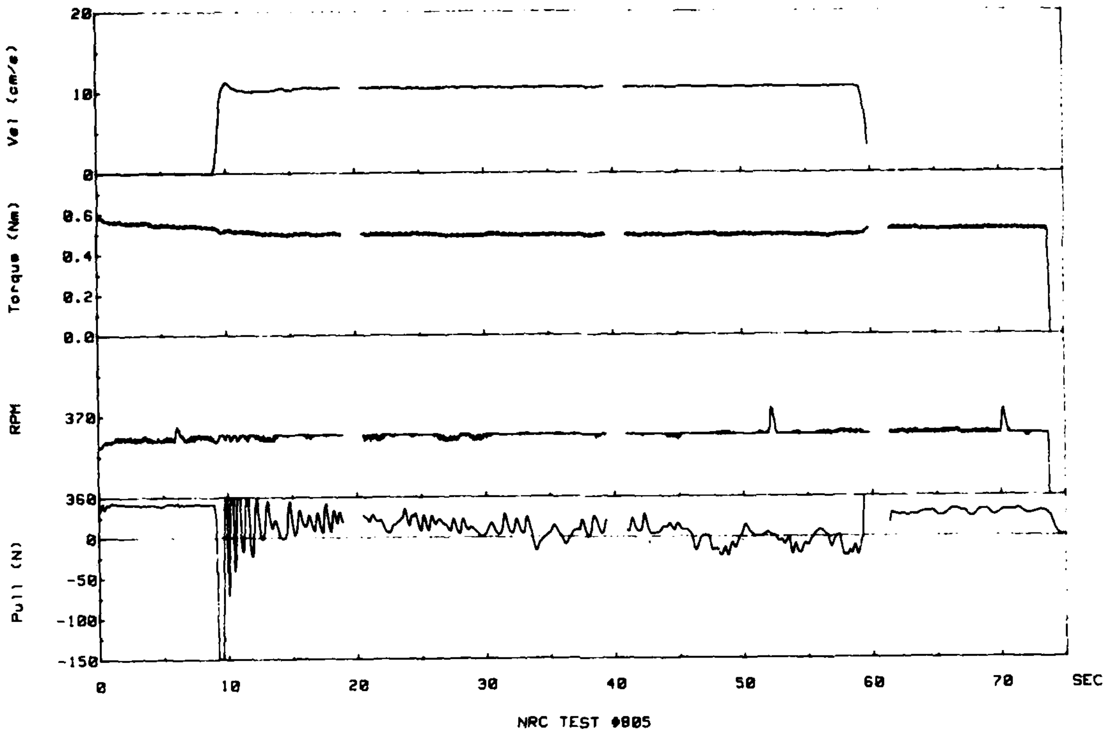
Each ice testing facility has its particular technique for analyzing, interpreting and extrapolating the test data to full-scale conditions. One technique is to perform a regression analysis on the raw test data. For example, the measured ice resistance is assumed to be a polynomial function of speed, ice thickness, and ice flexural strength. Another method is to break the total resistance into several components and perform regression analyses, assuming different forms of the regression equation for each component. Still another technique is to make similar analyses in a dimensionless form.

Extrapolation of the model test data to full-scale conditions is made either strictly by using the Froude scaling law or by also introducing empirical correction factors based on past experience or on available full-scale data (see, for example, Enkvist and Mustamaki 1986).

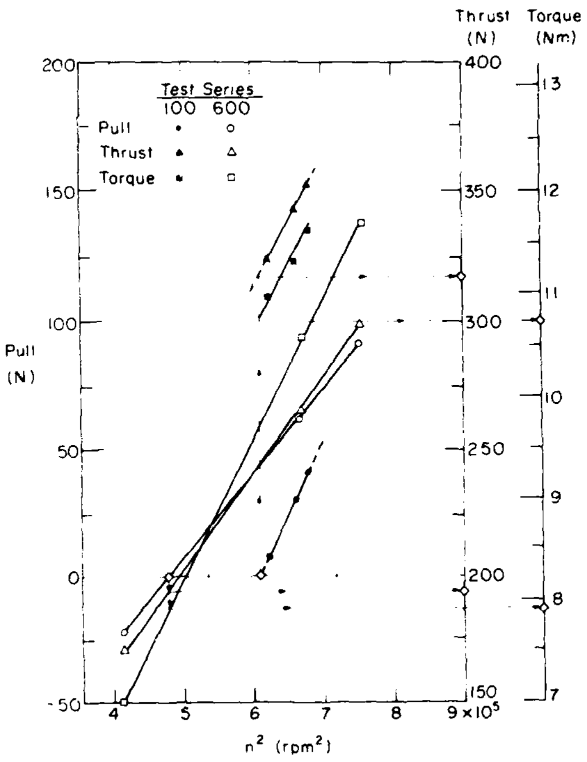
In all cases, because of the scatter inherent in test data from ice model tests, some sort of regression analysis is used to smooth the results. The analysis may be made on the model data or the extrapolated values, in dimensional or dimensionless form. Based on this author's experience, and until a more reliable theoretical analysis of ship–ice interaction is available, the form of the regression should be kept as simple as possible. It should be selected by visual inspection of plots of the dependent variables versus the independent variables that are believed to be of primary importance. Since any regression analysis is valid only over the range of test parameters (or the corresponding full-scale values), the final results should not be extrapolated beyond that range, which needs to be specified.

