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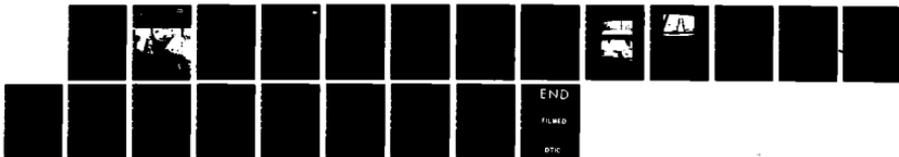
PROPULSION TESTS IN LEVEL ICE ON A MODEL OF A 140-FT
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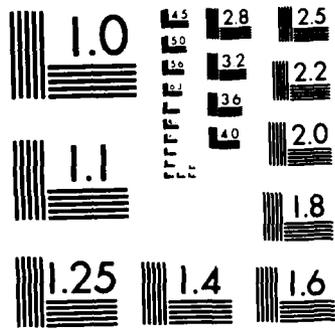
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*Propulsion tests in level ice on a model
of a 140-ft WTGB icebreaker*



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Cover: Icebreaker model during a propulsion test.

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March 1985



Propulsion tests in level ice on a model of a 140-ft WTGB icebreaker

Jean-Claude Tatinclaux

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PREFACE

This report was prepared by Dr. Jean-Claude Tatinclaux, Research Hydraulic Engineer, Ice Engineering Research Branch, Experimental Engineering Division, U.S. Army Cold Regions Research and Engineering Laboratory. Funding for the project was provided by the U.S. Coast Guard under Contract No. MIPR Z70099-2-06490.

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PROPULSION TESTS IN LEVEL ICE ON A MODEL OF A 140-FT WTGB ICEBREAKER

Jean-Claude Tatinclaux

INTRODUCTION

The United States Coast Guard initiated a model experimental program in ice at the U.S. Army Cold Regions Research and Engineering Laboratory (CRREL) on models of the 140-ft WTGB at scales of 1:9.273 and 1:24. The 140-ft WTGB is a Great Lakes icebreaker designed to operate in the continuous mode of ice breaking at a speed of 1.5 m/s (3 knots) in 0.46 m (18 in.) of level ice.

Following resistance tests in level ice on two models of the 140-ft WTGB icebreaker (Tatinclaux 1984), propulsion tests in level ice were conducted on the larger model (scale 1:9.273). The resistance test program was completed in December 1982, and the propulsion tests were made in April-May 1984. Between the two test programs at CRREL, the model was refurbished and was to be tested in ice-free water at the U.S. Naval Academy, Annapolis, Maryland. This report presents the results of the propulsion tests in ice.

TEST CONDITIONS

The model tests were restricted to only one ice thickness corresponding to a full-scale thickness of 0.46 m (18 in.) and to a narrow range of ice flexural strengths close to a full-scale value of 800 kPa. The majority of the tests were conducted at a model speed corresponding to a full-scale ship speed of 1.54 m/s (3 knots). Only one test series each was conducted at model speeds corresponding to full-scale values of 1.03 and 2.06 m/s (2 and 4 knots). In addition, two resistance tests were conducted at the equivalent full-scale ice thickness of 0.46 m and ship speed of 3 knots.

The model had been refurbished after the resistance test program and prior to the propulsion tests. The friction coefficient between the ice and the newly repainted hull averaged 0.12, compared to 0.14 for the previous conditions. The lower friction factor turned out to significantly reduce the model resistance in ice. The results of the friction tests are given in Table 1.

EXPERIMENTAL SET-UP AND PROCEDURES

The ship model came equipped with a four-bladed stock propeller with a nominal diameter of 28 cm (11 in.) used in earlier, ice-free tests (West 1975). The propeller shaft was connected to a thrust-torque dynamometer rated at 1100 N (250 lb) in thrust and 11.5 Nm (100 in.-lb) in torque. The input shaft of the dynamometer was driven by

Table 1. Results of friction coefficient tests.

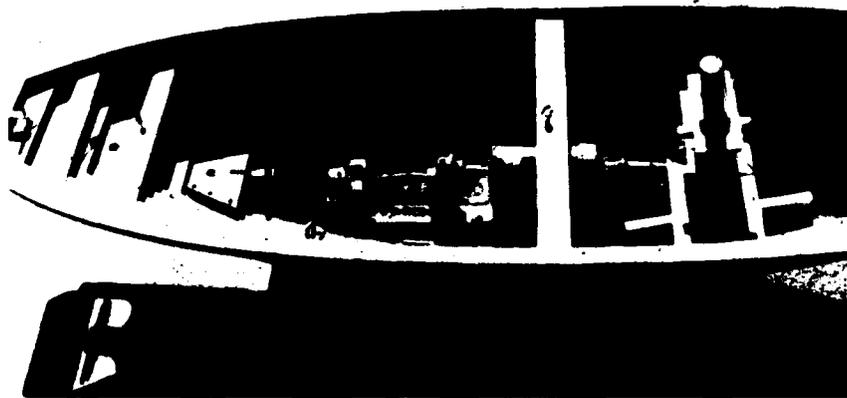
	N (N)	T (N)	μ_k	$\bar{\mu}_k$
Top surface	783	108	0.138	
of ice	783	106	0.135	0.134 ± 0.005
	783	101	0.129	
Bottom surface	783	84.3	0.108	
of ice	783	86.7	0.111	0.108 ± 0.003
	783	82.9	0.106	

Overall average: $\bar{\mu}_k = 0.121 \pm 0.014$.