In the case of resistance tests, the data analysis method used by this author consists first of subtracting the open water resistance from the total resistance in level ice to obtain the net ice resistance. The open water resistance is measured by towing the model in the ice model basin free of ice. The dimensionless net ice resistance is plotted versus the Froude number with the dimensionless ice strength as a parameter. A regression analysis is performed on the basis of these plots, the result of which is applied to full-scale conditions to predict the ice resistance of the prototype. The open water resistance of the prototype, determined from traditional open water tests, is added to the ice resistance to give the total resistance in level ice at full scale. While the open water resistance is usually small compared to the ice resistance, in thin ice at high speed (6 to 8 knots [3 to 4 m/s]) it can become a sizable component of the total resistance. The results of EHP and SHP model tests are used to evaluate the thrust deduction factor, t, and propulsive efficiency, η_p, as functions of the advance coefficient $J = V/nd$. Until better understanding of ice–propeller interaction, and possible corresponding scale effects, is reached, the model results for $t(J)$ and $\eta_p(J)$ are assumed to be applicable to full scale.

Examples of full-scale performance predictions following the above technique of data analysis are shown in Figure 5.



a. Initial test results.



b. Determination of self-propulsion test point.

Figure 4. Example of propulsion tests results (captive model).

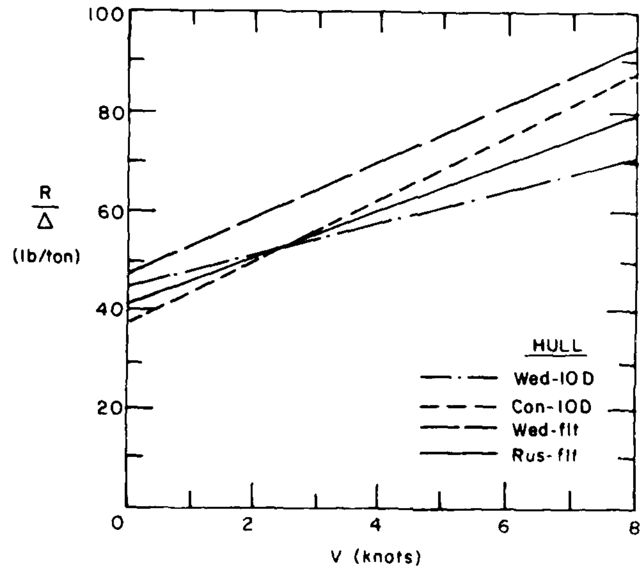


Figure 5. Full-scale resistance prediction from model test results.

Comparison with full-scale data

The validity of model test results can be ascertained only by comparison with full-scale trial measurements. There are very few icebreakers and other ice-going vessels that have been tested and whose full-scale trials results are not proprietary. Even among the full-scale data available (e.g., Vance 1980, Vance et al. 1981, Edwards et al. 1981, Michailidis and Murdey 1981) there are often gaps in the data presented, or the full-scale conditions are significantly different from the scaled up model test values. This is not altogether surprising when one considers the difficulties involved in full-scale ice trials. Furthermore, it is extremely rare to encounter in the field level ice sheets devoid of snow, while the model ice sheets are always so. In addition, the presence of snow may significantly increase the full-scale resistance, depending upon the thickness and consistency (dry or wet snow) of the snow cover.

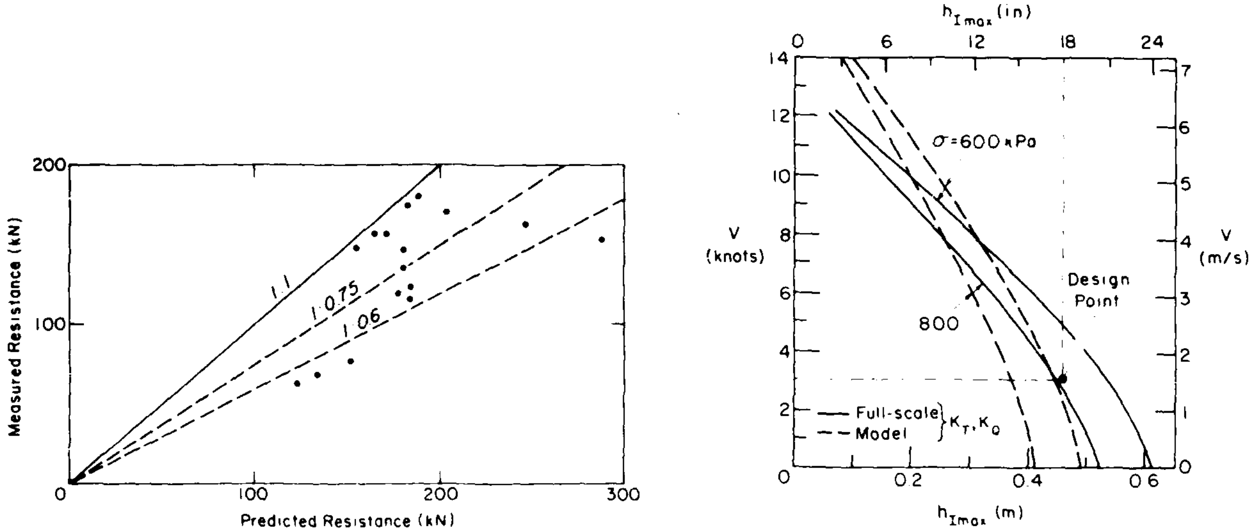
In this author's opinion, some of the best sets of full-scale data currently available are those collected by Vance (1980) and Vance et al. (1981) with the USCGC *Katmai Bay*, and by Michailidis and Murdey (1981) with the CCGC *Franklin*. Comparison of the ship performance predictions from model tests conducted at CRREL (Tatinclaux 1984a,b, 1985) with full-scale measurements for both of these ships are shown in Figure 6. As can be seen, the power predictions from model tests are consistently greater than field measurements. This author believes that this discrepancy is at least in part attributable to incorrect modeling of the ice piece size (Keinonen 1983) resulting from incorrect strain modulus, fracture toughness and density of the model ice. This may lead to exaggerated, unrealistic ice–propeller interaction in the model.