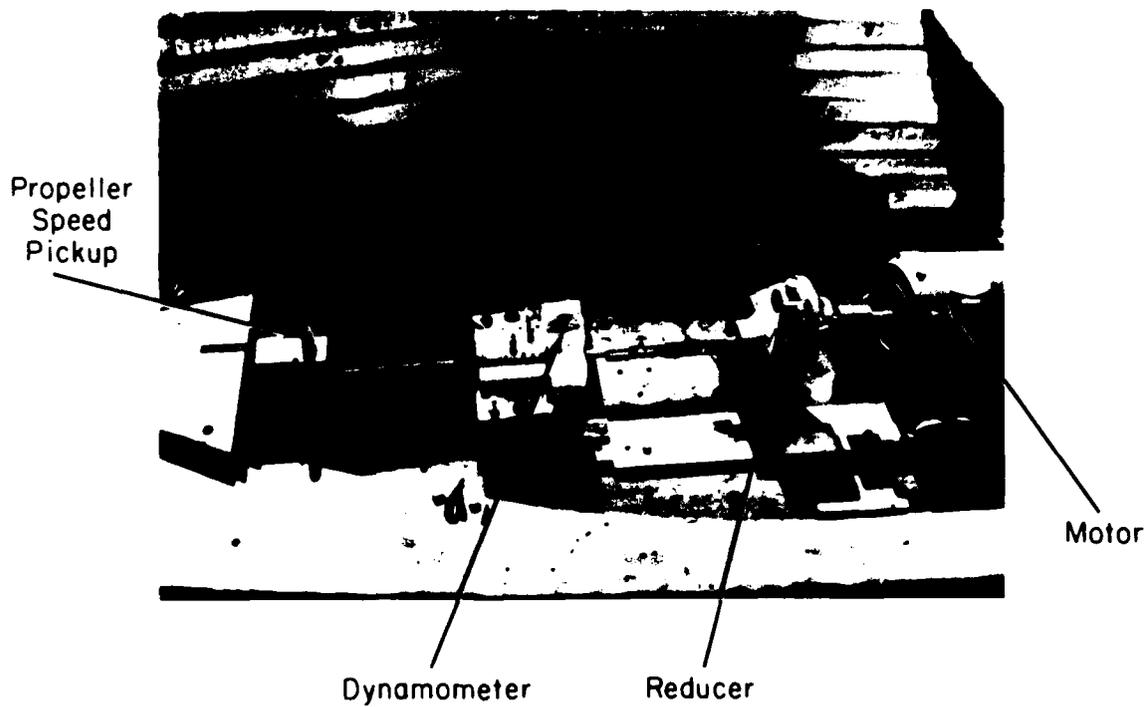
N = total normal load applied on ice sample.

T = measured tangential force.

μ_k = friction coefficient = T/N .

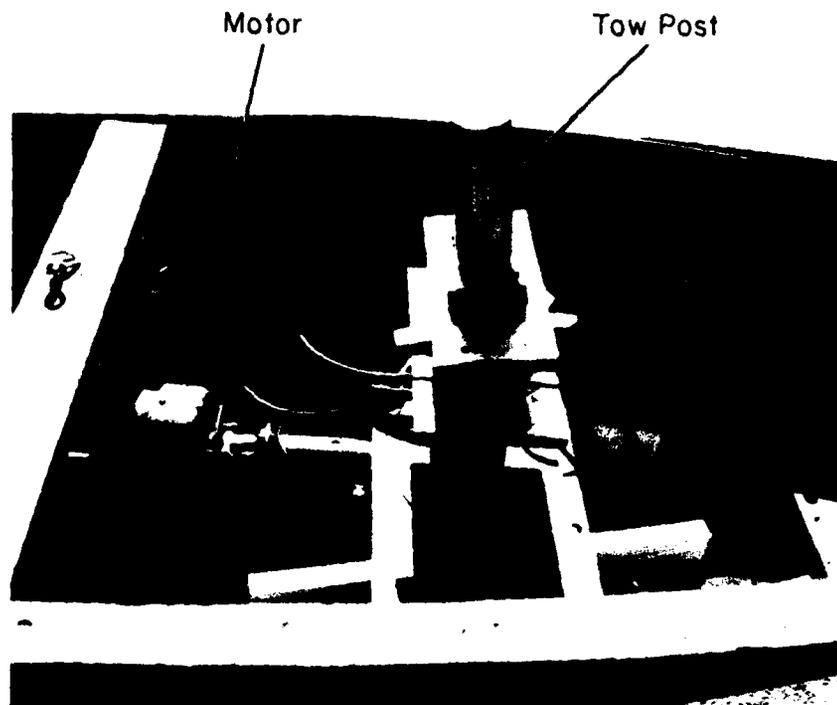


a. General view.



b. Drive system.

Figure 1. Views of model equipped for propulsion tests.



c. Tow post assembly.

Figure 1 (cont'd).

an 1100-W (1.5-hp) variable-speed motor via a 1:1.7 gear reducer. The shaft rotational speed was measured by a magnetic pickup over a 60-tooth gear mounted on the shaft. The propulsion assembly is shown in Figure 1.

In the propulsion tests the model remained connected to the towing post of the test basin carriage. For each ice sheet the carriage, and therefore the model speed, was kept constant, and two to three runs at different propeller speeds were made. The corresponding thrust and torque on the propeller and pull on the tow post were measured. A positive pull indicated that the model was restrained by the tow post, i.e. that its self-propulsion speed was higher than that imposed by the carriage.

Prior to the actual propulsion tests in ice, a series of forward bollard tests were made to check the overall propulsion assembly by comparing the measured pull against that obtained in similar tests at the Naval Ship Research and Development Center (NSRDC) (West 1975). These tests were also used to calibrate the dynamometer against the NSRDC results, since CRREL does not have the equipment necessary for in situ calibration. Forward bollard tests were also made immediately be-

fore most of the propulsion tests in ice to ensure that the propulsion and measurement systems were functioning properly.

In the current tests the heave and pitch angle of the ship model were measured. The vertical displacements d_b and d_s at two points, one in the bow, the other in the stern, at equal distances L from the center of gravity along the ship centerline, were measured by two linear displacement transducers. The heave H and pitch angle ϕ are given by

$$H = \frac{d_s + d_b}{2} \quad (1)$$

$$\phi = \tan^{-1} \left(\frac{d_b - d_s}{2L} \right) \quad (2)$$

RESULTS

Bollard tests

The results of the bollard tests are listed in Table 2. The measured pull is plotted against propeller speed in Figure 2, which also shows the data obtained in ice-free water at NSRDC. The data

Table 2. Bollard test results.

Test no.	Propeller speed n (rpm)	Pull (N)	Thrust T_{1A} (N)	Torque Q_{1A} (Nm)	Thrust coefficient K_T	Torque coefficient $10K_Q$
30	452	94.1	102.9	3.08	0.298	0.319
	558	145.5	152.8	4.81	0.290	0.327
50	663	205.8	219.5	6.83	0.277	0.329
	718	242.6	258.8	8.00	0.297	0.328
	772	280.4	295.3	9.27	0.293	0.329
	827	322.4	339.0	10.68	0.293	0.330
	876	345.4	361.7	11.98	0.278	0.330
	772	279.9	320.0	9.26	0.317	0.329
60	507	118.2	134.5	3.86	0.309	0.317
	679	214.6	225.9	7.11	0.289	0.326
	843	332.7	351.0	11.06	0.292	0.329
	872	355.9	375.9	11.84	0.292	0.329
411*	791	274.7	325.2	9.52	0.307	0.322
421	837	326.3	337.6	10.96	0.285	0.331
511	794	292.8	297.8	9.77	0.279	0.328
531	729	248.4	252.1	8.25	0.280	0.328
611	857	342.7	362.1	11.49	0.291	0.331
621	767	275.0	286.9	9.14	0.288	0.328
631	592	162.6	193.9	5.33	0.327	0.322

* Tests 411-631 were run immediately before propulsion tests.

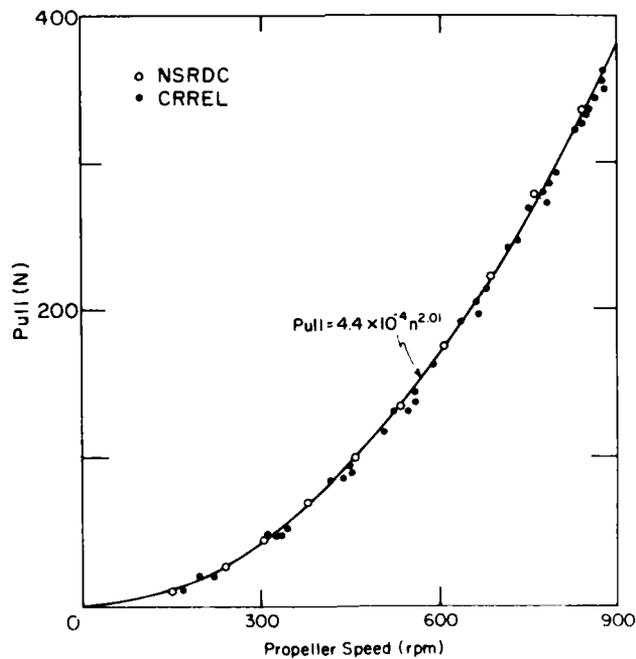


Figure 2. Comparison between NSRDC and CRREL bollard tests. Pull vs propeller speed.

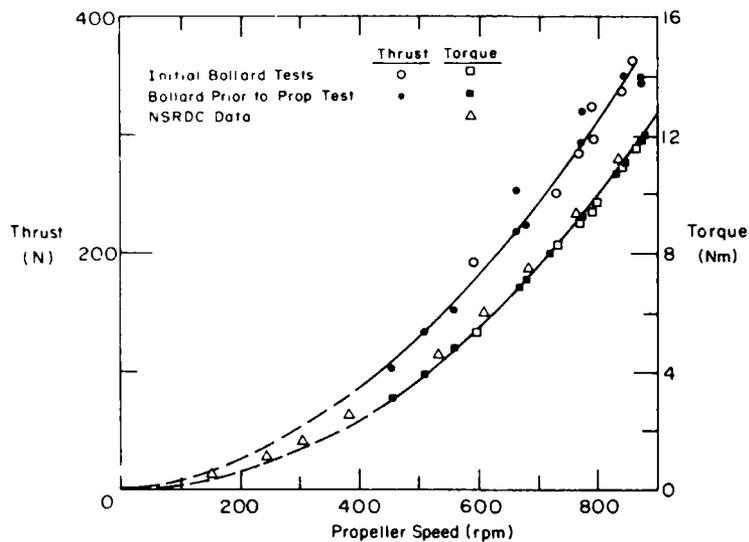


Figure 3. Results of bollard tests. Thrust and torque vs propeller speed.

Table 3. Results of model propulsion tests.