ANALYTICAL AND EMPIRICAL PREDICTORS

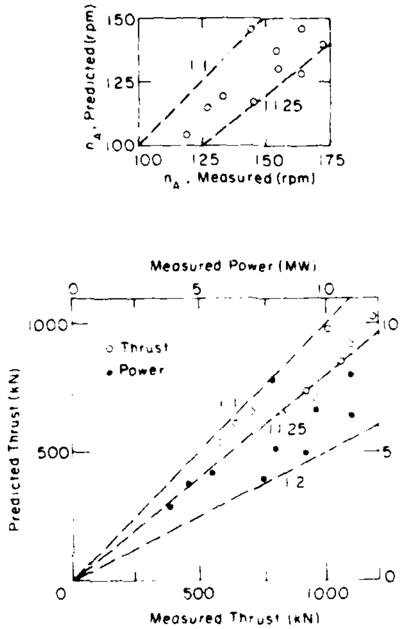
In parallel with the development of laboratory model testing techniques, efforts have been made to develop predictor equations or numerical schemes for the level ice resistance and propulsion performance of ice-going vessels. These equations or schemes can be divided into two categories: 1) empirical and 2) analytical or semi-analytical.

Empirical predictors

Empirical predictor equations for the resistance or propulsion characteristics in level ice, or both, have been proposed by Kashtel-



a. USCGC Katmai Bay.



b. CCGC Franklin.

Figure 6. Comparison between predictions and full-scale trials measurements.

yan et al. (1968), Enkvist (1972), Lewis et al. (1982), and Tsoy (1983). The equations were obtained by multiple regression analysis of available full-scale and model test data. As for any empirical formula, these equations are valid only over the range of parameters for which they were determined. In particular, the data bases for all the equations were obtained from classical icebreaker hull shapes. Therefore, it is unlikely that the predictors may be used for the new hull shapes currently under development and discussed in a following section.

The set of equations proposed by Tsoy (1983) was found by this writer to be of particular practical interest. It predicts the limiting ice thickness capable of being broken by a given ship, i.e., her design point in level ice. Given the total shaft power, P_w in kilowatts, and the propeller diameter, d_p in meters, the thrust (T_h) developed at near-mooring operating conditions is estimated by

$$T_h = k_1 (d_p \bullet P_w)^{2/3} \text{ (kN)}$$

where k_1 is an empirical coefficient: $k_1 = 0.78$ for a single-screw ship, $k_1 = 0.98$ for a double-screw ship, and $k_1 = 1.12$ for a triple-screw ship, assuming all propellers to be identical and that power is equally distributed among the propellers.

The limiting ice thickness, h_i in meters, that the ship is capable of breaking in the continuous mode (i.e., at a speed of 3 knots [1.5 m/s]) is then given by

$$h_i = k_2 \sqrt{T_h / B \Delta}^{\,1/6}$$

where B is the ship beam in meters, Δ is the ship displacement in metric tonnes, and k_2 is an empirical coefficient given by Tsoy as

$$k_2 = 0.031 \text{ to } 0.035$$

for icebreakers, and

$$k_2 = 0.039 - 0.025\,\beta$$

for ice-reinforced ships, with β being the ship block coefficient.

Once this limiting ice thickness is estimated, and when the maximum ship speed in open water is known, the ship performance curve, maximum speed vs ice thickness, can be drawn under the assumption that it is linear. Such performance curve was estimated for the USCGC *Katmai Bay* and compared with model tests predictions in Figure 7.

Analytical and semi-analytical schemes

All analytical and semi-analytical derivations of ship resistance in level ice (Milano 1973, Carter 1982, Kotras et al. 1983) available in the literature assume that the ice resistance can be divided into several components, namely a breaking resistance due to ice crushing, shearing, bending or buckling (or all four), a frictional resistance, and a component due to ice floe submergence and entrainment. The various authors follow either a force balance (Carter, Kotras et al.) or an energy balance (Milano) approach. The mathematical models of Milano and Carter appear to be purely analytical, since the only inputs required are the ice properties and the ship hull geometry. The resistance equation proposed by Kotras et al. is considered semi-analytical, since it still contains empirical coefficients that need to be adjusted for each ship studied from a few model test data or full-scale trial data; the equation may then be applied to conditions other than those used in determining the coefficients.

Milano has applied his method to numerous ships of various shapes and sizes (e.g., Milano 1982) with reasonable correlation between predicted and measured ice resistance. Milano also claims that his analytical model is applicable to any hull form. Carter's (1982) comparisons between measured and predicted resistance are also quite satisfactory, in spite of his equation totally neglecting inertial and buoyancy forces due to submergence of ice floes by the moving vessel. Furthermore, his treatment of the effect of ship velocity on ice resistance remains unconvincing to this writer. Finally, his equation is based in part on elliptical approximations of the ship waterlines, and therefore may not be readily applicable to the new, unconventional icebreaker hull forms currently under development.

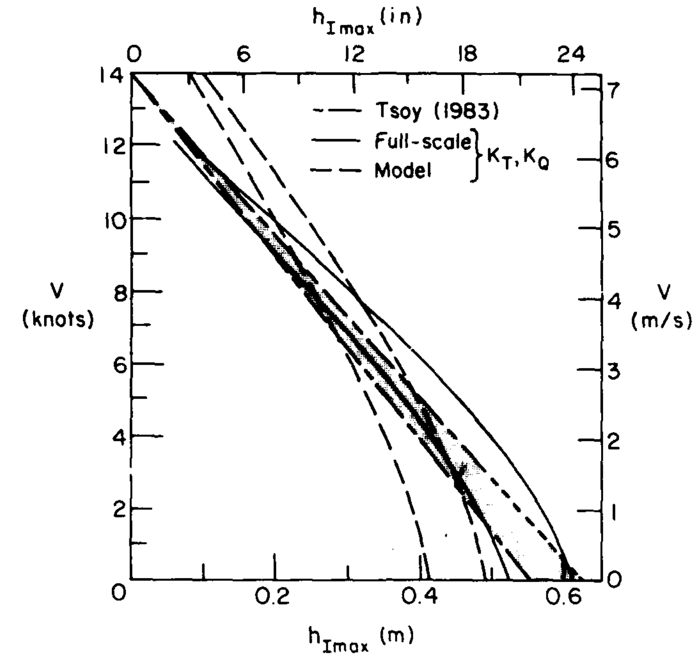


Figure 7. USCGC Katmai Bay performance curve in level ice measured during trials, predicted from model tests, calculated by Tsoy's (1984) method.

CURRENT RESEARCH EFFORTS IN ICE MODELING

Research and development efforts at ice modeling facilities are pursued in many directions: improvement of model ice, field and laboratory measurements or characterizations of ice properties, scale effects and test data corrections, ice–propeller interaction, etc. International cooperative efforts between research facilities are also underway under the aegis of the ITTC Committee on Performance of Ships in Ice-Covered Waters (Ice Committee for short).

At the outset it can be pointed out that because of particular characteristics and conditions (size, refrigeration system type and capacity, local environment, etc.) each ice tank has developed its own method for manufacturing a level ice sheet of prescribed mechanical properties. Modifications to seeding, growth monitoring and tempering techniques (in the case of doped ice) are constantly introduced to improve the model ice consistency and repeatability.

International cooperative research

One of the tasks of the ITTC Ice Committee is to develop standard methods for measurement of ice properties both in the field and in the laboratory. It is also attempting to develop guidelines showing which quantities need to be documented during model tests and full-scale trials. The purpose of these standards and guidelines is to allow meaningful comparison between results obtained at different facilities. Obviously, they need to be periodically revised as progress in the understanding of ship–ice interaction, testing methodology, and testing equipment is made.

The main recent effort of the Ice Committee was the testing of a standard model by all participating ice tanks. The standard model selected was that of the Canadian Coast Guard "R"-class icebreaker. Fiberglas models at the scales of 1:20 and 1:40 were constructed by the National Research Council of Canada and circulated to the participants. The ice research facilities who participated in the joint research program were IMD/NRC (Canada), CRREL (USA), HSVA (Germany), WARC (Finland), AARI (USSR), JSRI and NKK (Japan). The test program (ITTC 1981) included resistance and propulsion tests at two ice thicknesses and two ice strengths. The results of the first series of tests were reported to the International Towing Tank Conference in Goteborg, Sweden (ITTC 1984). This international cooperative research program is continuing, the results of which are to be reported periodically to the ITTC.

Ice testing

Testing for the mechanical properties of ice is a difficult and time-consuming task. Furthermore, all current methods give only local values with the assumption that these values are representative of the whole ice sheet. Baker et al. (1987) have proposed an ice-indexer for laboratory use that would measure ice flexural strength, shear strength and crushing strength simultaneously and continuously. This ice-indexer is still under development and evaluation.

While measurement of the friction coefficient of ice is standard procedure in the laboratory, no satisfactory field apparatus had been devised. Kitagawa and Izumiyama (1986) have recently reported on a portable field device for ice friction measurements that could be a significant addition to the tools needed to characterize field ice.

It is only recently that the fracture toughness of ice has received increasing attention as a material property significantly affecting ship resistance in ice. As far as this writer knows, the Institute for Marine Dynamics of the National Research Council of Canada, St. John's, Newfoundland, is the only ice modeling facility where the fracture toughness of its model ice or some related index is measured routinely. No publication is yet available on the relation between fracture toughness and ship model resistance, or on how to modify the full-scale prediction to include K_{Ic}. CRREL has recently initiated an investigation of the fracture toughness of urea-ice (Bentley et al., in press), a study to be expanded to freshwater ice. Standard measurement procedures and apparatus are yet to be devised.

CRREL research on ship–ice interaction

As was mentioned earlier, in this author's experience the power requirements predicted by direct Froude scaling of model tests results were consistently greater than those measured during full-scale trials. From visual observation via underwater video and conversation with icebreaker operators, in particular personnel of the U.S. Coast Guard, the conclusion was reached that ice ingestion by the propellers is far greater in the model tests than at full scale. This conclusion is in agreement with observations by Keinonen (1983) who attributed this excessive ice–propeller interaction to model ice-floes being relatively larger than full-scale floes.

This author investigated the size distribution of ice floes created by a simple wedge (idealized icebreaker bow) towed through ice sheets of varying thickness, flexural strength and strain modulus (Tatinclaux 1986). It was found that the plan area and largest dimension of the floes followed a log-normal probability density function (Fig. 8). Similar results were presented by McKindra and Lutton (1981) from trial data with a USCG Great Lakes icebreaker (WTGB class). The ratio of model floes' mean plan area to ice thickness squared, A/h_i^2, was found to be only proportional to the dimensionless strength, σ_f/γ_h, but independent of other parameters such as the strain modulus or characteristic length (Fig. 9). The coefficient of proportionality depended on the type of model ice (urea-doped or synthetic ice). The available full-scale data were insufficient to confirm these last results.

A subsequent study investigated the effect of floe size on propeller torque (Tatinclaux 1987). Captive model propulsion tests were made with the 1:10 model of the USCGC *Katmai Bay* previously tested at CRREL. The tests were made in pre-sawn channels with floe sizes ranging from 1/2 to 1/6 the model beam, and in brash-ice-filled channels. At a given advance coefficient, the torque coefficient K_q, increased linearly with floe size (Fig. 10), and the torque standard deviation S_q increased with velocity, the rate of increase being some function of floe size. Also, it appeared that below a certain ship speed no ice–propeller interaction occurred, and that this critical velocity decreased with increasing floe size (Fig. 11).