Test no.	Ice thickness h (cm)	Ice flexural strength σ (kPa)	Modulus of elasticity of ice E (MPa)	Ship velocity V (cm/s)	Propeller speed n (rpm)	Pull (N)	Thrust T_{IA} (N)	Torque Q_{IA} (Nm)	Heave H (cm)	Pitch angle ϕ (deg)
110	5.2	85	105	33.5	790	7.4	323.1	10.97	0.8	1.0
120	5.2	85	105	33.5	814	29.9	342.5	11.31	0.9	0.9
130	5.2	85	105	33.7	825	40.6	352.7	11.62	0.8	0.9
210	4.9	75	115	51.7	870	18.6	315.8	10.81	0.7	0.9
220*	4.9	75	115	51.7	0	-213.1	—	—	0.6	0.6
230	4.9	75	115	52.2	835	-8.3	318.7	11.40	0.6	0.8
310	5.3	76	112	66.7	826	-91.6	281.8	11.88	0.8	1.0
320	5.3	76	112	66.8	732	-137.7	234.5	11.86	0.7	1.0
330	5.3	76	112	66.7	724	-132.5	222.5	12.06	0.8	0.9
410	5.3	75	146	50.6	813	-51.0	284.3	12.03	0.7	1.0
420	5.3	75	146	50.1	798	-45.3	258.1	12.06	0.8	1.0
430*	5.3	75	146	50.2	0	-252.8	—	—	0.8	0.8
510	4.8	90	76	50.6	827	5.0	258.6	11.86	0.7	0.8
520	4.8	90	76	50.2	811	26.1	263.3	11.64	0.6	0.7
530	4.8	90	76	50.2	775	-14.6	228.5	10.62	0.6	0.7
610	4.2	65	80	50.5	869	90.9	298.7	11.69	0.5	0.7
620	4.2	65	80	50.4	818	61.2	264.4	10.58	0.4	0.6
630	4.2	65	80	50.3	647	-21.3	171.7	7.01	0.5	0.5

* Tests 220 and 430 were resistance tests (idle propeller).

from NSRDC and CRREL are in excellent agreement. The torque and thrust values are plotted versus propeller speed in Figure 3 for the initial bollard test results and for those just before the propulsion tests in ice; all those results are in agreement.

Propulsion and resistance tests

The conditions and results of the tests in level ice are listed in Table 3. Six series of propulsion tests were made. Within each test series the ice properties and model tow speed were constant, and only the propeller speed was varied. Sixteen

propulsion tests and two resistance tests were done. The results of these resistance tests were critical to the analysis of the propulsion tests, and more such tests would have been extremely useful.

ANALYSIS OF TEST RESULTS

Resistance tests

From the previous resistance test results (Tatinclaux 1984), the following regression equation for the total resistance in level ice R_{ii} had been obtained

$$\frac{R_{ii}}{\gamma B h^2} = 2.28 + 0.784 F_n^2 + C_n [0.042 + 0.0063 F_n] + \frac{R_{ow}}{\gamma B h^2} \quad (3)$$

where γ = specific weight of water

B = maximum beam at water level

h = ice thickness

$F_n = V/\sqrt{gh}$

V = ship velocity

g = acceleration due to gravity

$C_n = \sigma_i/(\gamma h)$

σ_i = ice flexural strength.

The quantity R_{ow} is the ship resistance in ice-free water and was estimated by

$$R_{ow} = 13.84 V^{2.02} \quad (4)$$

for the ship model, and by

$$R_{ow} = 586 V^{2.13} \quad \text{for } V < 5 \text{ m/s}$$

$$R_{ow} = 38 V^{3.81} \quad \text{for } 5 < V < 7.2 \text{ m/s} \quad (5)$$

for the full-scale ship. In eq 4 and 5, R_{ow} is expressed in newtons and V is in meters per second.

When applied to the conditions of the two resistance tests (tests 220 and 430), eq 3 predicted ice resistance values ($R_{ii} = R_{ii} - R_{ow}$) of 264.2 and 289.0 N, respectively. The measured ice resistances, 209.5 N for test 220 and 249.4 N for test 430, averaged 83% of the predicted values. In this test series the model hull ice friction coefficient was only 0.121, or 86% of the friction factor measured in the earlier series of resistance tests. Because of the apparent correlation between the friction factor and ice resistance, and for lack of additional data, it was assumed that the ice resistance (total resistance minus open water resistance) in this

series of propulsion tests could be estimated to be 83% of that predicted by eq 3, that is

$$\frac{R_{ii}}{\gamma B h^2} = 1.89 + 0.65 F_n^2 + C_n [0.035 + 0.0052 F_n] + \frac{R_{ow}}{\gamma B h^2} \quad (6)$$

Of course the variation in the hull friction coefficient may affect the various components of the ice resistance to varying degrees, but the two resistance tests were insufficient to determine the effect on each component.

Propulsion tests

For the conditions of the propulsion tests listed in Table 3, the corresponding total resistance in ice R_{ii} was calculated by eq 6, and the thrust deduction factor t was then obtained from

$$t = 1 - \frac{R_{ii} + Pull}{T_{IA}} \quad (7)$$

where $Pull$ is the average force restraining the model and T_{IA} is the average measured thrust in ice. The advance coefficient

$$J_v = V/nD \quad (8)$$

the thrust coefficient

$$K_T = T_{IA}/(\rho n^2 D^4) \quad (9)$$

and the torque coefficient

$$K_Q = Q_{IA}/(\rho n^2 D^5) \quad (10)$$

were also calculated, with

n = propeller speed

D = propeller diameter

ρ = water density

Q_{IA} = average measured torque in ice.

The results of these calculations are given in Table 4.

In view of the scatter in the data and the narrow range over which J_v was varied, it was unjustified to attempt to find variation of t , K_T and K_Q with J_v . Only the average values and standard deviations were calculated: $\bar{t} = 0.214 \pm 0.150$, $\bar{K}_T = 0.255 \pm 0.028$ and $\bar{K}_Q = 0.0359 \pm 0.0025$.

Model self-propulsion points

Two methods can be used to determine the self-propulsion points of the model, i.e. the propeller

Table 4. Analysis of model test results.

Test no.	Advance coefficient J_a	Thrust coefficient K_T	Torque coefficient $10K_Q$	Froude number F_n	Cauchy number C_n	Total resistance in ice R_{ii}^* (N)	Thrust deduction factor t^\dagger
110	0.091	0.306	0.372	0.469	166.6	246.3	0.219
129	0.088	0.305	0.361	0.469	166.6	246.3	0.198
130	0.088	0.306	0.361	0.472	166.6	246.5	0.186
210	0.128	0.246	0.303	0.746	156.0	222.4	0.237
220	—	—	—	0.746	156.0	222.4	—
230	0.134	0.270	0.345	0.753	156.0	222.7	0.327
310	0.173	0.244	0.368	0.925	146.6	261.0	0.399
320	0.196	0.259	0.467	0.925	146.6	261.0	0.474
330	0.198	0.251	0.486	0.925	146.6	261.0	0.423
410	0.137	0.254	0.384	0.718	144.3	244.1	0.321
420	0.135	0.239	0.400	0.696	144.3	242.7	0.234
430	—	—	—	0.695	144.3	242.7	—
510	0.131	0.223	0.367	0.737	191.1	247.4	0.024
520	0.133	0.236	0.374	0.732	191.1	247.1	-0.038
530	0.139	0.225	0.374	0.732	191.1	247.1	-0.018
610	0.125	0.234	0.327	0.787	157.0	166.4	0.139
620	0.132	0.233	0.334	0.785	157.0	166.3	0.140
630	0.167	0.242	0.354	0.784	157.0	166.3	0.156

* Total resistance R_{ii} , calculated by eq 6.

† Thrust deduction factor t calculated by eq 7.

speed and corresponding thrust and torque at which the pull is zero.

Interpolation method

Since the series of tests for each ice sheet was conducted under practically identical ice conditions and model speeds but at two or three propeller speeds, the self-propulsion point of the model can be obtained by interpolating or extrapolating the data of each test series. For each test series the measured pull, thrust and torque are plotted against n^2 , the square of the propeller speed. The straight line drawn through the pull data points intersects the horizontal axis (pull = 0) at the self-propulsion value of n^2 , and the corresponding points on the thrust and torque lines give the thrust and torque at the self-propulsion point. Examples of this graphical method are given in Figure 4, and the results of this method of data analysis are given in Table 5.

Averaging method

The self-propulsion points can also be calculated from the average values of t , K_T and K_Q obtained from all the tests. For the ice properties and model speed of each test series, the total resistance

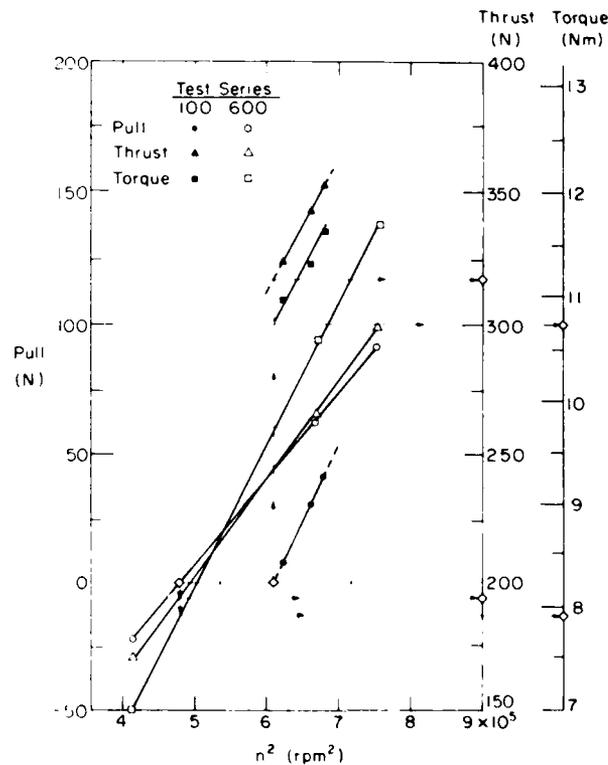


Figure 4. Graphical determination of self-propulsion points from test results.

Table 5. Model self-propulsion points.

Test series	Test conditions			Interpolation method			Average method*		
	h_i (cm)	σ_i (kPa)	V (cm/s)	n (rpm)	T_{IA} (N)	Q_{IA} (Nm)	n (rpm)	T_{IA} (N)	Q_{IA} (Nm)
100	5.2	85	33.5	782	317	10.8	852	313	12.3
200	4.9	75	52.0	846	317	11.0	810	283	11.1
300	5.3	76	66.7	984	413	—	876	331	13.0
400	5.3	75	51.0	—	—	—	847	310	12.2
500	4.8	90	50.3	814	249	11.5	854	314	12.4
600	4.2	65	50.4	695	194	7.9	701	212	8.3

* $t = 0.214$; $K_T = 0.255$; $K_Q = 0.0359$.

is calculated by eq 6. The required thrust is then given by

$$T_{IA} = \frac{R_{II}}{1-t} \quad (11)$$

The corresponding propeller speed is obtained from

$$n = \left(\frac{T_{IA}}{\rho \bar{K}_T D^4} \right)^{1/2} \quad (12)$$

and the corresponding torque is given by

$$Q_{IA} = \rho n^2 D^5 \bar{K}_Q \quad (13)$$

The results of these calculations for the six test conditions are also presented in Table 5.

The results obtained by the two methods show significant differences, which is to be expected since even relatively small variations in either t , K_T or K_Q will affect the results. For example, for test series 100 at a thrust of 313 N, if one assumes a value of K_T of 0.306 instead of 0.255 (an increase of 20%), the computed propeller speed becomes 777 rpm (a 9% decrease), while the computed torque decreases by 17% to 10.3 Nm and the resulting shaft power ($P_{DI} = 2 \pi n Q_{IA}$) decreases by 24% from 1097 to 834 W.

COMPARISON WITH FULL-SCALE DATA

Full-scale trials of the 140-ft Great Lakes icebreaker USCG *Katmai Bay* were conducted between January and March 1979. The results have been reported by Vance (1980a, b). The full-scale trial conditions and measured quantities of thrust, torque and propeller speed for those runs made in level ice with no bubblers on are listed in Table 6,

together with the corresponding values of J_v , K_T and K_Q .