On the basis of the above study, it is suspected that model ice specific gravity and the ice–hull friction coefficient may significantly

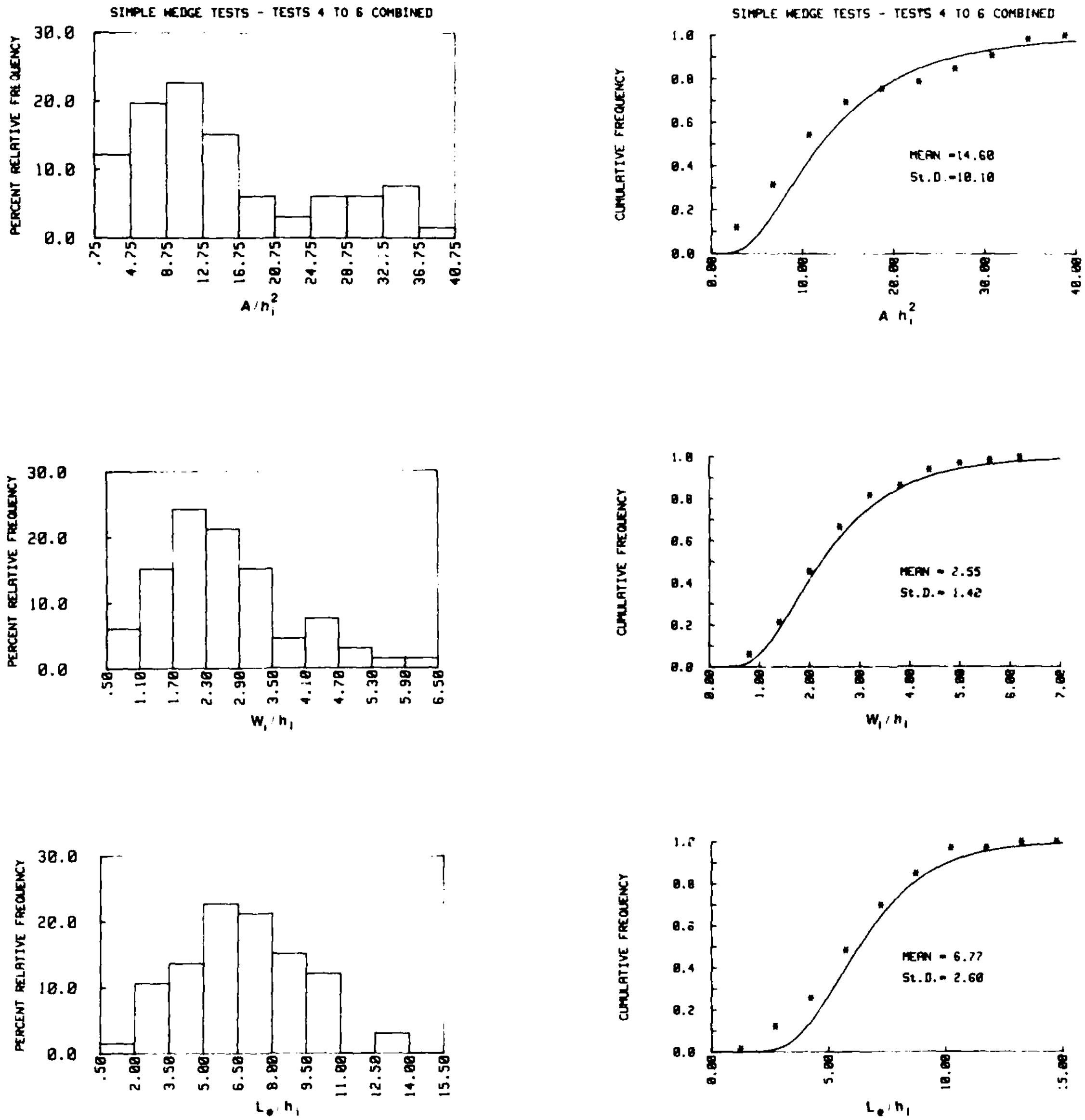
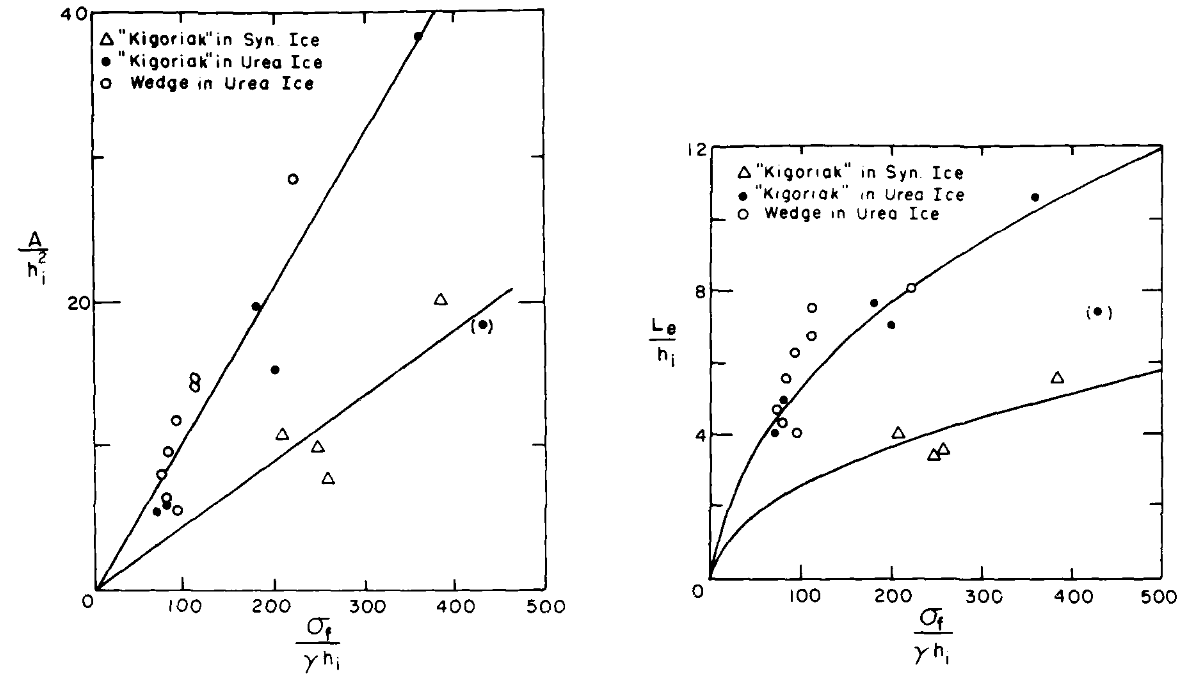


Figure 8. Floe size distribution from tests in level ice with an idealized icebreaker bow (Tatinclaux 1986).



a. Floe area. *b. Floe length.*

Figure 9. Dimensionless test results (Tatinclaux 1986).