Most of the full-scale values of the Froude number F_n , which ranged from 0.27 to 2.9, are outside the range of the model Froude number, namely 0.47–0.93. Similarly the values of J_v ranged from 0.09 to 0.5 in the full-scale trials but only from 0.09 to 0.2 in the model tests. On the other hand the large majority of the full-scale values of C_n , ranging from 155 to 227, fall within the range of the model test values, 147–191.

Propeller characteristics

The full-scale and model-scale values of K_T and K_Q are plotted against J_v in Figure 5. The full-scale thrust coefficient decreases from about 0.32 at $J_v = 0.1$ to 0.24 at $J_v = 0.4$. In the model test range of J_v , the full-scale values of K_T are consistently higher than the model data. The full-scale torque coefficient K_Q is nearly constant with J_v , with an average value of 0.0340, slightly lower than the average value of K_Q obtained from model tests.

The difference in the model and full-scale values of K_T can be attributed to two factors: 1) the model propeller was a stock propeller, which may have a lower thrust efficiency than the actual propeller used on the USCG *Katmai Bay*; and 2) it has been reported (Keinonen 1983, Arctec Canada Ltd. and Canadian Marine Drilling Ltd. 1984) that model ice floes broken in the bow region by model icebreakers are relatively larger than the full-scale floes and are more readily entrained into the propeller disk, thereby reducing the thrust and increasing the torque at comparable propeller speed, or requiring higher model propeller speed to achieve a model thrust comparable to the full-scale value. In addition, since the model scale value of K_Q is slightly higher than its full-scale value, a higher propeller speed at a given thrust will result in an excessive predicted torque Q_{IA} and an

Table 6. Full-scale data in level ice.

Run	Ice thickness h (cm)	Ship velocity V (m/s)	Ice flexural strength σ_i^* (kPa)	Propeller speed n (rpm)	Thrust T_{IA} (kN)	Torque Q_{IA} (kNm)	Advance coefficient J_v	Thrust coefficient K_T	Torque coefficient $10K_Q$
30 Jan 79									
1000	30.5	0.72	610	148	86	24.1	0.113	0.312	0.339
1010	38.1	2.88	580	209	149	48.5	0.319	0.273	0.343
1020	27.9	4.01	600	245	185	65.3	0.379	0.246	0.336
1030	27.9	4.52	580	259	196	75.0	0.405	0.234	0.346
31 Jan 79									
1100	35.6	0.50	660	133	79	19.8	0.088	0.357	0.347
1110	36.8	2.78	660	214	154	49.6	0.301	0.269	0.334
1120	35.6	5.44	650	252	191	67.2	0.499	0.240	0.325
1130	38.1	4.62	650	267	203	71.9	0.401	0.228	0.311
1200	38.1	2.82	(620)	204	145	47.5	0.321	0.278	0.353
1210	33.0	3.74	(620)	237	169	60.0	0.366	0.242	0.334
1220	27.9	4.51	620	263	196	72.0	0.397	0.226	0.321
9 Feb 79									
1300	38.1	1.00	(640)	192	96	41.9	0.120	0.207	0.349
1310	40.6	1.87	(640)	219	184	53.6	0.197	0.305	0.343
1320	41.9	2.58	(640)	247	213	67.9	0.242	0.279	0.344
1330	40.6	2.24	(640)	250	225	74.9	0.207	0.286	0.368
1331	36.8	2.87	640	254	218	75.0	0.261	0.269	0.353

* The values for σ_i within parentheses are values assumed equal to the strength actually measured for one run of the corresponding test series.

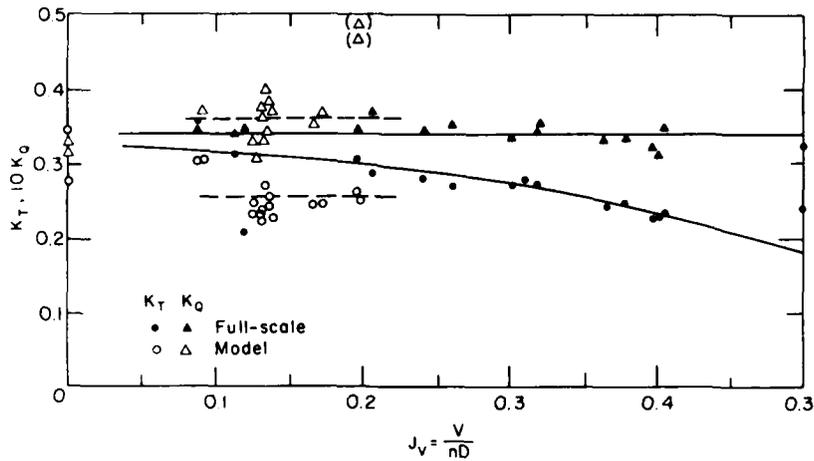


Figure 5. Propeller characteristics. K_T and K_Q vs J_v .

even larger prediction of the required shaft power P_{DI} , since $P_{DI} = 2 \pi n Q_{IA}$. Indeed, underwater video observation of the model stern area showed severe ice entrainment into the propeller, which continuously milled ice.

Thrust

For the full-scale conditions of ice thickness, ice strength and ship speed, the total ice resistance

was calculated according to eq 6, and the required thrust was obtained assuming a thrust deduction factor equal to that determined from the model tests ($t = 0.214$). The predicted thrust is listed in Table 7 and plotted against the measured thrust on Figure 6a. It can be seen that 81% of the calculated thrust values (13 out of 16) lie between 90% and 150% of the measured values. The ratio of calculated thrust to measured thrust has an aver-

Table 7. Predicted full-scale performance.

Run	T_{IA} (kN)	From model tests K_T, K_Q			From full-scale K_T, K_Q		
		n (rpm)	Q_{IA} (kNm)	P_{DI} (HP)	n (rpm)	Q_{IA} (kNm)	P_{DI} (HP)
1000	112	188	40.9	1080	169	31.3	743
1010	194	247	70.7	2452	236	61.5	2038
1020	177	236	64.7	2144	242	64.4	2189
1030	192	245	69.9	2405	257	72.9	2631
1100	144	213	52.6	1573	190	39.6	1057
1110	201	251	73.1	2577	238	62.6	2092
1120	307	310	111.8	4867	321	113.6	5121
1130	279	296	101.9	4236	297	97.5	4067
1200	201	251	73.2	2580	240	63.2	2130
1210	202	252	73.8	2612	251	69.2	2439
1220	199	250	72.5	2545	261	75.2	2756
1330	160	224	58.6	1843	202	45.2	1282
1310	192	245	70.1	2412	226	56.4	1790
1320	219	262	80.1	2947	246	67.0	2315
1330	202	252	73.6	2605	235	61.0	2013
1331	199	250	72.7	2552	238	62.6	2092

Table 8. Average ratio between predicted and measured full-scale performance (excluding runs 1120 and 1130).

		Thrust*	Propeller speed	Torque	Shaft horsepower
From model K_T, K_Q	Mean	1.201	1.123	1.345	1.582
	Std. dev.	0.283	0.175	0.450	0.869
From full-scale K_T, K_Q	Mean	1.201	1.070	1.149	1.263
	Std. dev.	0.283	0.127	0.293	0.523

* Thrust calculated from predicted resistance (eq 6) and model thrust deduction factor 0.214.

age value of 1.20, with a standard deviation of 0.28 (Table 8).

Propeller speed, torque and shaft power

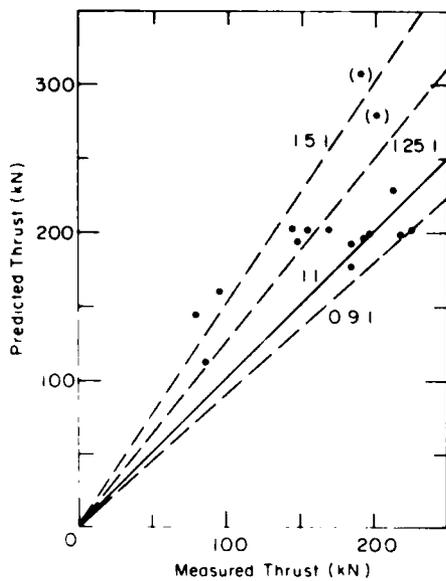
Once the thrust has been calculated, the corresponding propeller speed, torque and power are obtained from the thrust coefficient K_T and torque coefficient K_Q . Two sets of calculations were done. First the values of $K_T = 0.255$ and $K_Q = 0.0359$ obtained from model tests were used. In the second the full-scale values of $K_Q = 0.0340$ and K_T obtained from Figure 5 were used. The results of these calculations are listed in Table 7 and plotted in Figure 6b for propeller speed, Figure 6c for torque and Figure 6d for delivered power.

The predicted values are usually higher than the measured ones and are even more so when the val-

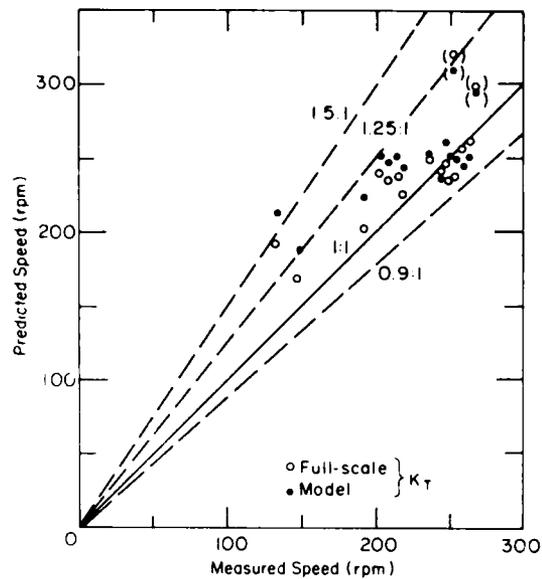
ues of K_T and K_Q obtained from the model test results were used. The average and standard deviation of the ratios of predicted value over measured value for propeller speed, torque and delivered power are listed in Table 8.

PREDICTION OF SHIP ICEBREAKING CAPABILITY

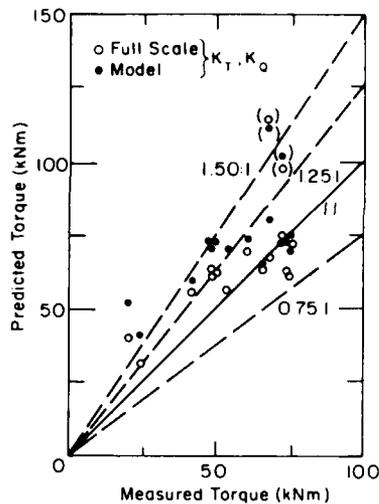
The 140-ft WTGB icebreaker is equipped with a shaft horsepower of 2500 hp. Once the equation for the ship resistance in ice and the propeller characteristics t, K_T and K_Q are known, it is possible to predict the maximum ice thickness h_{Imax} that the ship is capable of breaking at full power and at a given speed. Such predictions were calculated using the resistance equation, the value of t obtained



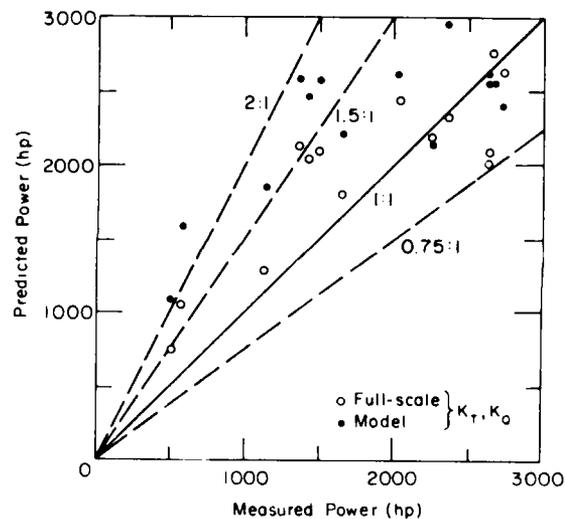
a. Thrust.



b. Propeller speed.



c. Torque.



d. Delivered shaft power (runs 1120, 1130 excluded).