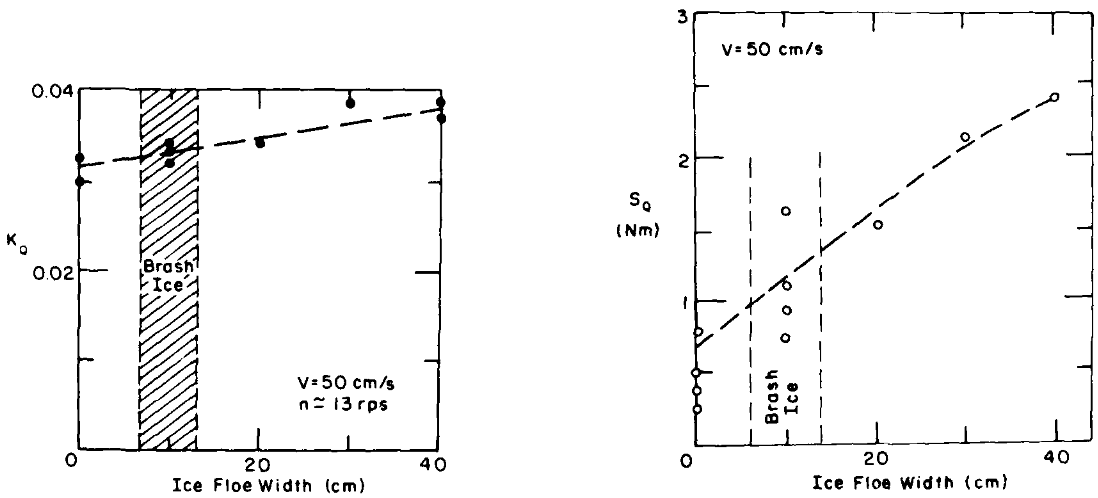


Figure 10. Effect of floe size on propeller performance (Tatinclaux 1987).

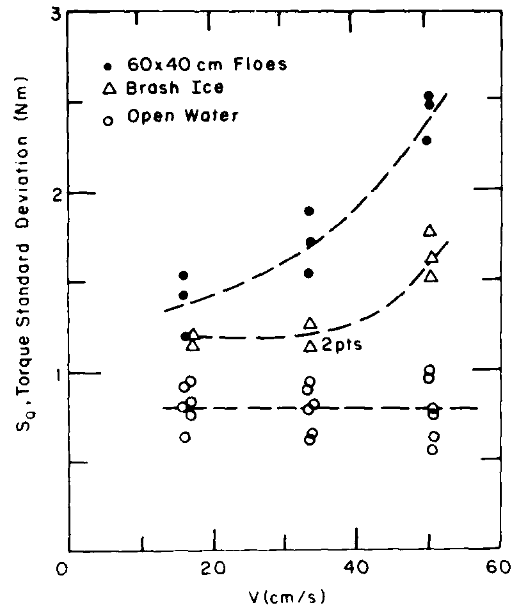


Figure 11. Effect of floe size and velocity on propeller torque standard deviation (Tatinclaux 1987).

ffect the trajectory of the ice floes along the ull and therefore the ice–propeller interaction. As a ship (model or prototype) travels hrough ice, the broken floes are submerged y the bow to some depth, and they then rise because of buoyancy. Ice may be ingested if the hip has traveled one ship-length before the loes have fully risen to near the surface. Since model ice is usually somewhat denser han field ice, the model floes may be submerged deeper and rise slower than full-scale ice floes. Therefore, it can be expected that ice will be ingested by the propeller at a ship speed lower than at full scale, and that it will also be more severe. An analytical and experimental study has been initiated to address these questions. The results of a first crude mathematical model of ice floe trajectory along a rigid surface are shown in Figure 12.

As a final comment, it is again emphasized that one main difficulty in comparing results of model studies with full-scale results is the lack of reliable and complete sets of prototype data.

NOVEL ICEBREAKING BOW DESIGNS

The past decade has witnessed the development of new icebreaking bows, the shapes of which depart radically from the conventional ones. A bow shape, first proposed and patented by Waas (1976), has been further developed and extensively tested in West Germany both in the laboratory and in the field (Freitas 1981, 1982; Hellmann 1982; Freitas and Nishizaki 1985; Schwarz 1986). From its original conception (Fig. 13) the Waas bow has evolved into radically new shapes (Fig. 14). Basically, it has square shoulders, a very low stem angle at the water line, and an initially flat bottom that evolves into a wedge. This bow first shears the level ice at the shoulders, then breaks it in bending into pairs of regularly shaped ice floes, which are deflected outwards under the remaining ice sheet. According to its developers, the main advantages of the Waas bow over conventional icebreaker bows are: more efficient icebreak-

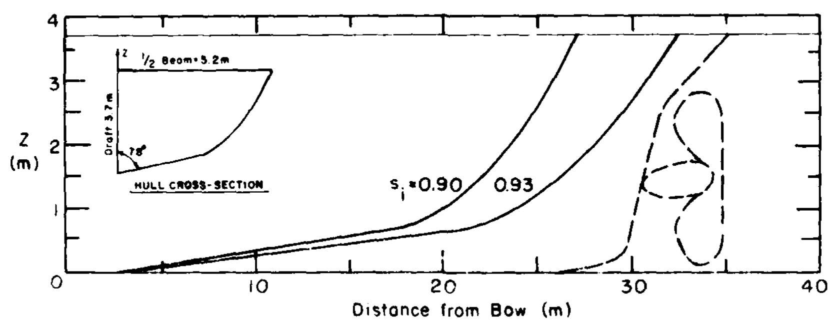


Figure 12. Expected effect of ice density on ice floe trajectory along a ship hull.

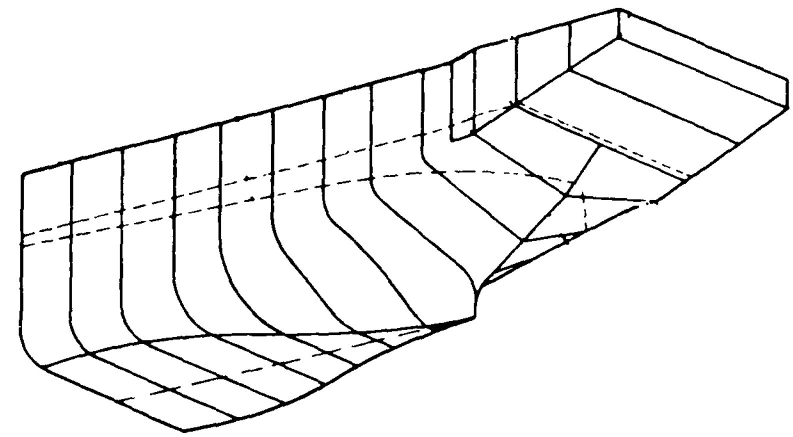


Figure 13. Original Waas bow concept (Waas 1976).

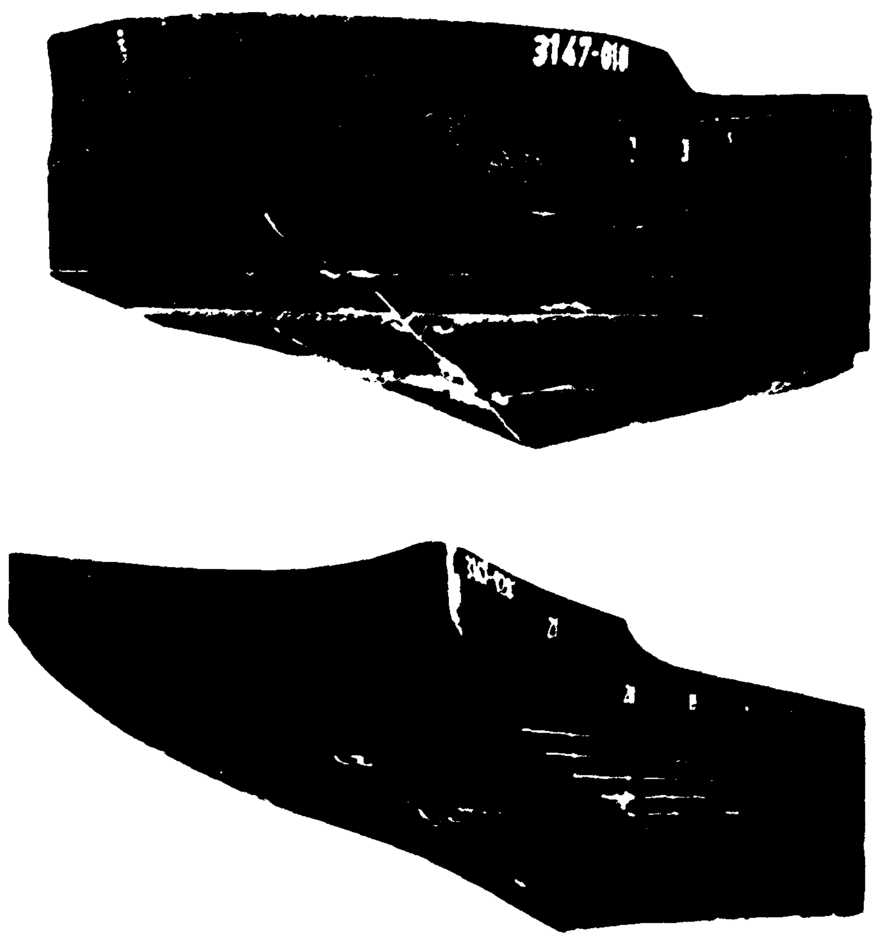


Figure 14. Recent developments in Thyssen-Waas bow (From Transactions of the ASME, Journal of Energy Resources, *A. Freitas and R.S. Nishizaki, June 1986).*