Figure 6. Comparison between measured and predicted full-scale performance.

from the model tests, and the values of K_T and K_Q obtained from both model tests and full-scale trials. The calculations were also made for two ice strengths: 600 and 800 kPa.

The results of these calculations are presented in Figure 7. The model data underpredict the full-scale performance for ship velocity below 8 knots and overpredict it above 8 knots. This cross-over occurs because the model value of K_T is initially smaller than the full-scale value for $J_v < 0.35$ but is larger for $J_v > 0.35$. Overall, the agreement be-

tween model predictions and full-scale data is reasonable.

DISCUSSION OF RESULTS

The results presented in Figures 6 and 7 and Table 8 indicate that, on average, the model tests somewhat underpredict the actual ship performance. Since it is presumed that the full-scale measurements of ice conditions and ship perfor-

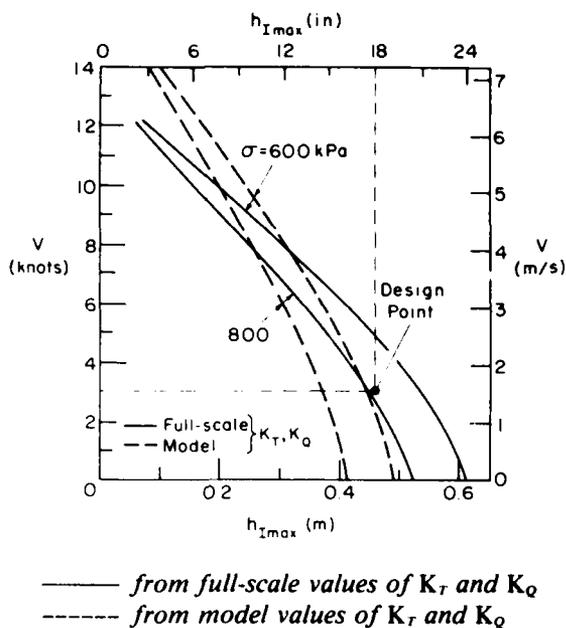


Figure 7. Predicted icebreaking capability at maximum installed shaft power of 2500 hp.

mance are correct, the discrepancy between predicted and actual performance must be due to the model test conditions and techniques.

The model test conditions, especially the Froude number, did not cover the full-scale conditions, so the model results could not be directly extrapolated to the ship conditions.

The ship model was equipped with a stock propeller that may not have performed as well as the propeller installed on the full-scale ship. To check this possibility, it would be necessary to repeat the model tests with an exact model of the actual propeller.

The ship model hull may have had a greater ice friction factor than the prototype. The model would then yield exaggerated predictions of ice resistance and consequently of the required thrust, propeller speed, torque and delivered power. Furthermore, if the model hull is rougher, the broken ice floes would tend to "slide" up the hull less readily, so more ice should be ingested into the propeller, with detrimental effects on performance. In this respect, the full-scale data in Table 6 indicate that the ship performance worsened between the trials of 31 January and those of 9 February (for example, compare the results of runs 1331 and 1110). Also, the predicted thrust, propeller speed, torque and power for the later trial runs are nearly equal to or even less than the measured values. It is possible that the hull roughness and

friction factor increased somewhat during the full-scale trials. The effect of the friction factor can and should be investigated in model tests by performing similar test programs at two or more friction factors.

Broken floes in model ice have been observed to be relatively larger than those at full scale. This difference in size has been attributed to the two-layer structure of the model ice and to its higher fracture toughness than that of ice in the field. Model ice may also contain fewer flaws and microcracks than field ice. Larger broken floes will tend to rise slower along the hull, because of increased friction, before they reach the stern area. More ice is thus ingested by the propeller, detrimentally affecting propeller characteristics, namely the thrust deduction factor, the thrust coefficient and the torque coefficient. The effect of ice floe size on propeller characteristics and resulting ship performance could be investigated by running overload propulsion tests in a precut ice channel for a range of sizes of the precut ice floes.

The dimensionless parameters F_n and C_n are assumed to be the only governing parameters for the ice resistance of a given ship. The dimensionless ice resistance, which does not contain the effect of friction explicitly derived from model tests, is then assumed to apply to the full-scale conditions. In other words, it is assumed that no scale effects are present, and that no correlation allowance, such as is applied in estimating full-scale resistance in ice-free water from model test results, is needed for the ice resistance. Tests in ice on geometrically similar models (Geosims) over a wide range of scaling ratios would be necessary to verify this assumption. However, tests in level ice with large models would require very large ice model tanks, which are only beginning to be put into operation and are very expensive.

CONCLUSIONS

On the average the predictions based on model test results of the ship performance compared reasonably well to that measured during full-scale trials. Among the several possible sources of errors that have been identified, duplication at the model scale of the ship's ice friction coefficient is considered to be critical in determining the ice resistance (and therefore the required thrust to be delivered by the propeller) and the other propulsion characteristics, such as propeller speed, torque and delivered power.

In spite of the difficulties in exactly modeling full-scale conditions, the icebreaking capabilities predicted from the model tests are in reasonable agreement with those observed during full-scale trials.

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