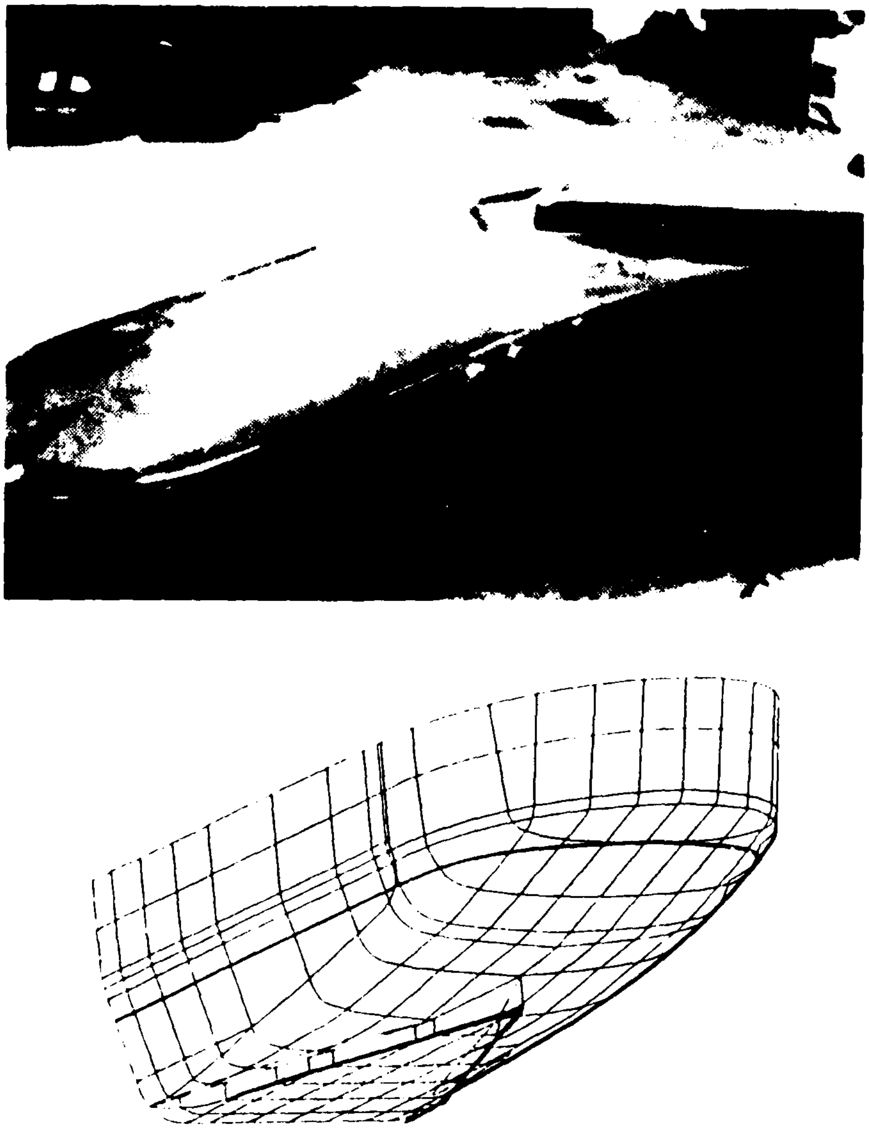


Figure 15. Wartsila experimental bow (From Enkvist and Mustamaki 1986).

ing, i.e., reduced ice resistance and required power; improved maneuverability in level ice; and creation of a nearly ice-free channel with little or no ice–propeller interaction up to speeds of 5 knots [2.5 m/s]. The effects of the Waas bow on a vessel's seakeeping capabilities, performance in waves and ice ridges remain a subject of controversy. A soviet icebreaker has recently been retrofitted with such a bow, the U.S. Coast Guard has initiated an evaluation program of its performance potential, and its developers are attempting to adapt this bow to shallow draft icebreakers for operation in estuaries and rivers.

Another experimental icebreaking bow has been recently designed and tested at model and full scales in Finland (Enkvist and Mustamaki 1986). This bow has a small stem angle, circular waterlines and a plow or deflector vanes to deflect the broken ice floes outwards (Fig. 15). Model and full-scale tests showed a significant decrease in icebreaking resistance in level ice over a conventional bow, but no essential improvement of performance in ridges and old broken channels, and no improvement in maneuverability in ice. An increase in open water resistance and in slamming during transit in head sea was observed. Enkvist and Mustamaki did not recommend this innovative bow for vessels operating primarily in open water or in ice ridges or rubble ice. They would limit the operation of this bow to areas of thick level ice such as rivers, lakes and sheltered regions along a sea coast. In the oral presentation of their paper, Enkvist and Mustamaki indicated that the experimental bow was mounted on a towboat and used to open the Saima Canal to navigation at the end of the 1985-86 winter. They reported that a navigation channel, nearly free of ice, was opened in less than a day, when in previous years it had taken several days for a towboat working alone to open the navigation channel, which contained a large amount of brash ice.

While not radically different from conventional icebreaker bows, a new bow was recently designed by Melville Shipping Ltd, Ottawa, for the cargo ship MV *Arctic*. This Melville bow proved to significantly improve the ice performance of the MV *Arctic* (Baker and Nishizaki 1986), confirming the model tests carried out at various facilities.

CONCLUSIONS AND FINAL REMARKS

Since the mid-1970s significant improvements have been made in the methodology of ship testing in ice for both EHP and SHP tests, as well as in the development and characterization of model ice. The art and science of model testing in ice has now reached the point where model tank operators are confident that model test results can be used in predicting the performance of ice-going vessels, in suggesting modifications to existing ships to improve their ice performance (e.g., Baker and Nishizaki 1986), and in designing radically new bow shapes for icebreakers and other ice-going vessels. The progress thus made has allowed the construction of ice-going vessels with improved ice performance at lower power requirements. Further improvements are to be expected in the future as better understanding of the physics of ship–ice interaction is gained and, especially, as more and better field data are acquired from full-scale trials. Areas where improvements are more urgently needed are:

1. Knowledge of the effect of fracture toughness on icebreaking resistance, breaking pattern and ice floe size distribution.

2. Knowledge of the effect of ice floe size and model ice density on floe trajectory, ice–propeller interaction and propeller performance (thrust, torque and shaft power).

3. Measurement of ice–hull friction coefficient at model and full scales and its effect on icebreaking resistance and propeller performance.

4. Analytical description of ship–ice interaction.

5. Detailed documentation of full-scale trials in ice, especially of the ice mechanical properties.

6. Development of apparatus and standardized methods for measuring ice properties, both at model and full scales; in particular, an apparatus for field measurement of ice–hull friction coefficients.

While this paper dealt only with modeling of ships in level ice, it should be mentioned that research efforts are also actively pursued in areas of ship motion in brash and mush ice, and of ship–ice-ridge interaction (ramming tests) (ITTC 1984). The latter is of particular importance since extensive fields of level ice are the exception in the arctic and subarctic regions, while ridges are ever present and can seldom be entirely avoided.

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